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PRELIMINARY EVALUATION OF THE LIFECYCLE COSTS AND MARKET BARRIERS OF REFLECTIVE PAVEMENTS

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ABSTRACT

The objective of this study is to evaluate the lifecycle costs and market barriers associated with using reflective paving materials in streets and parking lots as a way to reduce the urban heat island effect.

We calculated and compared the lifecycle costs of conventional asphalt concrete (AC) pavements to those of other existing pavement technologies with higher reflectivity – portland cement concrete (PCC), porous pavements, resin pavements, AC pavements using light-colored chip seals, and AC pavements using light-colored asphalt emulsion additives. We found that for streets and parking lots, PCC can provide a cost-effective alternative to conventional AC when severely damaged pavements must be completely reconstructed. We also found that rehabilitating damaged AC streets and intersections with thin overlays of PCC (ultra-thin whitetopping) can often provide a cost-effective alternative to standard rehabilitation techniques using conventional AC. Chip sealing is a common maintenance treatment for low-volume streets which, when applied using light-colored chips, could provide a reflective pavement surface. If the incremental cost of using light-colored chips is low, this chip sealing method could also be cost-effective, but the incremental costs of light-colored chips are as of yet uncertain and expected to vary. Porous pavements were found to have higher lifecycle costs than conventional AC in parking lots, but several cost-saving features of porous pavements fell outside the boundaries of this study. Resin pavements were found to be only slightly more expensive than conventional AC, but the uncertainties in the cost and performance data were large. The use of light-colored additives in asphalt emulsion sealcoats for parking lot pavements was found to be significantly more expensive than conventional AC, reflecting its current niche market of decorative applications.

We also proposed two additional approaches to increasing the reflectivity of conventional AC, which we call the “chipping” and “aggregate” methods, and calculated their potential lifecycle costs. By analyzing the potential for increased pavement durability resulting from these conceptual approaches, we then estimated the incremental costs that would allow them to be cost-effective compared to conventional AC. For our example case of Los Angeles, we found that those allowable incremental costs range from less than $1 to more than $11 per square yard ($1 to $13 per square meter) depending on street type and the condition of the original pavement.

Finally, we evaluated the main actors in the pavement market and the existing and potential market barriers associated with reflective pavements. Apart from situations where lifecycle costs are high compared to conventional AC, all reflective paving technologies face a cultural barrier based on the belief that “black is better”. For PCC, high first costs were found to be the most significant economic barrier, particularly where agencies are constrained by first cost. Lack of developer standards was found to be a significant institutional barrier to PCC since developers are often not held accountable for the long-term maintenance of roads after initial construction, which creates a misplaced incentive to build low first-cost pavements. PCC also faces site-specific barriers such as poorly compacted base soils and proximity to areas of frequent utility cutting.

I. INTRODUCTION

During the summer months, many cities experience the "urban heat island" effect – an increase in air temperature 6-8ºF beyond that of the surrounding rural areas. Heat islands are caused by the absence or reduced frequency of vegetation, especially trees, which normally serve to cool the air via shading and evapotranspiration, and by the presence of dark-colored surfaces, particularly roofs and pavements, which absorb sunlight and reradiate solar energy as heat (Akbari *et al.*, 1996). Heat islands are an air quality concern because they increase the frequency of smog episodes and the intensity of smog formation, a temperature-dependent photochemical reaction. Heat islands are also an energy efficiency concern because increased air temperatures raise air-conditioning loads in buildings, in turn raising energy consumption, peak energy demand, and energy prices.

Research and support for light-colored or "reflective" pavements as a way to reduce the heat island effect is just beginning in earnest. Research into other methods to reduce the heat island effect, however, has been active. Currently, three programs exist: (1) the American Society of Heating, Refrigerating, and Air Conditioning Engineers[1] (ASHRAE), which writes building energy standards, recently revised its standards to include reflective roofs as a means to reduce building air-conditioning loads (Akbari *et al.*, 1998; Akbari *et al.*, 2000a); (2) the U.S. Environmental Protection Agency (EPA) runs the ENERGY STAR Roof Products Program[2], which markets light-colored roof products via consumer education and industry partnerships; and, (3) The EPA also administers the comprehensive Heat Island Reduction Initiative[3] which includes the Urban Heat Island Pilot Project and the Cool Communities Partnership. These initiatives involve working with individual cities to quantify heat island reduction targets and implement heat island reduction strategies with a strong focus on strategic tree planting and reflective roofing.

Pavement reflectance and surface temperature are not new subjects to the scientific community. Lighting engineers have long considered pavement reflectance in the design of roadway lighting systems in Europe (CIE, 1976). In 1983, the American

[1] See www.ashrae.org
[2] See www.energystar.gov
[3] See www.epa.gov/appdstar/purchasing/programs.htm

National Standards Institute (ANSI) recognized the contribution of pavement reflectance to the performance of roadway lighting systems in its publication *American Standard Practice for Roadway Lighting* (ANSI, 1983). More recently, pavement engineers have examined the relationship between pavement surface temperature and air temperature. Solaimanian and Kennedy (1993) and Dempsey *et al.* (1995) measured and modeled both diurnal- and peak-temperature differences between air and pavement and predict that, during the summer months, pavements can get up to 40ºF hotter than the surrounding air. The relationship between pavement reflectance and surface temperature has also been studied quantitatively (Solaimanian and Kennedy, 1993; Pomerantz *et al.*, 2000b), demonstrating that increasing pavement reflectance can indeed lower pavement surface temperatures significantly.

SCOPE OF STUDY

The objective of this study is to bring the existing body of scientific knowledge into the context of today's pavement market in order to evaluate what opportunities may currently and potentially exist for reflective pavements. Specifically, we wish to evaluate the lifecycle costs and market barriers associated with using reflective paving materials in urban environments as a measure to mitigate the heat island effect.

Since heat islands are necessarily an urban phenomenon, reflective pavements for the purpose of heat island mitigation are necessarily urban pavements – streets, parking lots, sidewalks, and private surfaces like driveways, patios, and walkways. Recent studies have shown that among the different types of urban pavements, streets and parking lots account for the majority of paved surfaces in cities (Akbari *et al.*, 2000b). Thus, we have chosen to focus this study on street and parking lot pavements.

The primary purpose of this study is to calculate and compare the lifecycle costs of conventional asphalt concrete pavements to pavements with higher reflectivity. We consider five existing reflective pavement technologies – portland cement concrete, porous pavements, resin pavements, light-colored chip seals, and light-colored asphalt emulsion sealcoats – and two proposed approaches that would increase the reflectivity of asphalt concrete. We then briefly examine the market actors and driving forces associated with urban pavements, and outline the existing market barriers faced by reflective pavement technologies.

II. DETERMINING THE LIFECYCLE COSTS OF REFLECTIVE PAVEMENTS

The next section provides brief descriptions of the basic components of pavements and the pavement technologies considered in this study. We then briefly describe the methodology and data sets necessary to calculate pavement lifecycle costs and the limitations of the data used in this study.

DEFINITION OF TERMS (THE LANGUAGE OF PAVEMENTS)

The two basic components of pavements are the *aggregate* and the *binder*. The aggregate provides strength while the binder acts as glue and provides stiffness. The two most prevalent pavement technologies are *asphalt concrete* (AC) and *portland cement concrete* (PCC). *Concrete* refers to the composite of aggregate and binder while *portland cement* and *asphalt* refer to the type of binder. AC is the most common type of pavement and is typically composed of about 7% asphalt binder and 93% aggregate by weight (Asphalt Institute, 1989). PCC is the most common type of pavement for heavy traffic roads and is typically composed of about 11% portland cement binder, 33% sand, and 56% coarse aggregate (ACPA, 2000). Two other pavement types that occupy small niches in the pavement market are *porous pavements* and *resin pavements*. Porous pavements use lattices, typically made of plastic or concrete, to hold aggregate, soil, and/or grass thereby creating high-strength gravel or grass surfaces. They are porous in nature because water passes through the structure directly into the ground. Resin pavements are similar to AC except that the binder is a modified emulsion of tree resin.

Depending on the characteristics of the underlying soils, pavements are often built upon *base courses* of crushed aggregate in order to provide a stable foundation and proper drainage. Base courses can also be composed of cement- or asphalt-treated aggregate when base courses require additional strength.

As pavements age or become damaged, repair is needed. In this study we refer to two types of pavement repair – *rehabilitation* and *maintenance*. Rehabilitation refers to major repairs and typically occurs once or twice over the course of a pavement's lifetime. Maintenance refers to minor repairs that can happen as often as annually or biannually. Rehabilitation techniques for AC include patching, surface milling, overlays of new AC wearing surface,[4] and/or overlays of PCC directly on top of existing AC (commonly referred to as whitetopping).[5] Rehabilitation techniques for PCC include diamond grinding, full- and partial-depth repair, overlays of new PCC wearing surface, and/or AC overlays directly on top of existing PCC.[6] Maintenance techniques are mostly applications of surface treatments such as chip seals, asphalt emulsion sealcoats, slurry seals, and bituminous crack sealants that act to prevent the entry of moisture into the pavement, improve skid resistance, and extend pavement life.

When pavements are no longer repairable, reconstruction is necessary. *Surface reconstruction* entails removing only the AC or PCC pavement and laying new pavement on the existing base course. *Total reconstruction* includes the removal of the existing base course, grading the underlying basement soils, and placing new base course. For detailed discussions about maintenance, rehabilitation, and reconstruction techniques including materials and equipment specifications, visit the websites of the Asphalt Institute (www.asphaltinstitute.org) and the American Concrete Pavement Association (www.pavement.com).

Although not considered a part of the language of pavements until recently, pavement reflectance is a central part of this study. We characterize pavement reflectance using *albedo* (â). Albedo is defined as the reflectance of a surface averaged over a hemisphere and the solar spectrum. A perfect solar reflector has â = 1, and a perfect absorber has â = 0.

METHODOLOGY OF PAVEMENT LIFECYCLE COST ANALYSIS

We chose to follow the latest lifecycle cost analysis (LCCA) methodology recommended by the Federal Highway Administration (FHWA), modified to allow us to make comprehensive observations about the lifecycle costs of reflective and conventional

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[4] AC overlays are also called "hot mix" overlays, referring to the application method, and are typically 1.5"–2.5" thick.

[5] "Conventional" whitetopping is typically 4" thick, and "ultra-thin whitetopping" can be as thin as 2".

pavement designs over a wide range of scenarios. As an investment decision-making tool, the boundaries of pavement LCCA are drawn at the project-level such that all the pavement designs considered provide the same level of performance. In this study, we wish to compare alternative pavement designs that provide not only equivalent performance but also increased reflectivity at the pavement surface. Additionally, we wish to make observations about how pavement lifecycle costs vary over a wide range of controlling parameters such as functional class (e.g., arterial streets vs. residential streets) and maintenance policy. In this way, we draw two sets of boundaries in this study – the first being at the project-level in order to compare specific conventional and reflective pavement designs, and the second being at the pavement network-level in order to evaluate how the lifecycle costs of pavements vary in different situations. We now briefly describe the LCCA methodology applied in this study with special attention to the modifications necessary to accommodate our comprehensive approach.[7] A more detailed description of our methodology can be found in Appendix A.

Simply put, pavement LCCA is a way of calculating and comparing all the costs associated with constructing, maintaining, and rehabilitating different pavement structures over the long-term. Once alternative pavement designs have been established, the next step is to choose an analysis period and discount rate. We chose to use a real discount rate of 4% and an analysis period of 35 years as recommended by the FHWA. The third step is to estimate agency costs for each pavement design. Agency costs include the costs of construction, maintenance, and rehabilitation of pavements. Another important agency cost is residual value, sometimes referred to as salvage value. Residual value is a measure of the economic value of pavements, expressed as a discounted cost, that have service life remaining at the end of the chosen analysis period. Total agency costs are thus the sum of construction, maintenance, and rehabilitation costs over the analysis period, minus the residual value.

The fourth step is to estimate user costs for each pavement design. User costs are defined by the FHWA as "costs that are incurred by the highway user over the life of the project" (FHWA, 1998). User costs include vehicle operating costs, user delay costs,

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[6] AC overlays on top of PCC are sometimes referred to by the surface preparation method. For example, "crack and seat" refers to the cracking and stabilization of PCC slabs followed by an AC overlay.

[7] FHWA'S methodology is available online at http://restructure.fhwa.dot.gov/dp115/newfull.PDF.

and crash costs. Calculation of user costs requires data that were not available for this study, thus we did not include user costs in our LCCA. We acknowledge, however, that user costs associated with construction and major rehabilitation can be significant enough to be a determining factor in economic analyses.

Once agency costs have been estimated, net present value (NPV) is then calculated for each pavement design strategy. As shown in equation 1 below, NPV is a process by which future agency costs (maintenance or rehabilitation) are discounted (using discount rate i) in the year they occur (n), summed together with initial agency costs (construction), and then corrected for any residual value remaining at the end of the analysis period. The result is a total lifecycle cost that reconciles the timing and magnitude of future expenditures with the time value of money.

(equation 1)

$$\text{NPV} = \text{initial cost} + \sum_{n=1}^{N}\left[\text{future cost}_n \bullet \left(\frac{1}{(1+i)^n}\right)\right] - \text{residual value}$$

Residual values are calculated when the last maintenance or rehabilitation included in the analysis extends a pavement's useful life beyond the analysis period. When this situation exists, that future cost is discounted in the year it occurs and multiplied by the fraction of its service life remaining at the end of the analysis period, as described in equation 2 below. This process is a simplified way of calculating annualized costs and follows the method described in FHWA (1998).[8]

(equation 2)

when $n+\text{L}_n > \text{N}$,

$$\text{residual value} = \left[\text{future cost}_n \bullet \left(\frac{1}{(1+i)^n}\right)\right] \bullet \left(\frac{(n+\text{L}_n)-\text{N}}{\text{L}_n}\right)$$

where N = final year of analysis period
L_n = service life of future cost_n

It should be reiterated here that pavement LCCA was developed as a tool to compare the costs of alternate pavement designs that deliver equivalent levels of service, i.e.

[8] Strict calculation of annualized costs involves discounting each year's average expenditures separately.

performance. From an engineering standpoint, equivalent pavement designs are those that can support the same number of axle loads over a given period of time. Axle loads are a measure of the weight, quantity, and type of vehicles that are expected to use a given road or parking lot pavement. Starting with a minimum number of "design" axle loads, pavement engineers then typically use the design equations developed by the American Association of State Highway and Transportation Officials (AASHTO) to determine the thickness required for each component of the pavement structure, e.g. the base and surface layers.[9] These design equations require detailed measures of the physical properties of the in situ soils or subgrade and the proposed base and surface layer materials.[10]

In the absence of such physical data, there is no strict way to compare alternate pavement structures. However, there is an industry rule-of-thumb that provides first-order approximations of structural equivalency. The design equations for AC pavements include an abstract measure called a structural number (SN) which represents a composite of the physical properties and thickness of each pavement layer. SN is the product of a layer's thickness, structural coefficient (SC), and drainage coefficient (DC). Each layer's SN is then summed to derive the total SN of the pavement structure. When AASHTO engineers were developing AASHTO's design equations in the 1970s, they determined average SC's for AC wearing course, AC binder course (often called blackbase), and crushed stone base course. These values are 0.44, 0.34, and 0.14, respectively (AASHTO, 1993).[11] While SC's are not a part of the design equations for PCC, AASHTO engineers did attempt to derive SC-equivalents for PCC. The research yielded estimates ranging from 0.5 to 1.0, and many engineers and PCC-marketers have since been using 0.5 as a conservative estimate of the SC for PCC (Mack, 2000; McMullough, 2000). When comparing AC and PCC pavements in this study, we calculated SN's wherever possible in order to ensure comparison of equivalent pavement structures, to first order.

[9] For details, see AASHTO (1993).

[10] Such measures include the modulus of elasticity, the modulus of rupture, the modulus of subgrade reaction, the resilient modulus of the subgrade, and the resilient modulus of the base (AASHTO, 1993).

[11] For practical purposes, DC's are often assumed to be 1.0 (AASHTO, 1993).

DATA ISSUES

Three basic types of data were required for our study: pavement unit cost data, pavement performance data, and pavement albedo data. Analytical issues and caveats exist for each data type and are described below.

The unit costs of pavement construction (typically expressed in dollars per square yard) are difficult to generalize. From a national standpoint, unit costs can vary by as much as ±30% from region to region (RS Means, 2000). This variability is related to regional differences in labor markets and the cost and availability of raw materials (see **Table 1**).

Table 1. Average relative unit costs of site construction in selected U.S. cities (index, national average = 100)

	Relative Unit Costs		
	Material	**Labor**	**Total**
Phoenix	81.5	100.3	96.0
Los Angeles	87.0	109.5	104.2
San Francisco	131.9	111.2	116.0
Miami	106.8	73.9	81.6
Atlanta	113.4	95.6	99.8
Vegas	65.5	103.9	95.0
Washington, DC	103.5	91.0	93.9
New York City	142.9	128.3	131.7
Salt Lake City	85.1	100.0	96.5
Houston	126.9	80.7	91.5

Source: RS Means, *Site Construction & Landscape Cost Data 2000.*

Additionally, from a project standpoint, pavement unit costs are subject to large economies of scale such that the unit costs for paving projects under 1,000 square yards can be as much as 100% higher than those for identical paving projects over 10,000 square yards (see **Table 2**). For the most part, however, one can reconcile regional differences and economies of scale given enough information about location and project size.

Table 2. National average unit costs ($/square yard) for basic pavement components based on project size expressed in square yards (SY)

	Project Size	
	≤1,000 SY	≥10,000 SY
Prepare subbase	$1.35	$0.82
Grade subgrade	$0.72	$0.34
Stone base, 6”	$11.55	$7.70
Tack coat emulsion	$1.03	$0.50
AC binder course, 3”	$7.47	$5.15

Source: RS Means, *Site Construction & Landscape Cost Data 2000.*

For this study, pavement performance “data” take two forms – individual pavement/surface treatment lifetimes and long-term pavement maintenance strategies. Pavement and surface treatment lifetimes measure the service life of full-depth pavements or surface treatments up to the point where significant repair is necessary to maintain a desired level of functionality. For example, the lifetime of new, full-depth PCC pavements is usually 30 years whereas the lifetime of hot-mix asphalt overlays is usually 8-10 years. The lifetimes used in LCCA are engineering estimates (hence the previous quotations) based on performance data from past projects. Actual lifetimes can vary significantly due to climate, soil conditions, traffic, and construction practices. For this study, we account for this variability by using ranges of lifetimes for each type of pavement and surface treatment.

Long-term pavement maintenance strategies are the most critical determinant of lifecycle costs and perhaps the most variable. These strategies specify the timing and type of maintenance and/or rehabilitation for a given section or type of pavement over the entire analysis period (see **Figure 1**).

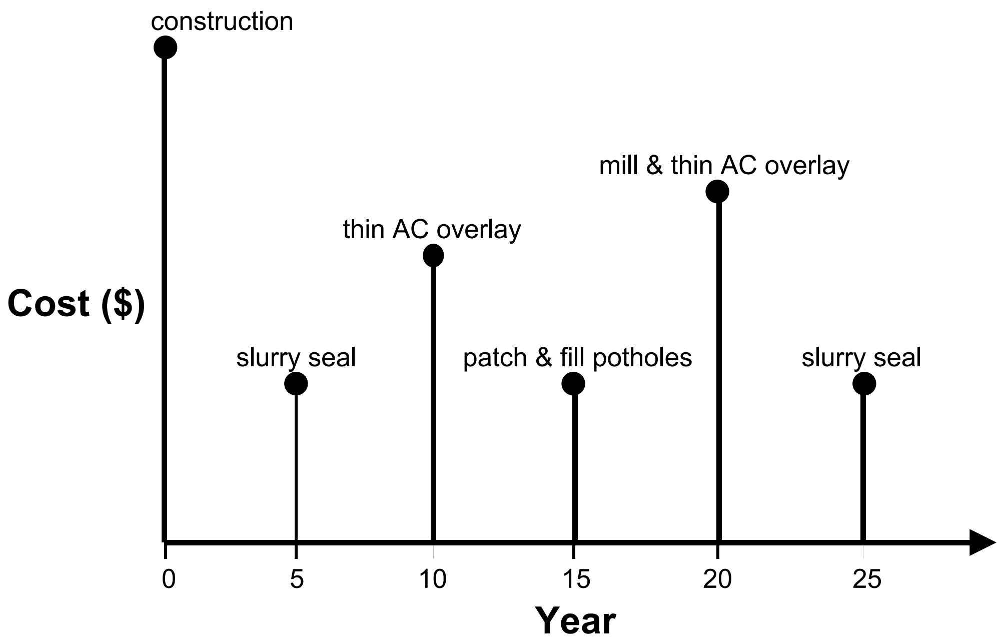

Figure 1. Example of a long-term maintenance strategy for conventional AC pavement

Constructing long-term maintenance strategies for comparative purposes such as LCCA is complex. As with pavement lifetimes, these strategies are based on engineering estimates. And although long-term strategies are commonly constructed for budget planning purposes, exactly how strictly such strategies are actually followed is difficult to determine. Deviations from long-term maintenance strategies, of course, significantly affect actual lifecycle costs. In addition to these general estimation issues, another source of variability among strategies comes from the fact that maintenance policies can vary widely. Some agencies take the "don't fix it until it's broken" approach where pavements are allowed to deteriorate significantly before major repair, while some agencies choose to maintain pavements in good condition using more frequent but less costly maintenance treatments. As with pavement lifetimes, we account for this variability by using a range of long-term maintenance strategies for each pavement type.

Pavement albedos vary from region to region (and even within regions) due to differences in the albedos of the constituent materials and particularly that of the aggregate. Pavement albedos also vary over time due to weathering, oxidation at the pavement surface, dirt and dust accumulation, tire wear, and oil deposits. The application of surface treatments also changes pavement albedo dramatically. Still, two generalizations can be made concerning how pavement albedos change over time.

First, AC pavements all start off black with albedos around 0.05 and get lighter over time, usually approaching 0.12 (see Pomerantz, 1999a). Second, PCC pavements all start off fairly light with albedos around 0.35 and get darker over time, approaching 0.25 (see Pomerantz *et al.*, 1997). Given enough data about pavement albedo and age, one can construct a relationship of pavement albedo over time. For this study, we used data collected by LBNL to construct such a relationship, the derivation and application of which is described in Section III and Appendix C later in this report.

DATA SOURCES & AVAILABILITY

As 95% of urban pavements in the United States are AC (Asphalt Institute, 2000)[12], we were able to gather comprehensive data for AC and asphaltic surface treatments with relative ease. Obtaining similar data for PCC and other pavement types proved more difficult and required the use of multiple data sources. Below, we briefly describe the data sources used for each pavement type in our study. Detailed descriptions of our data sources can be found in Appendix B.

The Metropolitan Transportation Commission's (MTC) Pavement Management System (PMS) was our primary data source for AC street pavements. MTC is the transportation-planning agency for the San Francisco Bay Area. MTC's PMS contains construction cost, maintenance cost, and lifetime estimates for AC and asphaltic surface treatments under a wide range of functional class[13] and pavement condition scenarios. These estimates are based on records from member jurisdictions and a comprehensive study of pavement maintenance practices in the Bay Area (Smith *et al.*, 1985). We complemented the data from MTC's PMS with the cost information published in the RS Means family of construction cost data books. We used the Means data in four ways: 1) to provide a common source of cost data when comparing structurally equivalent pavement designs; 2) to crosscheck other cost data sets; 3) to reconcile regional differences in materials and labor markets using their "City Cost Indexes"; and 4) to adjust historical construction cost data for inflation using their "Historical Cost Indexes".[14]

[12] The situation is quite different for interstate freeways, highways, and bridge decks where the split between AC and PCC is much more even.
[13] Functional class refers to residential streets, collector streets, and arterial streets.
[14] We investigated using producer price indexes (from the Bureau of Labor Statistics) as our inflator series but determined that the PPI series only reflect the manufacture of paving materials and not the practice of constructing pavements which includes labor and equipment costs.

Unfortunately, MTC's PMS does not contain any such information for PCC street pavements. Consequently, we used several data sources for PCC street pavements. We obtained estimates of lifetimes and maintenance strategies for full-depth PCC from the cities of Seattle and Houston, both of which maintain networks of full-depth PCC pavements. Engineers at the American Concrete Pavement Association (ACPA) provided additional input on lifetimes and maintenance strategies for full-depth PCC. We used unit cost data primarily from RS Means, supplemented by cost data collected from the Texas Department of Transportation.

We used a similar array of data sources for whitetopping. Unit costs were collected from existing projects in Washington, Tennessee, Missouri, and Kansas and supplemented by RS Means cost data. Based on input from whitetopping contractors in Missouri and Kansas and engineers at ACPA, we established conservative estimates of whitetopping lifetimes and maintenance strategies for this study based on the current 20-year design lives.[15]

We used four data sources for AC and PCC parking lot pavements. Local contractors provided the estimates of lifetimes and maintenance strategies that serve as our best-guess estimates. We also obtained unit cost estimates and maintenance strategies from previous lifecycle cost analyses (RMCPC, 1999; NRMCA, 2000; NRMCA, 1992). Again, we used RS Means data to provide a common cost data source for comparisons, crosscheck other cost data sets, reconcile regional differences, and adjust historical data. We used manufacturer estimates of unit costs and lifetimes for an asphalt emulsion color additive[16] that is available in light shades and currently occupies niche markets for which we were unable to obtain estimates from other sources.

For whitetopped parking lots, unit costs were collected from existing projects in California and Utah and supplemented by RS Means cost data. Conservative estimates of lifetimes and maintenance requirements were established using input from contractors and ACPA engineers.

[15] Since the practice of whitetopping, especially ultra-thin whitetopping, has developed only over the last decade, most existing projects have yet to reach the end of their predicted service lives, making it difficult for agencies to judge the expected lifetimes and maintenance requirements of whitetopped streets.

Our main data sources for the costs of porous pavements and resin pavements were the manufacturers themselves.[17] In the case of porous pavements, because they are mostly grass, sand, and stone, we were able to use RS Means cost data for the constituent materials based on the manufacturers' specifications for design and maintenance. The exception, of course, is that the unit costs of the porous pavement structures themselves come directly from the manufacturers.

The albedo data used in this study all come from direct measurements taken by LBNL (Pomerantz *et al.*, 2000b). For AC pavements, the data set is comprised of 38 field measurements each with a corresponding pavement age. For PCC pavements, we use a similar set of 18 measurements taken in the field. Albedo measurements of colored asphalt seal coats were limited to those taken from a local demonstration site. Measurements for resin pavements were limited to a set of lab samples provided by the manufacturer.

III. ESTIMATING THE DURABILITY BENEFITS OF HIGH-ALBEDO AC PAVEMENT

In this section, we provide a brief overview of the existing scientific evidence that supports the notion that lowering maximum surface temperatures will significantly increase the durability of AC pavements. We then propose three methods to increase the albedo of AC pavements and describe how we apply preliminary estimates of increased AC durability to the lifecycle cost analyses of those proposed methods.

In 1987, Congress established the Strategic Highway Research Program (SHRP), a five-year $150 million research effort to improve the performance, durability, and safety of U.S. roads. The final product of SHRP's asphalt research program was a system called SUPERPAVE (SUperior PERforming asphalt PAVEments) which established a new specification system for the components of AC, improved AC mix designs, and improved AC pavement performance prediction, all aimed at improving the overall performance and durability of AC. The binder specifications that emerged from SUPERPAVE use

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[16] Asphacolor Corporation (www.asphacolor.com).

maximum and minimum pavement temperatures as the key parameters for determining the binder's required "performance grade". Specifically, higher maximum pavement temperatures require higher "performance grade" binders (Cominsky *et al.*, 1994).

These specifications prominently acknowledge the importance of pavement temperature ranges, i.e. yearly maxima and minima, on the durability of AC pavement. To maintain performance over a wide range of temperatures (which is difficult for typical AC), SHRP's solution is to enhance binders with polymer additives; this makes the binder more expensive. A recent LBNL study (Pomerantz *et al.*, 2000a) has taken a different approach – lowering maximum pavement temperatures (via increased reflectivity) as a way to shrink pavement temperature ranges and improve AC durability. Specifically, the study used laboratory testing methods to establish a first order relationship between maximum pavement temperature and common AC pavement distress mechanisms, namely rutting and shoving. The results indicated a strong relationship between increases in pavement temperature and accelerated failure rates due to rutting and shoving.[18] A study by the California Department of Transportation on the relationship of temperature and embrittlement in AC pavements (a common cause of pavement cracking) yielded similar conclusions. Hardening rates were found to accelerate at higher temperatures, indicating a strong, non-linear relationship between pavement temperature and embrittlement (Kemp and Predoehl, 1981).

The results, however convincing, must be taken in context. The laboratory environment did not account for possible mitigating factors such as the cooling effects of vehicles (through shading and stirring of the surrounding air) and tire wander. Still, any increase in pavement lifetime reduces lifecycle costs, and thus we wish to incorporate the effect to some extent in our economic analysis. In order to do so, we have established a preliminary method to approximate the increase in AC pavement lifetime resulting from increases in AC pavement albedo. The method is overtly conservative in that the strong, non-linear relationship described by the laboratory results is represented by a linear relationship. Appendix C describes the method in detail.

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[17] Invisible Structures, Inc. (www.invisiblestructures.com); Bartron Corporation (www.grassroad.com); Presto Products Company (www.prestogeo.com); and Soil Stabilization Products Company, Inc. (www.sspco.org).

For this study we consider four methods to increase the albedo of AC pavements. The first method we propose is the use of high-albedo chip seals in conjunction with AC and AC overlays, which we shall refer to as the "chip seal method". Chip seals are non-structural surface treatments that consist of spreading and rolling small open-grade aggregates, or "chips", onto a layer of asphalt emulsion. Chip seals are commonly used on low-volume roads as a means to protect the underlying pavement from moisture intrusion and oxidation at the pavement surface while also providing enhanced skid resistance. In addition to using high-albedo chips in chip seals, we propose applying such chip seals in conjunction with the installation of AC and AC overlays. Since the top layer of chips are immediately exposed, this chip seal method would tend to immediately maximize the durability benefits provided to the underlying pavement from lower surface temperatures.

The second method we consider is the use of light-colored additives in asphalt emulsion sealcoats. Sealcoats are applied to AC parking lot pavements on a regular basis to prevent moisture intrusion and oxidation at the surface as well as to maintain appearance. Light-colored emulsion additives are available for decorative applications, and we propose using them in conjunction with newly constructed parking lots so as to immediately maximize the durability benefits provided to the underlying pavement from lower surface temperatures.

The third mechanism we consider is the "chipping" of new AC pavements and overlays with high-albedo chips, which we shall refer to as the "chipping method". Although not currently used in the U.S., chipping is a common practice in Great Britain as a means to provide skid resistance (Hunter, 1994). Chipping differs from chip sealing in that the chips are bitumen-coated and rolled directly into fresh AC before the binder sets without using an additional layer of asphalt emulsion. If new AC pavements and overlays were chipped with uncoated high-albedo chips, the top layer of chips would then be immediately exposed. As with the chip seal method, the chipping method would tend to

[18] This exponential relationship was demonstrated over a limited range of temperatures (40ºC, 50ºC, 60ºC). It should be noted, however, that these temperatures are representative of seasonal maximum temperatures experienced in the major heat island cities of the U.S.

immediately maximize the durability benefits afforded to the underlying pavement resulting from reduced surface temperatures.

The fourth mechanism involves substituting high-albedo aggregates for conventional aggregates in full-depth AC and AC overlays, which we shall refer to as the "aggregate method". In this method, asphalt binder would initially coat the aggregates, therefore we must take into account the lag time between the installation of new AC and the time when constituent aggregates become exposed at the surface. Derivation and application of this lag time is described in Appendix C.

IV. DEVELOPMENT OF PAVEMENT LIFECYCLE SCENARIOS

This section describes the development of the long-term maintenance strategies used for calculating lifecycle costs in this study. We first describe the development of what we determined to be the most likely range of long-term maintenance strategies applied to conventional AC pavements in major U.S. cities. We then isolate the appropriate conventional AC "base cases" against which to compare reflective pavement alternatives and describe the long-term maintenance strategies developed for those reflective alternatives. For the remainder of this report, we use the term "lifecycle scenario" to describe the construction and/or long-term maintenance of a given pavement over the analysis period.

CONVENTIONAL AC STREET SCENARIOS

The information in MTC's PMS (Smith, 1987) allowed us to develop 42 lifecycle scenarios for conventional AC streets. The determining parameters in each scenario were based on functional class and beginning and ending (or terminal) pavement condition. MTC uses a Pavement Condition Index (PCI) designed specifically for the Bay Area that allows them to compile pavement condition information in a uniform manner. PCI is a numerical rating of pavement condition. Pavement condition information, such as roughness and the types and severity of existing pavement distress, is collected in the field by technicians and used to calculate a weighted index scaled to 100. Pavements with PCI's of 70-100 are considered to be in "very good to excellent" condition, those with PCI's of 50-70 are in "fair to good" condition, those with PCI's of 25-

50 are in “poor to fair” condition, and those with PCI’s of 0-25 are in “poor” condition. There is also a distinction within the 50-70 range between the existence of “load-related” distress (e.g., rutting and shoving) and “non-load related” distress (e.g., cracking and weathering). This distinction is necessary because the repair of load-related distress is significantly different from that of non-load related distress. We use PCI to represent different maintenance policies in that we construct scenarios that reflect “don’t fix it until it’s broke” policies, policies that maintain streets in very good condition, and versions in between. We also use PCI to differentiate pavements that experience load-related distress from pavements that experience non-load related distress.

We developed lifecycle scenarios for each functional class of urban streets – arterial, collector, and residential. To account for differences in pavement maintenance policies, we consider that these streets could be maintained at different levels of deterioration (as measured by PCI) depending on the maintenance practices of local agencies. To do this, we developed one set of scenarios based on a terminal PCI of 70, another based on a terminal PCI of 50, and another based on a terminal PCI of 50 with load-related distress. For example, we begin with an arterial street whose PCI is 70-100 and choose a terminal PCI of 70. The MTC PMS states that the PCI will deteriorate from 70-100 to 70 after 7 years. The PMS then recommends application of a slurry seal. This treatment maintains the pavement’s PCI above 70 for another 7 years. At year 14, the PMS then recommends a thin AC overlay. This overlay maintains the PCI above 70 for the following 8 years. At year 22, a slurry seal is again applied which maintains the pavement’s PCI above 70 for another 7 years. Finally, at year 29, the pavement surface is milled and a thin overlay is placed which maintains the pavement’s PCI over 70 through the end of the 35-year analysis. Following these PCI-based “lifetimes” and treatment sequences of the MTC PMS, we apply the same approach to the other functional classes and terminal PCI’s. To the best of our knowledge the three terminal PCI’s we have chosen (70, 50, and 50 with load-related distress) represent the most common pavement maintenance policies.

To further develop the range of scenarios for existing streets, we also consider that streets could be in varying states of deterioration at the beginning of the analysis period. This is done by letting the starting pavement condition vary from “very good” to “poor” using four different starting PCI’s. Varying the starting PCI influences the choice and timing of only the first treatment in the analysis period and thus mainly influences the pavement's initial costs. For example, in an arterial street scenario with a starting PCI of 70-100 and terminal PCI of 70, the first treatment of the analysis period (a slurry seal) occurs only after the PCI has declined below 70 (year 7). If we change the starting PCI to 25-50, MTC's PMS recommends a different first treatment (a thick AC overlay) and that this treatment occur in the very beginning of the analysis period (year zero) since the terminal PCI is 70. In this way, varying the starting PCI's allows us to evaluate the likely range of initial costs (mostly dependent on original pavement condition), whereas varying the terminal PCI's allows us to evaluate the likely range of future costs (mostly dependent on maintenance policy).

In total, the result is a set of 4 different starting points within each of the three "maintenance policy" frameworks, applied to each of three functional classes, which totals 24 different lifecycle scenarios for existing, conventional AC streets. These scenarios are shown in Appendix D.

We also developed lifecycle scenarios that describe reconstructed pavements where adequate pavement performance cannot be easily maintained without completely rebuilding the pavement. These can be thought of as new pavements that replace old, unserviceable pavements. In these scenarios, the analysis periods all begin with the reconstruction of the pavement. Using the same terminal-PCI approach, we developed one set of scenarios based on a terminal PCI of 70, another based on a terminal PCI of 50, and another based on a terminal PCI of 50 with load-related distress. We also differentiated starting points by separating totally reconstructed streets, i.e. surface and base reconstruction, from streets with only surface reconstruction.[19] This was necessary because the cost and service lives of totally reconstructed streets are much higher than those of surface reconstructed streets. Developing these sets for each of the three functional classes results in 18 different lifecycle scenarios for reconstructed conventional AC streets. These scenarios are shown in Appendix E.

[19] Surface reconstruction differs from "surface rehabilitation" techniques like milling and hot-mix overlays in that surface reconstruction involves complete removal and replacement of the pavement layers above the base course.

Together, the above lifecycle scenarios represent our approximation of the most likely range of AC street pavement lifecycles that occur in major cities. **Table 3** summarizes the main parameters used to develop each of these scenarios.

Table 3. Matrix of lifecycle scenarios developed for conventional AC streets listed by determining parameter

Street Status	Functional Class	Starting PCI	Terminal PCI
Existing			
	Arterial	70-100	70
		70-100	50
		50	70
		50	50
		50*	70
		50*	50*
		25-50	70
		25-50	50
	Collector	70-100	70
		70-100	50
		50	70
		50	50
		50*	70
		50*	50*
		25-50	70
		25-50	50
	Residential	70-100	70
		70-100	50
		50	70
		50	50
		50*	70
		50*	50*
		25-50	70
		25-50	50
Surface Reconstructed			
	Arterial	SR	70
		SR	50
		SR	50*
	Collector	SR	70
		SR	50
		SR	50*
	Residential	SR	70
		SR	50
		SR	50*
Totally Reconstructed			
	Arterial	TR	70
		TR	50
		TR	50*
	Collector	TR	70
		TR	50
		TR	50*
	Residential	TR	70
		TR	50
		TR	50*

PCI = pavement condition index
50* = PCI of 50 with load-related distress
SR = surface-only reconstruction
TR = total reconstruction (surface layers and base course layer)

HIGH-ALBEDO AC STREET SCENARIOS

We developed lifecycle scenarios for high-albedo AC streets based on those developed for existing and reconstructed conventional AC streets. We apply our lifetime extension estimates, as described in Appendix C, to the lifetimes of AC pavements and AC overlays. We do not apply lifetime extensions to non-structural surface treatments (e.g., slurry seals or pothole patching). The methods to increase the albedo of AC street pavements considered in this study are partly conceptual and/or not currently used in the U.S. Therefore, we must make assumptions about what levels of increased albedo would likely be achievable in order to estimate the extended pavement lifetimes afforded by reductions in pavement surface temperature. We chose to evaluate high-albedo AC pavements using two levels of increased albedo, $\Delta\hat{a}=0.1$ and $\Delta\hat{a}=0.2$.

We base our lifecycle scenarios for high-albedo AC streets on the load-related distress scenarios developed for conventional AC streets, i.e. those whose terminal PCI is 50 with load-related distress. We chose to only use the load-related distress scenarios primarily because the evidence behind increased durability of high-albedo AC is highly preliminary and what evidence exists is linked to the mitigation of load-related distresses, i.e. rutting and shoving, in addition to climate-related embrittlement. We therefore do not attempt to claim durability benefits outside of the parameters described by Pomerantz *et al.* (2000a) and Kemp and Predoehl (1981).

We first evaluate lifetime extension estimates for AC overlays and reconstructed AC resulting from the chip seal, chipping, and aggregate methods at albedo increases of both $\Delta\hat{a}=0.1$ and $\Delta\hat{a}=0.2$. These lifetime extension estimates are then applied to all AC overlays and AC reconstruction that occur in the lifecycle scenarios previously developed for streets with load-related distress. Following this process for each functional class[20] and differentiating between existing, surface reconstructed, and totally reconstructed streets gives us a total of 36 lifecycle scenarios for high-albedo AC streets. **Table 4** summarizes the main parameters used to develop each of the high-albedo AC street scenarios. These scenarios are shown in Appendices D and E.

[20] We chose to apply the chip seal method only to existing streets and the chipping method only to reconstructed streets. The aggregate method was applied to both existing and reconstructed streets. The sealcoat method was only applied to parking lots.

Table 4. Matrix of lifecycle scenarios developed for high-albedo AC streets listed by determining parameter

Street Status	Method	Functional Class	$\Delta\hat{a}$	Starting PCI	Terminal PCI
Existing					
	Aggregate method	Arterial	0.1	50	50*
			0.2	50	50*
		Collector	0.1	50	50*
			0.2	50	50*
		Residential	0.1	50	50*
			0.2	50	50*
	Chip seal method	Arterial	0.1	50	50*
			0.2	50	50*
		Collector	0.1	50	50*
			0.2	50	50*
		Residential	0.1	50	50*
			0.2	50	50*
Surface Reconstructed					
	Aggregate method	Arterial	0.1	SR	50*
			0.2	SR	50*
		Collector	0.1	SR	50*
			0.2	SR	50*
		Residential	0.1	SR	50*
			0.2	SR	50*
	Chipping method	Arterial	0.1	SR	50*
			0.2	SR	50*
		Collector	0.1	SR	50*
			0.2	SR	50*
		Residential	0.1	SR	50*
			0.2	SR	50*
Totally Reconstructed					
	Aggregate method	Arterial	0.1	TR	50*
			0.2	TR	50*
		Collector	0.1	TR	50*
			0.2	TR	50*
		Residential	0.1	TR	50*
			0.2	TR	50*
	Chipping method	Arterial	0.1	TR	50*
			0.2	TR	50*
		Collector	0.1	TR	50*
			0.2	TR	50*
		Residential	0.1	TR	50*
			0.2	TR	50*

$\Delta\hat{a}$ = assumed increase in pavement albedo
PCI = pavement condition index
50* = PCI of 50 with load-related distress
SR = surface-only reconstruction
TR = total reconstruction (surface layers and base course layer)

PCC AND WHITETOPPED STREET SCENARIOS

As discussed earlier, MTC's PMS does not contain estimates of the lifetimes or maintenance strategies for PCC or ultra-thin whitetopping (UTW). However, the long-term maintenance and performance of full-depth PCC pavements tends to vary only slightly across functional classes, thus the range of likely lifecycle scenarios is much smaller than that for AC pavements. Based on information obtained from contractors, ACPA engineers, and municipal pavement managers in Seattle and Houston, we developed one lifecycle scenario for each functional class resulting in three lifecycle scenarios for full-depth PCC street pavements. In the attempt to compare structurally-equivalent AC and PCC pavements, we considered PCC pavement designs with structural numbers of 6, 5, and 4.5 for arterial, collector, and residential streets, respectively.[21] These scenarios are shown in Appendix E.

We were afforded even less detail in developing lifecycle scenarios for whitetopped streets due to a lack of historical data on whitetopping performance over various starting pavement conditions or functional classes. Based on information from contractors in Missouri and Kansas[22] and engineers at ACPA, we developed two lifecycle scenarios that represent the most common application of whitetopping in city streets today – the rehabilitation of severely distressed AC intersections using 4" UTW and the surface reconstruction of AC streets using 3" UTW. In order to fairly compare the lifecycle costs of whitetopping against conventional AC, we also developed lifecycle scenarios for reconstructing distressed AC streets (using the same method described previously for conventional AC) and a severely distressed AC intersection (using frequent conventional AC overlays). These scenarios are shown in Appendices D and E.

PARKING LOT SCENARIOS

For parking lots, developing lifecycle scenarios for LCCA is more straightforward than for streets. Generally, parking lots are maintained by private firms that rely on contractor-recommended practices to determine how and when to rehabilitate their pavements. Parking lot maintenance is often based on maintaining appearance as well as performance, so parameters like pavement condition do not necessarily determine how those pavements are maintained. For this study, we developed lifecycle scenarios for parking lots based on past studies and recommendations from contractors. In the case of porous pavements and resin pavements, we put together scenarios based on manufacturer-recommended practices.

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[21] These structural numbers imply plain jointed PCC pavement depths of 12", 10", and 9" for arterial, collector, and residential streets, respectively.

[22] These two states along with Tennessee have the majority of installed whitetopping in the U.S. For more information on the state of whitetopping in the U.S., visit the ACPA website at http://www.pavement.com/.

We developed 17 lifecycle scenarios for parking lots: three conventional AC scenarios, three PCC scenarios, three porous pavement scenarios, one resin pavement scenario, six high-albedo AC scenarios, and one whitetopping scenario. All of the lifecycle scenarios begin with construction of the pavement and, where possible, assume a structural number of 2.5. The three conventional AC scenarios differ in the timing and type of maintenance or rehabilitation applied and represent our upper bound, best guess, and lower bound estimates. The same applies to the three PCC scenarios. The lifecycle scenarios for porous pavements differ only in the costs of construction, which mainly reflects differences in the costs of the lattice units and the constituent materials used for base courses. The lifecycle scenario for resin pavements is based on typical maintenance for AC parking lots but with different construction costs.

We consider one mechanism to increase the albedo of AC parking lots – the sealcoat method described earlier.[23] We base our lifecycle scenarios for high-albedo AC parking lots on those developed for conventional AC. Assuming that sealcoats enhanced with light-colored additives are applied during initial construction, we apply our lifetime extension estimates to the underlying AC pavement using no lag time. We consider two levels of increased albedo ($\Delta\hat{a}$=0.1 and $\Delta\hat{a}$=0.2) within each scenario (lower bound, best guess, and upper bound), yielding a total of six lifecycle scenarios for high-albedo AC parking lots. All parking lot scenarios are shown in Appendix F.

V. RESULTS OF PAVEMENT LIFECYCLE COST ANALYSES

The complete results of our pavement lifecycle cost analyses (LCCA's) are shown in Appendices D, E, and F. The unit cost data sets used in those analyses are listed in Appendices G, H, and I. We summarize the results of our pavement lifecycle cost analyses below.

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[23] Chipping and chip sealing are not used as surface treatments in parking lots and are thus not considered in our high-albedo scenarios for parking lots.

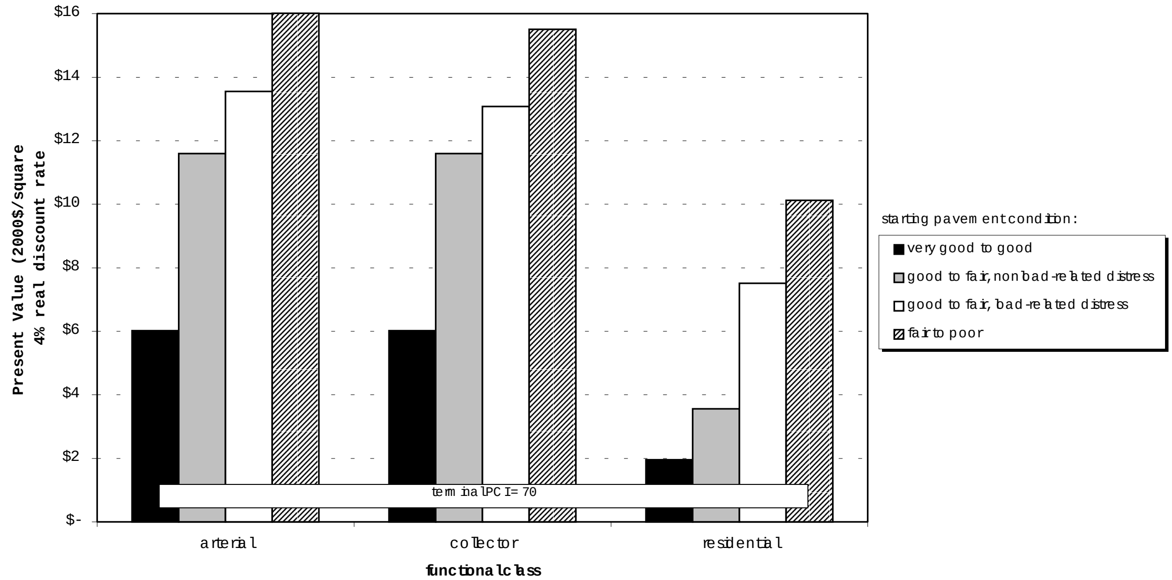

Figure 2. Total lifecycle costs ($/SY) of existing AC streets using terminal pavement condition index (PCI) of 70

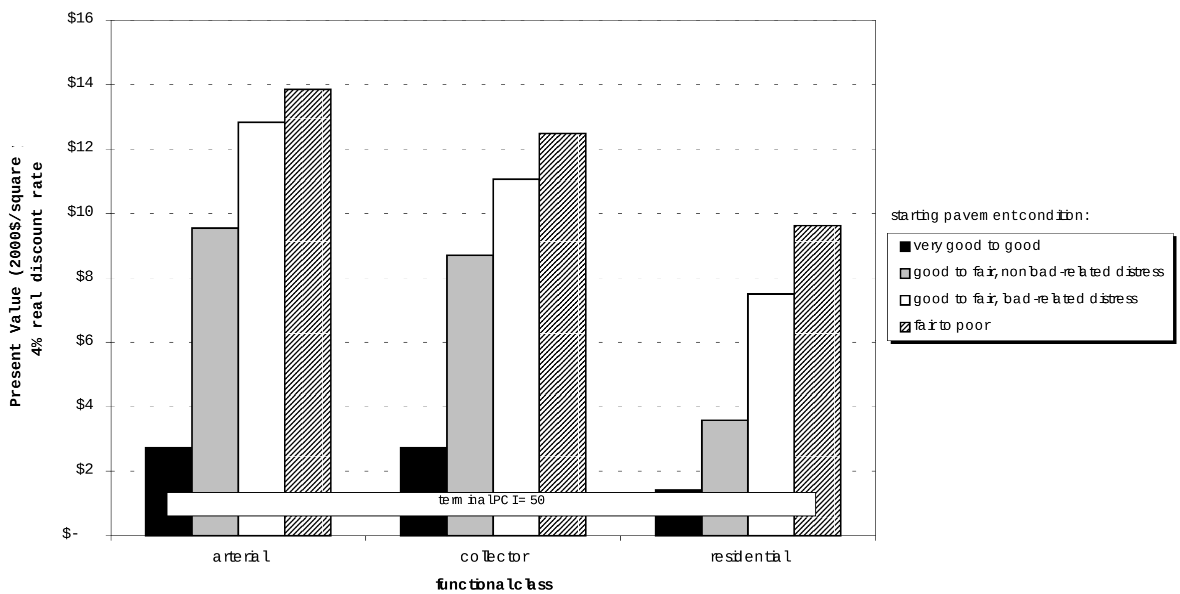

Figure 3. Total lifecycle costs ($/SY) of existing AC streets using terminal pavement condition index (PCI) of 50

CONVENTIONAL AC STREETS

We present first the results of our LCCA's for conventional AC streets. These results are based mainly on the information obtained from MTC's PMS; therefore the results are specific to pavements in the San Francisco Bay Area and should not be interpreted as representative for all major cities. All costs are expressed in 2000 dollars.

The results of our LCCA's for existing, conventional AC streets are summarized in **Figures 2 and 3.** The results are presented this way so as to illustrate the relative magnitudes of the lifecycle costs of existing AC streets across starting PCI, terminal PCI, and functional class. From Figures 2 and 3, we can see that there is little difference between the lifecycle costs of AC arterial streets and AC collector streets, but the lifecycle costs of AC residential streets are significantly lower. We can also see that the relative costs of arterial and collector streets starting in "good to fair" and "fair to poor" condition are much higher than those starting in "very good" condition. Another important observation is that streets with load-related distress have significantly higher lifecycle costs than similar streets with nonload-related distress.

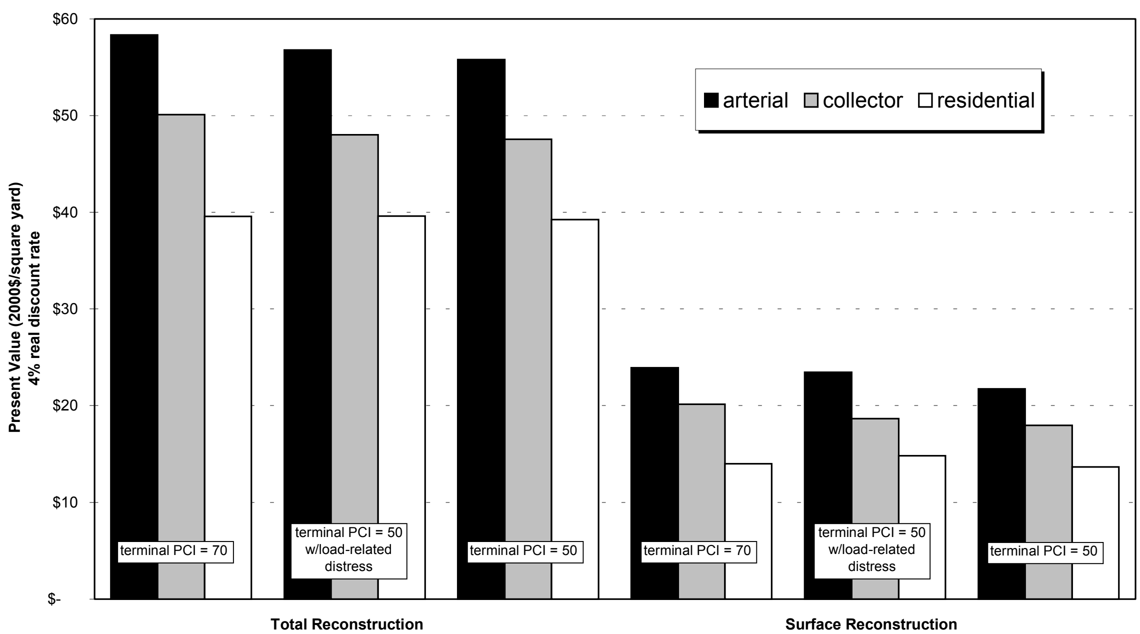

Figure 4. Total lifecycle costs ($/SY) of reconstructed AC streets using terminal pavement condition index (PCI) of 70, 50 w/load-related distress, and 50 w/nonload-related distress

The results of our LCCA's for reconstructed AC streets are summarized in **Figure 4**. We can see from Figure 4 that the difference in lifecycle costs between arterial and collector streets is significant for reconstructed streets, which was not the case for existing streets. Additionally, we see that the effect of varying the terminal PCI has less of an impact on the costs of reconstructed streets than existing streets.

HIGHER REFLECTIVITY STREETS

We now summarize the results of our LCCA's comparing conventional AC street pavements to alternatives with higher reflectivity.

Two important comments about interpreting these results. First, the scenarios comparing conventional AC and reflective pavement alternatives describe prices and weather conditions in Los Angeles (as opposed to San Francisco). Qualitatively, we chose LA mainly because it is a more significant heat island than San Francisco, but also because the smog- and energy-savings potential from the use of reflective pavements has been previously estimated by researchers at LBNL (Taha, 1997). Thus, our results can be set in a relevant context with previous heat island research. Quantitatively, we have chosen to use data for Los Angeles in our calculations because the lifetime extension estimates applied to the high-albedo AC scenarios are city-specific (see Appendix C).[24] As such, we have also scaled the unit costs from MTC's PMS and the RS Means databooks to LA prices. All costs are expressed in 2000 dollars.

Second, we were unable to reasonably estimate the incremental costs of using high-albedo aggregates in the high-albedo AC scenarios.[25] In our calculations, we were therefore forced to assume no incremental costs associated with using the aggregate, chip seal, and chipping methods in our LCCA's. In order to interpret the results of our high-albedo AC scenarios correctly, we present a "delta cost" for each high-albedo AC scenario which is the cost difference from the "base case" (conventional AC) scenario. These "delta costs" are negative and are best interpreted as an approximation of the allowable incremental cost of using high-albedo aggregates that permits high-albedo AC

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[24] We obtained enough weather data to estimate AC pavement durability benefits from increased-albedo for Phoenix, Houston, Sacramento, New Orleans, Salt Lake City, Atlanta, and Miami (see Appendix C).
[25] See the "Future Work" section later in this report for a discussion of the issues involved with estimating the incremental cost of using high-albedo aggregates.

to be cost-effective compared to conventional AC. Large delta costs therefore represent better opportunities for cost-effectiveness than small delta costs. If it is the case that high-albedo aggregates are readily available for little or no incremental cost, the "delta costs" then represent the range of lifecycle cost savings potentially afforded by high-albedo AC. In the absence of such knowledge, however, it is more appropriate to consider these "delta costs" as the allowable margins for cost-effectiveness compared to conventional AC. Note that these "delta costs" are not expressed for full-depth PCC, ultra-thin whitetopping, porous, or resin pavements since all the costs of these pavements were known and referenced. All lifecycle cost results are displayed using three significant digits.

Our results for existing streets comparing the lifecycle costs of conventional AC to the lifecycle costs of high-albedo AC using the aggregate method and the chipseal method are shown in **Table 5**.

Table 5. Lifecycle costs ($/SY) of conventional and high-albedo AC pavements, using lifecycle scenarios describing existing streets and load-related distress

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost	Delta Cost
Arterial Streets					
Conventional AC	$ 6.53	$ 6.07	$ 1.08	$ 11.50	
High-â AC (aggregate method), Δâ=0.1	$ 6.53	$ 3.48	$ 0.20	$ 9.81	$ (1.71)
High-â AC (aggregate method), Δâ=0.2	$ 6.53	$ 3.31	$ 0.54	$ 9.31	$ (2.22)
High-â AC (chipseal method), Δâ=0.1	$ 7.19	$ 3.25	$ 1.19	$ 9.25	$ (2.27)
High-â AC (chipseal method), Δâ=0.2	$ 7.19	$ 2.96	$ 1.58	$ 8.57	$ (2.95)
Collector Streets					
Conventional AC	$ 6.53	$ 3.71	$ 0.30	$ 9.94	
High-â AC (aggregate method), Δâ=0.1	$ 6.53	$ 2.62	$ 1.33	$ 7.82	$ (2.12)
High-â AC (aggregate method), Δâ=0.2	$ 6.53	$ 2.44	$ 1.41	$ 7.56	$ (2.38)
High-â AC (chipseal method), Δâ=0.1	$ 7.19	$ 2.43	$ 1.74	$ 7.89	$ (2.05)
High-â AC (chipseal method), Δâ=0.2	$ 7.19	$ 0.42	$ 0.06	$ 7.56	$ (2.38)
Residential Streets					
Conventional AC	$ 5.19	$ 1.55	$ -	$ 6.74	
High-â AC (aggregate method), Δâ=0.1	$ 5.19	$ 1.24	$ 0.35	$ 6.07	$ (0.67)
High-â AC (aggregate method), Δâ=0.2	$ 5.19	$ 1.16	$ 0.39	$ 5.96	$ (0.78)
High-â AC (chipseal method), Δâ=0.1	$ 5.85	$ 1.06	$ 0.51	$ 6.41	$ (0.33)
High-â AC (chipseal method), Δâ=0.2	$ 5.85	$ 0.46	$ 0.05	$ 6.26	$ (0.48)

From Table 5, we observe that the increased AC pavement lifetimes afforded by increases in albedo appear to have a significant impact on lifecycle costs. For arterial and collector streets, the delta costs are ~$2/SY (~$2.40/m^2). For residential streets, the delta costs are much less, averaging approximately ~$0.60/SY (~$0.70/m^2). This difference reflects the fact that residential streets have lower initial costs and longer expected lifetimes than arterial and collector streets. Thus, potential increases in AC lifetime have a smaller impact on the lifecycle costs of residential streets compared to arterial or collector streets when evaluated over a 35-year period. Table 5 also suggests that for existing streets, the aggregate method has approximately the same impact on lifecycle costs as the chipseal method, despite the lag time associated with the aggregate method.

Table 6 presents the results of our whitetopping LCCA for existing streets. Currently, the most common application of whitetopping is the rehabilitation of distressed AC intersections. For comparison, we developed a lifecycle scenario for a conventional AC intersection requiring overlays every four years (see Appendix D). Since the real-world lifecycle of whitetopping is still unknown, we also scale the analysis periods of the whitetopped and conventional AC intersection scenarios to the current "design life" of whitetopping, 20 years. From information gathered from contractors and ACPA engineers, we determined that using analysis periods over 20 years to evaluate the lifecycle costs of whitetopping is problematic since there is still very little real-world experience with "post-whitetopping" rehabilitation.

Table 6. Lifecycle costs ($/SY) of conventional AC and ultra-thin whitetopping pavements, using lifecycle scenarios describing the rehabilitation of a severely distressed intersection

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
Conventional AC	$ 9.61	$ 19.30	$ -	$ 28.90
UTW (4")	$ 24.50	$ 3.39	$ -	$ 27.90

From Table 6 we observe that the lifecycle costs of an intersection rehabilitated with whitetopping are approximately $1/SY (~$1.20/m^2) lower than those of an intersection rehabilitated with conventional AC overlays. Given the amount of uncertainty involved in this comparison, however, a more reasonable observation is that the lifecycle costs of the two rehabilitation approaches appear to be very close. There are significant differences in future costs between the two approaches, however. This difference reflects the low-maintenance requirements of whitetopping versus the high frequency of AC overlays. Although we do not calculate user costs in this study, it is safe to assume that the work zone user costs of the AC overlay approach, resulting from rehabilitation work every four years, would be much higher than those of the whitetopping approach since little to no maintenance or rehabilitation has been necessary over the design life of existing whitetopping projects.

We now summarize our LCCA results for reconstructed streets. First we present the results for totally reconstructed streets (which includes base layer reconstruction) and compare the lifecycle costs of total reconstruction with conventional AC, plain jointed PCC, and high-albedo AC using the aggregate method and the chipping method. Again, we use Los Angeles as our example city and scale unit costs to Los Angeles prices. For conventional and high-albedo AC, we compare results based on “load-related distress” lifecycle scenarios. The results are shown in **Table 7**.

Table 7. Lifecycle costs ($/SY) of conventional AC, PCC, and high-albedo AC pavements, using lifecycle scenarios describing totally reconstructed streets and load-related distress

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost	Delta Cost
Arterial Streets					
Conventional AC	$ 49.60	$ 2.18	$ 0.76	$ 51.00	
Plain, Jointed PCC (6”)	$ 43.90	$ 9.30	$ 5.49	$ 47.70	
High-â AC (aggregate method), Δâ=0.1	$ 49.60	$ -	$ -	$ 49.60	$ (1.40)
High-â AC (aggregate method), Δâ=0.2	$ 49.60	$ -	$ 5.09	$ 44.50	$ (6.50)
High-â AC (chipping method), Δâ=0.1	$ 50.00	$ -	$ 5.13	$ 44.90	$ (6.10)
High-â AC (chipping method), Δâ=0.2	$ 50.00	$ -	$ 10.20	$ 39.80	$ (11.20)
Collector Streets					
Conventional AC	$ 42.20	$ 2.06	$ 1.13	$ 43.10	
Plain, Jointed PCC (5”)	$ 41.30	$ 4.22	$ 5.16	$ 40.40	
High-â AC (aggregate method), Δâ=0.1	$ 42.20	$ -	$ -	$ 42.20	$ (0.90)
High-â AC (aggregate method), Δâ=0.2	$ 42.20	$ -	$ 4.33	$ 37.90	$ (5.20)
High-â AC (chipping method), Δâ=0.1	$ 42.60	$ -	$ 4.37	$ 38.20	$ (4.90)
High-â AC (chipping method), Δâ=0.2	$ 42.60	$ -	$ 8.71	$ 33.90	$ (9.20)
Residential Streets					
Conventional AC	$ 34.80	$ 1.98	$ 1.18	$ 35.60	
Plain, Jointed PCC (4.5”)	$ 38.20	$ -	$ 4.77	$ 33.40	
High-â AC (aggregate method), Δâ=0.1	$ 34.80	$ -	$ 1.88	$ 32.90	$ (2.70)
High-â AC (aggregate method), Δâ=0.2	$ 34.80	$ -	$ 5.09	$ 29.70	$ (5.90)
High-â AC (chipping method), Δâ=0.1	$ 35.20	$ -	$ 5.15	$ 30.10	$ (5.50)
High-â AC (chipping method), Δâ=0.2	$ 35.20	$ -	$ 7.82	$ 27.40	$ (8.20)

From Table 7 we again observe that the increased AC pavement lifetimes afforded by increases in albedo appear to have a significant impact on lifecycle costs. For arterial and collector streets, the delta costs are between \$5-\$11/SY (\$6-\$13/m^2) with the exception of the Δâ=0.1 scenarios using the aggregate method which exhibit delta costs of only ~\$1/SY. These scenarios suggest that for reconstructed streets, the impact of the aggregate method’s lag time could significantly compromise potential lifecycle cost savings. For residential streets, the delta costs of high-albedo AC are much larger for reconstructed streets than for existing streets. This is because the initial costs of reconstructed residential streets are much higher than those of existing residential streets.

From Table 7 we also observe that the lifecycle costs of full-depth PCC streets appear to be \$2-\$6/SY (\$2-\$7/m^2) less than those for conventional AC. This result, although consistent with what we expect, contains large uncertainties, as we were unable to establish strict structural equivalency between these pavements due to a lack of information on the structural designs of totally reconstructed AC pavements as described in MTC's PMS.

Our LCCA results for surface reconstructed streets are presented in **Table 8**. We compare the lifecycle costs of surface reconstruction with conventional AC and high-albedo AC using the aggregate method and the chipping method. We scale unit costs to LA prices and base comparisons on "load-related distress" lifecycle scenarios. From Table 8 we observe that the delta costs of high-albedo AC in surface-reconstruction scenarios are ~\$1-2/SY and that the aggregate method yields approximately the same lifecycle cost benefit as the chipping method.

Table 8. Lifecycle costs (\$/SY) of conventional AC and high-albedo AC pavements, using lifecycle scenarios describing surface reconstructed streets and load-related distress

Present Values using 4% real discount rate, expressed in 2000\$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost	Delta Cost
Arterial Streets					
Conventional AC	\$ 18.20	\$ 3.11	\$ 0.12	\$ 21.20	
High-â AC (aggregate method), Δâ=0.1	\$ 18.20	\$ 2.05	\$ 1.11	\$ 19.10	\$ (2.10)
High-â AC (aggregate method), Δâ=0.2	\$ 18.20	\$ 1.88	\$ 1.24	\$ 18.80	\$ (2.40)
High-â AC (chipping method), Δâ=0.1	\$ 18.60	\$ 1.76	\$ 1.27	\$ 19.10	\$ (2.10)
High-â AC (chipping method), Δâ=0.2	\$ 18.60	\$ 0.37	\$ 0.22	\$ 18.70	\$ (2.50)
Collector Streets					
Conventional AC	\$ 14.80	\$ 2.60	\$ 0.65	\$ 16.70	
High-â AC (aggregate method), Δâ=0.1	\$ 14.80	\$ 1.93	\$ 1.31	\$ 15.40	\$ (1.30)
High-â AC (aggregate method), Δâ=0.2	\$ 14.80	\$ 0.45	\$ -	\$ 15.20	\$ (1.50)
High-â AC (chipping method), Δâ=0.1	\$ 15.20	\$ 0.42	\$ 0.06	\$ 15.60	\$ (1.10)
High-â AC (chipping method), Δâ=0.2	\$ 15.20	\$ 0.37	\$ 0.26	\$ 15.30	\$ (1.40)
Residential Streets					
Conventional AC	\$ 11.40	\$ 2.60	\$ 0.65	\$ 13.30	
High-â AC (aggregate method), Δâ=0.1	\$ 11.40	\$ 1.93	\$ 1.31	\$ 12.00	\$ (1.33)
High-â AC (aggregate method), Δâ=0.2	\$ 11.40	\$ 0.45	\$ -	\$ 11.80	\$ (1.50)
High-â AC (chipping method), Δâ=0.1	\$ 11.80	\$ 0.42	\$ 0.06	\$ 12.20	\$ (1.10)
High-â AC (chipping method), Δâ=0.2	\$ 11.80	\$ 0.37	\$ 0.26	\$ 11.90	\$ (1.40)

In **Table 9**, we compare the lifecycle costs of total and surface reconstruction with conventional AC to the lifecycle costs of rehabilitation with whitetopping. Again, a 20-year analysis period is used in the comparison due to the uncertainty of the longer-term lifecycle of whitetopping.

From Table 9 we observe that the lifecycle costs of whitetopping are much lower than those of total reconstruction with conventional AC but \$2-9/SY (\$2-11/m^2) greater than those of conventional surface reconstruction. Again, due to the uncertainty involved, a reasonable conclusion would be that the lifecycle costs of whitetopping are in the range that provides a cost-effective alternative to the total reconstruction of AC streets. Second to the rehabilitation of AC intersections, whitetopping's most common application today is as an alternative to reconstructing distressed AC streets.

Table 9. Lifecycle costs (\$/SY) of conventional AC and ultra-thin whitetopping pavements, using lifecycle scenarios describing reconstructed streets

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
Totally Reconstructed Streets				
Conventional AC, arterial	$ 49.60	$ -	$ 7.35	$ 42.20
Conventional AC, collector	$ 42.20	$ -	$ 7.03	$ 35.20
Conventional AC, residential	$ 34.80	$ -	$ 6.96	$ 27.80
Surface Reconstructed Streets				
Conventional AC, arterial	$ 18.20	$ 0.65	$ 0.39	$ 18.50
Conventional AC, collector	$ 14.80	$ 0.65	$ 0.47	$ 15.10
Conventional AC, residential	$ 11.40	$ 0.65	$ 0.47	$ 11.60
UTW (3")	$ 20.90	$ 0.23	$ -	$ 21.10

PARKING LOTS

We now summarize the LCCA results for parking lot pavements. We compare the lifecycle costs of conventional AC, plain jointed PCC, porous pavement, resin pavement, and high-albedo AC using the sealcoat method. We also present the results of a parking lot reconstruction scenario comparing conventional AC and whitetopping. All lifecycle scenarios used in the parking lot comparisons begin with construction of the pavement and assume 35-year design lives (i.e., no residual values) with the exception of the reconstruction scenarios, which are scaled to the 20-year design life of whitetopping. Unlike our LCCA's for street pavements, we include the cost of "striping" (painting parking stalls) in our parking lot LCCA's since parking lots are restriped with much higher frequency than streets and as such restriping can have an impact (albeit small) on the long-term maintenance costs of parking lots.

Tables 10 and 11 show the results of our parking lot LCCA's. Full-depth PCC exhibits the lowest lifecycle costs, followed by conventional AC. Whereas the initial costs of PCC are slightly higher than conventional AC, the future costs of PCC are much lower and result in lower lifecycle costs. The lifecycle costs of high-albedo AC are higher than conventional AC in our parking lot scenarios due to the incremental cost of using high-albedo sealcoats. These light-colored asphalt emulsion sealcoats are currently used as decorative treatments and are up to \$3/SY (\$3.60/m^2) more expensive than the standard emulsion sealcoats commonly used on parking lot pavements.

Resin pavements exhibit fairly low lifecycle costs in our analysis. These results should be interpreted with caution, however, due to the uncertainty in unit costs, long-term performance, and maintenance. Currently, resin pavements are used mostly as historical walkways and bikeways, and little is known about their performance as parking lot pavements. Laboratory tests indicate that the strength of resin pavements is equivalent to AC pavements, but data on long-term performance and maintenance are not yet available.

Table 10. Lifecycle costs (\$/SY) of conventional AC, PCC, porous, resin, and high-albedo AC pavements, using lifecycle scenarios describing new parking lots

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
AC - high maintenance	$ 17.00	$ 14.00	$ -	$ 31.00
AC - best guess maintenance	$ 17.00	$ 7.89	$ -	$ 24.89
AC - low maintenance	$ 17.00	$ 7.78	$ -	$ 24.78
PCC - high maintenance	$ 17.70	$ 6.19	$ -	$ 23.90
PCC - best guess maintenance	$ 17.70	$ 5.08	$ -	$ 22.80
PCC - low maintenance	$ 17.70	$ 4.39	$ -	$ 22.10
Porous pavement - Invisible Structures, Inc.	$ 34.80	$ 6.22	$ -	$ 41.00
Porous pavement - Bartron Corp.	$ 42.50	$ 6.22	$ -	$ 48.70
Porous pavement - Presto Products Co.	$ 34.80	$ 6.22	$ -	$ 41.00
Resin pavement - Soil Stabilization Co.	$ 27.10	$ 5.03	$ -	$ 32.10
High-â AC (sealcoat method) - high, Δâ=0.1	$ 23.20	$ 15.20	$ -	$ 38.40
High-â AC (sealcoat method) - high, Δâ=0.2	$ 23.20	$ 13.00	$ -	$ 36.20
High-â AC (sealcoat method) - best guess, Δâ=0.1	$ 23.20	$ 12.50	$ -	$ 35.70
High-â AC (sealcoat method) - best guess, Δâ=0.2	$ 23.20	$ 12.10	$ -	$ 35.30
High-â AC (sealcoat method) - low, Δâ=0.1	$ 23.20	$ 11.20	$ -	$ 34.40
High-â AC (sealcoat method) - low, Δâ=0.2	$ 23.20	$ 11.20	$ -	$ 34.40

Porous pavements exhibit the highest lifecycle costs in our parking lot analyses. There is an important caveat to note, however, in that the primary cost benefit of porous pavements did not fall within the boundaries of our LCCA's. Reduced storm water management is one of the primary cost savings of porous pavements, since the need for extensive drainage systems is greatly reduced by draining runoff directly into the ground. We could not include drainage systems in our LCCA's because the design and resulting costs of such systems are dependent on factors which we could not account for in a comprehensive manner such as annual rainfall, parking lot size, and proximity to secondary sources of runoff. In terms of heat island mitigation, porous pavements also provide the additional benefit of increased grass cover, which can serve to cool surrounding air directly via evapotranspiration.

Table 11 compares the lifecycle costs of parking lots reconstructed with conventional AC to those rehabilitated with whitetopping. Again, the analysis period is reduced to 20-years to reflect the design life of whitetopping. The results indicate that the lifecycle costs of whitetopping are significantly lower than reconstructing a parking lot with conventional AC.

Table 11. Lifecycle costs ($/SY) of conventional AC and ultra-thin whitetopped pavements, using lifecycle scenarios describing reconstructed parking lots

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
Conventional AC - high	$ 23.60	$ 7.70	$ -	$ 31.30
Conventional AC - best guess	$ 23.60	$ 4.44	$ -	$ 28.00
Conventional AC - low	$ 23.60	$ 4.21	$ -	$ 27.80
UTW (4")	$ 15.90	$ 2.36	$ -	$ 18.30

In all our whitetopping comparisons, it is clear that whitetopping is a cost-effective alternative to reconstruction with conventional AC. It should be noted, however, that this comparison is only valid when conventional AC pavements have reached the end of their design lives and/or suffered significant pavement distress, particularly rutting and shoving. In these situations, conventional AC rehabilitation such as AC overlays have already run their course and the only remaining option is to reconstruct. This is the particular market niche in which whitetopping currently competes. It provides a medium-term alternative to AC pavement reconstruction (and defers those costs for up to 20 years), and, in the case of severely distressed AC, it provides a reliable structural rehabilitation for pavement sections prone to severe rutting and shoving.

VI. PAVEMENTS MARKET ASSESSMENT

With the perspective of our preliminary evaluation of pavement lifecycle costs, we now briefly examine the pavements market. We first describe the main actors and driving forces in the market for pavements and then outline the main market barriers that currently exist for reflective pavement designs.

ACTORS & DRIVING FORCES

The market for road pavements is unlike markets for other heat island-mitigation technologies like reflective roof products. In particular, road pavements are an integral part of the public infrastructure, and therefore the consumers of pavement services (the public) do not purchase those services directly. Rather, states and municipalities pay directly for pavement services using monies from public revenue sources (e.g., taxes, bonds, levies). Moreover, pavement services command large portions of public finances. In fiscal year 1997-98, for example, municipal expenditures on the construction and maintenance of city streets in California exceeded $2.6 billion (Office of the State Controller, 1999).

The three main actors in the market for road pavements are local governments (counties and municipalities) which pay to construct and maintain pavements, contractors which are paid to do the work, and the suppliers that provide the paving materials. State-level Departments of Transportation (DOTs) can influence contractors and material suppliers by determining specifications for the materials and designs used in public roads. Regional transportation planning agencies such as MTC often provide decision-making tools and resources to municipalities and can thus also influence pavement markets indirectly.

By and large, however, local governments are the most influential actors in pavement markets. The driving forces within local governments, therefore, tend to be the most influential driving forces in pavement markets. The amount of annual funding available for pavement construction and maintenance is the primary driving force at the local-government level. Funding levels determine how many paving contracts can be awarded and how those contracts are prioritized. Funding levels also influence the amount of staff-level resources available for managing pavements such as engineering and contract-management services. In fiscal year 1997-98, municipalities in the state of California derived 71.5% of their funding for street purposes from local sources,[26] 23.5% from state sources,[27] and 5% from federal sources (Office of the State Controller, 1999). Pavement maintenance policies are another important driving force within municipalities and can vary widely from one city to the next. While many cities have adopted proactive maintenance practices where emphasis is placed on frequent preventative maintenance (so as to avoid costly rehabilitation projects), some cities still operate under the "don't fix it until it's broke" paradigm where pavements are allowed to deteriorate significantly before repair. Such policies save money in the short-term but can also increase future costs.

Another important set of actors in the market for road pavements is the developers that build new roads, typically for new residential and commercial areas. Developers pay the initial costs of constructing new roads, but then municipalities inherit the responsibility of maintaining them. This is a unique facet of the pavements market in that new roads are often built by actors who are not obligated to maintain them over the course of their service life.

The market for parking lot pavements, on the other hand, is quite different. The actors are limited to contractors, material suppliers, and the private firms that pay to construct and maintain parking lots. In contrast to road pavements, state and regional agencies do not specify materials or pavement designs for parking lot pavements. The driving forces within private firms are fundamentally different than those in municipalities. Because firms are only responsible for a relatively small paved area, they do not need to actively "manage" their pavements as cities must do for roads. Thus firms do not require significant annual funding allocations for pavement services. Firms therefore seek to optimize cost and service and are more likely to make long-term pavement investments. Some private firms also tend to value the appearance of pavements as much as performance.

[1] Local funding sources include gasoline taxes, bonds, levies, general funds, and public utilities revenue.
[2] State funding sources include highway user taxes, motor vehicle license revenue, and state aid funds.

BARRIERS TO REFLECTIVE PAVEMENTS

AC currently dominates markets for road and parking lot pavements in the U.S. While there are some cities that use PCC streets and roads (e.g., Seattle and Houston), they are few and far between. The use of PCC in parking lots is more prevalent than in roads but is still secondary to the use of AC. The market for porous pavements is composed mostly of overflow parking lots and emergency access lanes, and the market for resin pavements is composed mostly of historical walkways and dust- and erosion-control applications.

Why is AC so dominant? In almost every scenario, the answer is first cost. Even in cases where the lifecycle costs of AC may be higher than a more reflective alternative, the low first costs of AC in many cases make it the only affordable choice for agencies or firms constrained by limited budgets and immediate needs. For developers, an opposite paradigm applies – the low first costs of AC make it the more profitable business choice in most cases. From the perspective of public agencies, this “misplaced incentive” is problematic in terms of pavement management in that it discourages developers from constructing low lifecycle-cost pavements with high first costs. This market barrier could be mitigated by the introduction of developer standards requiring low lifecycle cost pavement designs and by changing institutional arrangements such that developers are held responsible for pavement maintenance for longer periods of time after initial construction.

A similar “misplaced incentive” can also exist within agencies that have fixed budgets and many miles of roads needing repair. Because of the low first costs of reconstruction and/or repair with AC, more miles of road can be repaired in the short-term with AC compared to lower lifecycle-cost alternatives that have higher first costs. This barrier could be mitigated by requiring local agencies to consider lifecycle costs in pavement management decision-making. Such requirements already exist at the state and federal level (see references in Appendix A).

Why are the first costs of AC so low? The primary reason is that the costs of the constituent materials of AC are much lower than those of PCC, porous pavement, or resin pavement. For road pavements, the equipment costs associated with AC are also lower than those of PCC. The short project lengths involved with AC pavements also contribute to low first costs relative to PCC pavements. Newly-laid AC roads can be reopened to traffic in a matter of hours whereas new, full-depth PCC roads must cure over the course of days. The PCC industry has developed "fast-track" mixes and techniques[28] that allow for shorter project lengths, but they still lag significantly behind those of AC. The most competitive scenarios for PCC in terms of project length are applications of ultra-thin whitetopping using fast-track mixes which are reported to have curing times of as little as 8 hours (Sullivan, 2000).

For parking lots, another aspect of the dominance of AC is the general cultural belief that "black is better." Fresh, black AC is commonly equated with high-quality pavement. To this end, asphalt maintenance contractors actually add carbon black to parking lot slurry seals and asphalt emulsion seal coats (Reyner, 2000). The carbon black is an added cost that serves no real function other than to blacken the sealant. This market barrier applies not only to PCC, porous pavements, and resin pavements but also to light-colored asphalt emulsion additives like Asphacolor, high-albedo chip seals, and the use of high-albedo aggregate in AC.

Besides first costs and project length, there are important project-level barriers to the use of full-depth PCC, primarily the impact of utility cutting on pavement lifecycle costs. When street networks coincide spatially with utility networks (water, power, sewage, etc.), pavement sections must be removed when these utility networks need repair or augmentation. For streets where such utility activity is likely to occur many times over the life of the pavement, the total cost of repairing utility cuts is often a determining factor when agencies are considering paving alternatives. Because the unit costs of partial- and full-slab replacement for PCC streets are expensive compared to AC patching, conventional AC pavements are favored in these situations. The characteristics of the underlying soils can also be a determining factor when considering paving alternatives. Base soils of uniform strength and compaction are most favorable for full-depth PCC. However, where base soils are of non-uniform strength, the additional cost proper compaction or a stabilizing base course (often cement-treated) can be prohibitive.

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[3]See *Fast-Track Concrete Pavements*, TB004P, American Concrete Pavement Association, Skokie, IL, 1994.

There are also three important institutional-level market barriers specific to PCC. The first is a lack of information and knowledge both at the municipal- and contractor-level regarding the long-term performance advantages of PCC, especially whitetopping and ultra-thin whitetopping. Related to this is a relative lack of PCC contractors compared to AC contractors which inhibits competitive bidding on PCC projects and limits paving options for agencies and firms (Hawbaker, 2000). The lack of developer standards for new roads can also be considered an institutional barrier for PCC. Since arguments for the cost-effectiveness of PCC roads are based on long service life and low maintenance requirements, developers who are not required to consider low lifecycle-cost designs and are not held responsible for long-term or even medium-term maintenance of new roads simply have no incentive to invest in PCC.

VII. FUTURE WORK

Through the course of this study, we identified several data sets and estimation issues that affect the economic analysis of pavements and the comprehensive evaluation of reflective pavements as a heat island mitigation measure. We discuss the future work required to address these evaluation issues below.

What is the lifecycle of whitetopping?

Because whitetopping is a still a maturing technology, existing projects have yet to firmly establish the expected service life or optimal maintenance strategies for both conventional and ultra-thin whitetopping. Detailed cost and performance tracking of whitetopping projects is necessary in order to reconcile engineering predictions with real-world performance. Since we know that the performance of AC pavements varies depending upon functional class, it is also necessary to track projects by function, i.e. intersections vs. parking lots vs. streets, in order to determine how whitetopping performance varies.

What PCC pavement structures are most appropriate for comparing the lifecycle costs of different street pavements?

Due a lack of information about the structural designs of arterial, collector, and residential AC streets described in MTC's PMS, we were forced to assume that full-depth PCC pavements with structural numbers of 6.0, 5.0, and 4.5 were structurally equivalent to their AC counterparts. In the absence of site-specific data on the physical properties of in situ subgrades and soils, it is necessary to determine what PCC pavement structures are most appropriate for the comprehensive comparison of lifecycle costs across functional classes and design options.

How do the albedos of pavements and surface treatments change over time?

The albedo data sets used in this study did not include any measurements of common surface treatments like chip seals, slurry seals, or emulsion seal coats. To be able to accurately estimate the evolution of a pavement's albedo over its entire service life, it is necessary to know how albedo varies with the age of surface treatments. This can be done by measuring the albedo of pavements where the age of the surface treatment is known. Ages can be determined from contract records. Our albedo data set was also limited to pavements in the San Francisco Bay Area. Since we know that pavements age differently in different climates, it is also necessary to measure how pavement albedos change in other climates.

How much do the albedos of AC and PCC vary from region to region?

Again, since our albedo data set was limited to local pavements, it is necessary to determine if pavement albedos are significantly different in other regions of the country. From the information we obtained regarding regional production of different types of aggregates, we know that the aggregates used in Texas pavements are different from those used in San Francisco pavements, but exactly how much those pavements differ regionally in terms of albedo needs to be determined from direct measurements.

How do reductions in maximum surface temperature affect the durability of AC?

The results of Pomerantz et al. (2000a) indicate a strong, non-linear relationship between reduced surface temperature and increased AC pavement lifetime before failure due to rutting, shoving, and embrittlement. Based on these conclusions we established a preliminary method to estimate the durability benefits of high-albedo AC for the purpose of incorporating those benefits into our economic analyses. Since we have shown that those benefits can indeed have a significant impact on lifecycle costs, it is necessary to refine our estimates by making additional field or accelerated laboratory measurements of the relationship between maximum surface temperatures and AC pavement lifetime.

How much can the albedo of AC be increased by using high-albedo aggregates?

In this study, we proposed three mechanisms to increase the albedo of AC pavements through the use of high-albedo aggregates – the aggregate method, the chip seal method, and the chipping method. We assumed that these mechanisms would produce increases in albedo of 0.1 and 0.2. The extent and longevity of potential increases in albedo from these mechanisms under real-world conditions should be explored.

What are the incremental costs of using the highest-albedo aggregates available?

For our current economic analyses, we assumed no incremental costs associated with using high-albedo aggregates in AC. This assumption implies not only that high-albedo aggregates are available, but that they are located within 25 miles of the project (beyond which additional surcharges are usually applied). While we were able to find comprehensive aggregate production information by type and region from the U.S. Geological Survey, we could not reasonably estimate corresponding albedos without direct measurements and therefore could not determine what the potential incremental costs of using relatively high-albedo aggregates might be. In order to estimate the potential heat island benefits of using such aggregates in AC pavements, we must know the albedos of aggregates currently used for AC pavements and the albedos of the lightest-colored aggregates available in the region, if any. Similarly, in order to estimate the incremental costs of using high-albedo aggregate in AC pavements, we must also know the sources of both conventional and high-albedo aggregates. The application of a geographic information system to address these estimation issues should be explored.

What are the potential market penetration rates of reflective pavements and what are realistic energy- and smog-reduction potentials over time?

Current estimates of the energy- and smog-reduction potential from using reflective pavements are based on 100% market penetration. These estimates do not attempt to clarify the amount of time necessary to achieve 100% penetration. Given that economic arguments could be made for the use of reflective pavements or that policy mechanisms could be put in place to promote reflective pavements, it is necessary to estimate heat island reduction potentials over time using realistic penetration rates. This would not only frame the estimates in real-world parameters but provide planners and regulators with useful information.

VIII. SUMMARY

In this study, we calculated and compared the lifecycle costs of conventional AC and several reflective pavement technologies in the context of their use in urban streets and parking lots. We also assessed the primary market barriers associated with reflective pavement technologies. Our findings are summarized in **Table 12** and we discuss those findings below.

Full-depth PCC and high-albedo AC pavements exhibited the lowest lifecycle costs in our study. However, our cost estimates of full-depth PCC, although consistent with what we expected, contain large uncertainties due to the fact that we could not firmly establish that we were comparing equivalent pavement structures. Despite these uncertainties, however, full-depth PCC pavement is a proven technology that is used extensively in several major U.S. cities. PCC is the strongest pavement technology known today and is best suited for areas with high truck volumes as exhibited by its frequent use in bridge decks, interstates, and elevated highways. However, PCC is also used in low-volume areas because of its low maintenance requirements. The most significant market barrier to full-depth PCC pavements is its high first cost when compared to conventional AC. This barrier is augmented by the fact that county and municipal agencies are often constrained by first costs. Moreover, developers who build new roads and are not held accountable for the long-term maintenance of newly constructed roads tend to choose low first-cost pavement designs so as to maximize profit margins. At the project level, non-uniform strength or compaction of base soils and frequent utility cutting can also pose significant barriers to the use of full-depth PCC pavements.

Whitetopping also exhibited low lifecycle costs when compared to reconstructed and frequently-rehabilitated AC pavements. Whitetopping is a rapidly maturing technology with over 150 installations currently in city streets. Although the cost estimates used in our comparisons were confirmed by contractors and industry experts, we were forced to shorten the analysis period from 35 years to 20 years because of the uncertainty involved in estimating post-whitetopping paving options. Still, our results indicate that whitetopping is a cost-effective alternative to reconstructing conventional AC pavements and a cost-effective option for rehabilitating AC pavements prone to rutting and shoving distresses.

Our estimates of the lifecycle costs of increased-albedo AC pavements were the lowest of all the alternative pavement technologies considered. However, these estimates did not attempt to estimate the full incremental costs associated with these approaches because we could not reliably estimate the incremental cost of using high-albedo aggregates and chips. Thus the lifecycle cost savings implied by our results are better interpreted as approximations of the allowable incremental costs (delta costs) of using high-albedo aggregates that would permit these approaches to be cost-effective compared to conventional AC. From a technical perspective, chip sealing is already a common maintenance treatment used on AC pavements throughout the U.S. The chipping method is used extensively in Great Britain and while it is not currently optimized for reflectivity, the practice and method are well developed. In contrast, the proposed aggregate method is currently a conceptual approach and has yet to be tested in the field. Similarly, the use of uncoated chips in the chipping method is novel and needs testing. Still, both the aggregate method and the chip seal method do not require significant changes to current AC paving practices, and in that respect seem readily accessible once proven to be effective. Moreover, the evidence of increased AC pavement durability from decreased pavement surface temperature is convincing enough to warrant further investigation into these simple approaches. If the incremental costs of these pavements are indeed low and the durability benefits produce significant increases in pavement lifetimes, the lifecycle costs of these pavements would be significantly lower than conventional AC in cities with major heat islands.

The lifecycle costs of porous pavements and AC pavements using asphalt emulsion sealcoats with light-colored additives were higher than conventional AC pavements. In the case of porous pavements, some key cost savings fell outside the boundaries of this study (i.e., reduced storm water management) which, if considered, could lower the lifecycle costs significantly relative to conventional AC. Because of their grass and/or gravel surfaces, porous pavements are not suitable high-volume applications like streets or public parking lots, but they are suitable for low-volume applications such as overflow parking and emergency access lanes. Light-colored asphalt emulsion additives are an existing technology, but the incremental costs associated with them are significant. Because its existing market is decorative applications, the technology has not been optimized for reflectivity or high traffic-volume applications. However, given the development of a light-colored asphalt emulsion additive with lower incremental costs, its use in parking lot applications requires no changes in current paving practices other than choosing an alternative sealcoating product. As asphalt emulsion color additives gain market share, it is expected that their costs will come down over time.

Finally, the lifecycle costs of resin pavements, while only slightly higher than conventional AC, were the most uncertain of all the pavements considered in terms of unit costs, long-term performance, and maintenance. Laboratory tests indicate that the strength of resin pavements is equivalent to that of AC pavements. However, the performance of resin pavements in streets is still untested and few parking lot installations currently exist to provide reliable performance estimates.

Table 12. Summary of reflective pavement technology assessment

	Paving Technology	Applications				LCC	Tech Maturity	Pros	Cons	Market Barriers
		Arterial Streets	Collector Streets	Residential Streets	Parking Lots					
Technologies currently in use in U.S.	**Portland cement concrete**	X	X	X	X	LCC competitive with conventional AC reconstruction	Used extensively in several major cities; existing street installations up to 70 years old	Long service life; low maintenance requirements; high strength	High first cost	Agencies constrained by first costs; misplaced incentives for developers; future costs of repairing utility cuts can be prohibitive
	Whitetopping	X	X	X	X	LCC competitive with conventional AC reconstruction	Over 150 existing street installations up to 10 years old	Low maintenance; alternative to reconstructing distressed AC; performance of existing projects better than expected	High first cost; not suitable for high truck-volume streets	Lack of information; lack of contractors and competitive bidding
	High-albedo chip seals in conjunction with AC and ACOLs		X	X		If incremental costs low and durability benefits significant, LCC can be significantly lower than conventional AC	Common surface treatment on low-volume streets	Does not require changes in current maintenance methods; only that it be done in conjunction with all new/reconstructed AC and ACOLs using high-â chips	Incremental costs and availability of high-â chips unknown; low-volume streets only	Potential lack of proximity to sources of high-albedo aggregates
	Porous pavements				X	Current LCC higher than conventional AC	Used widely for parking lots & access lanes; many installations up to 15 years old	Long service life; low maintenance (watering/mowing); minimizes stormwater runoff; provides durable green space	High first cost; only suitable for low-volume parking lots and access lanes	Not suitable for high-volume applications
	High-albedo asphalt emulsion sealcoats				X	Current LCC higher than conventional AC	Established niche market for parking lots & private surfaces; existing installations up to 8 years old	Does not require changes in current construction/maintenance methods, only changes in selection of surface treatment	Expensive; existing high-â sealcoat emulsions are decorative; technology not yet optimized for reflectivity	"Black is better" culture
Technologies in development/not used in U.S.	**Resin pavements**				X	Current LCC higher than conventional AC	No existing street installations; few existing parking lot installations	Lab tests indicate strength equivalent to AC pavements	Existing installations mostly bikeways, walkways, access lanes; performance in streets and parking lots unknown	Lack of testing infrastructure and demonstration sites
	High-albedo aggregates in AC and ACOLs	X	X	X		If incremental costs low and durability benefits significant, LCC can be significantly lower than conventional AC	No existing installations	Does not require changes in current construction methods, only changes in selection of constituent aggregates	Incremental costs and availability of high-â aggregates unknown; lag time associated with realizing durability and reflectivity benefits	Potential lack of proximity to sources of high-albedo aggregates
	High-albedo "chipping" of AC and ACOLs	X	X	X		If incremental costs low and durability benefits significant, LCC can be significantly lower than conventional AC	No existing installations in U.S., common practice in Britain	Requires only small changes in current construction methods	Incremental costs and availability of high-â chips unknown; maintenance over long term unknown	Potential lack of proximity to sources of high-albedo aggregates Lack of US experience

ACOL = asphalt concrete overlay
â = albedo

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APPENDIX A. METHODOLOGY OF PAVEMENT LIFECYCLE COST ANALYSIS

The methodology of pavement lifecycle cost analysis (LCCA) is well established. Several state transportation agencies (Michigan, Iowa, and California) have mandated the use of LCCA on large highway projects since the 1980s. Beginning in 1991, the federal government has required the consideration of lifecycle costs in both metropolitan and statewide transportation planning. In 1993, the American Association of State Highway and Transportation Officials (AASHTO) revised its *Guide for Design of Pavement Structures* to include LCCA as the preferred tool for economic evaluation of design strategies (AASHTO, 1993). Since then, several additional federal mandates have further refined the principles and application of LCCA in pavement design. In 1998, the Federal Highway Administration (FHWA) published its recommended procedures for conducting LCCA of pavements, *Life-Cycle Cost Analysis in Pavement Design: In Search of Better Investment Decisions* (FHWA, 1998).

We have chosen to follow the latest FHWA-recommended procedures for our study, modified to allow us to make comprehensive observations about the lifecycle costs of reflective and conventional pavement designs over a wide range of scenarios. We now describe the LCCA methodology applied in this study with special attention to the modifications necessary to accommodate our comprehensive approach.[29]

Once alternative pavement designs have been established, the next step is to choose an analysis period and discount rate. The FHWA-recommended analysis period for highway pavements is 35 years minimum so as to account for at least one major pavement rehabilitation in the analysis. The FHWA recommends using real discount rates between 3% and 5%. These discount rates are used to deflate future maintenance and rehabilitation costs and can have a significant impact on the results. For this study, we have chosen to use a real discount rate of 4%.

The third step is to estimate agency costs for each pavement design. Agency costs include the costs of construction, maintenance, and rehabilitation of pavements. Each of these agency costs can be further separated into labor, material, equipment,

[4] FHWA's complete methodology is available online at http://restructure.fhwa.dot.gov/dp115/newfull.PDF.

engineering, and administration costs. Another agency cost important to LCCA is residual value, sometimes referred to as salvage value. Residual value is a measure of the economic value of pavements, expressed as a discounted cost, that have service life remaining at the end of the chosen analysis period. Total agency costs are thus the sum of construction, maintenance, and rehabilitation costs over the analysis period, minus the residual value.

The fourth step is to estimate user costs for each pavement design. User costs are defined by the FHWA as "costs that are incurred by the highway user over the life of the project" (FHWA, 1998). User costs are primarily separated into work zone user costs (associated with construction, rehabilitation, and maintenance) and normal operation user costs (associated with daily use). While work zone user costs can vary significantly between pavement designs, differences in normal operation user costs are often negligible. Similarly, major work zone user costs associated with construction and rehabilitation projects significantly outweigh minor work zone user costs associated with routine maintenance. Major work zone user costs are separated into vehicle operating costs, user delay costs, and crash costs. The calculation of major work zone user costs requires detailed data on the characteristics of the work zone and normal traffic. The types of data needed include the following: work zone length, number and capacity of open lanes, duration and timing of lane closures, posted speeds, availability and characteristics of alternative routes, projected average annual daily traffic (AADT) volumes of normal and alternative routes, the respective 24-hour directional hourly demand distributions for those routes, and the vehicle classification distribution of projected traffic streams.

For this study, due to the lack of appropriate data, we have chosen not to calculate user costs. Fewer than half of state DOTs and very few municipalities include user costs in pavement LCCA. We acknowledge, however, that major work zone user costs can be significant enough to be a determining factor in economic analyses. For a detailed discussion of user cost estimation procedures, see Curry and Anderson (1972) and FHWA (1989).

The final step in pavement LCCA is to compute, using the cost variables described above, net present value (NPV) for each pavement design strategy. As shown in equation 1 below, NPV is a process by which future agency costs (maintenance or rehabilitation) are discounted (using discount rate i) in the year they occur (n), summed together with initial agency costs (construction), and then corrected for any residual value remaining at the end of the analysis period. The result is a total lifecycle cost that reconciles the timing and magnitude of future expenditures with the time value of money.

(equation 1)

$$\text{NPV} = \text{initial cost} + \sum_{n=1}^{N}\left[\text{future cost}_n \bullet \left(\frac{1}{(1+i)^n}\right)\right] - \text{residual value}$$

Residual values are calculated when the last maintenance or rehabilitation included in the analysis extends a pavement's useful life beyond the analysis period. When this situation exists, that future cost is discounted in the year it occurs and multiplied by the fraction of its service life remaining at the end of the analysis period, as described in equation 2 below. This process is a simplified way of calculating annualized costs and follows the method described in FHWA (1998).[30]

(equation 2) when $n+\text{L}_n > \text{N}$,

$$\text{residual value} = \left[\text{future cost}_n \bullet \left(\frac{1}{(1+i)^n}\right)\right] \bullet \left(\frac{(n+\text{L}_n)-\text{N}}{\text{L}_n}\right)$$

where N = final year of analysis period
L_n = service life of future cost_n

[5] Strict calculation of annualized costs involves discounting each year's average expenditures separately.

APPENDIX B. DATA SOURCES & AVAILABILITY

One sentence summarizes the availability of urban pavement lifecycle cost data – 95% of the urban pavements in the United States are asphalt (Asphalt Institute, 2000).[1] It follows then that while we have been able to gather comprehensive data for AC and asphaltic surface treatments with relative ease, obtaining similar data for PCC and other pavement types has proven much more difficult and required the use of multiple data sources. We now describe the data sources used for each pavement type in our study.

STREET PAVEMENTS – AC AND ASPHALTIC SURFACE TREATMENTS

Our primary data source comes from the Metropolitan Transportation Commission's (MTC) Pavement Management System (PMS). MTC is the transportation planning agency for the San Francisco Bay Area. In 1983, MTC began development of a software-based PMS to assist jurisdictions in network-level pavement management. The PMS contains three main components: 1) a survey-based pavement condition inventory, 2) a recommended schedule of maintenance treatments for each level of pavement condition by pavement type, and 3) a network-level decision tree that helps prioritize capital improvement projects. While MTC's PMS does not compute strict LCCA itself, it does contain construction cost, maintenance cost, and lifetime estimates for AC and asphaltic surface treatments under a wide range of functional class[2] and pavement condition scenarios. These estimates are based on records from member jurisdictions and a comprehensive study of pavement maintenance practices in the Bay Area (Smith *et al.*, 1985). Unfortunately, MTC's PMS does not contain any such information for PCC pavements or PCC overlays.

To complement the data from MTC's PMS, we also have chosen to use cost information published in the RS Means family of construction cost data books. The RS Means Company collects materials, labor, and equipment cost data from contractors, manufacturers, distributors, and dealers across the United States and Canada for over 50,000 construction items. They then calculate national averages for each item and

[1] The situation is quite different for interstate freeways, highways, and bridge decks where the split between AC and PCC is much more even.
[2] Functional class refers to residential streets, collector streets, and arterial streets.

publish the results in a series of annual cost data books. These books are primarily used as tools to provide construction cost estimates for architects, facilities managers, engineers, and the like. For this study, we use the Means data in four ways: 1) to provide a common source of cost data when comparing structurally equivalent pavement designs, 2) to crosscheck other cost data sets, 3) to reconcile regional differences in materials and labor markets using their "City Cost Indexes", and 4) to inflate historical construction cost data using their "Historical Cost Indexes".[3]

STREET PAVEMENTS – FULL-DEPTH PCC AND WHITETOPPING

We use several data sources for PCC street pavements. Lifetimes and maintenance strategies of full-depth PCC were surveyed from the cities of Seattle and Houston, both of which maintain networks of full-depth PCC pavements. Engineers at the American Concrete Pavement Association (ACPA) provided additional input on lifetimes and maintenance strategies of full-depth PCC. We use unit cost data primarily from RS Means and supplement that data set with cost data collected from the Texas Department of Transportation.

We use a similar array of data sources for whitetopping. Unit costs were collected from existing projects in Washington, Tennessee, Missouri, and Kansas. This primary cost data was also supplemented by RS Means cost data. Since the practice of whitetopping (especially ultra-thin whitetopping) has developed only over the last decade, most existing projects have yet to reach the end of their predicted service lives, making it difficult for agencies to judge the expected lifetimes and maintenance requirements of whitetopped streets. Based on input from whitetopping contractors in Missouri and Kansas and engineers at ACPA, we established conservative estimates of whitetopping lifetimes and maintenance for this study.

[3]We investigated using producer price indexes (from the Bureau of Labor Statistics) as our inflator series but determined that the PPI series only reflect the manufacture of paving materials and not the practice of constructing pavements which includes labor and equipment costs.

PARKING LOT PAVEMENTS – AC AND ASPHALTIC SURFACE TREATMENTS

We use four data sources for AC parking lots. Lifetimes and maintenance strategies were surveyed from local contractors and serve as our best-guess estimates. We also obtained unit cost estimates and maintenance strategies from previous lifecycle cost analyses published by PCC trade associations (RMCPC, 1999; NRMCA, 2000; NRMCA, 1992), which serve as our upper-bound estimates. As with AC street pavements, we use RS Means data to provide a common cost data source for comparisons, crosscheck other cost data sets, reconcile regional differences, and inflate historical data. Finally, we use manufacturer estimates[4] of unit costs and lifetimes for a light-colored asphalt emulsion sealcoat technology that currently occupies niche markets for which we were unable to obtain estimates from other sources.

PARKING LOT PAVEMENTS – FULL-DEPTH PCC AND WHITETOPPING

We use three data sources for full-depth PCC parking lots. As with our data for AC parking lots, lifetimes and maintenance strategies were surveyed from local contractors and serve as our best-guess estimates. We also obtained unit cost estimates and maintenance strategies from previous lifecycle cost analyses published by PCC trade associations (RMCPC, 1999; NRMCA, 2000; NRMCA, 1992), which serve as our lower-bound estimates. Again, RS Means data is used to provide a common cost data source for comparisons, crosscheck other cost data sets, reconcile regional differences, and inflate historical data.

For whitetopped parking lots, we use the same data collection approach that we use for whitetopped streets. Unit costs were collected from existing projects in California and Utah and supplemented by RS Means cost data. Conservative estimates of lifetimes and maintenance requirements were established using input from contractors and ACPA engineers.

[4] Asphacolor Corporation (www.asphacolor.com); California Pavement Maintenance.

PARKING LOT PAVEMENTS – POROUS PAVEMENTS

Similar to the situation with high-albedo emulsion sealcoat technology, our main data sources for the costs of porous pavements are the manufacturers themselves.[4] However, because porous pavements are mostly grass, sand, and stone, we are able to use RS Means cost data for the constituent materials based on the manufacturers' specifications for design and maintenance. The exception, of course, is that the unit costs of the porous pavement structures themselves come directly from the manufacturers.

PARKING LOT PAVEMENTS – RESIN PAVEMENTS

Resin pavements currently occupy the smallest niche market of all the pavement technologies included in this study. We rely solely on the unit cost and lifetime estimates provided by the manufacturer.[5]

PAVEMENT ALBEDO

The albedo data used in this study all come from direct measurements taken by LBNL (Pomerantz *et al.*, 2000b). For AC pavements, the data set is comprised of 38 field measurements each with a corresponding pavement age. For PCC pavements, we use a similar set of 18 measurements taken in the field. Albedo measurements of colored asphalt seal coats were limited to those taken from a local demonstration site. Measurements for resin pavements were limited to a set of lab samples provided by the manufacturer.

[5]Soil Stabilization Products Company, Inc. (www.sspco.org)

APPENDIX C. ESTIMATING INCREASED LIFETIME OF HIGH-ALBEDO AC

We developed the following method for estimating the increased lifetime of high-albedo AC pavements based on the results from Pomerantz *et al.* (2000a).

Damage to AC pavements due to rutting, shear stress (shoving), and embrittlement seems to have a critical onset at pavement temperatures of about 105ºF. If the cause of pavement failure is one of these mechanisms, then the rate of failure will depend on the amount of time the pavement is above 105ºF and the amount of traffic experienced during that time. An idealized function (equation C-1 below) describing the rate of temperature-related failure of AC pavements is the product of pavement temperature above the critical temperature, $T_p(t)$-T_c, the length of time above the critical temperature, t, and the amount of traffic during that time, N(t), integrated over time.

(equation C-1)

$$\text{damage} = K\int \left(T_p(t) - T_c\right)^a \bullet t^b \bullet N(t)^c \, dt$$

Ideally, the constant K and the exponents a, b, and c would be obtained from experimental data. However, in the simplest approximation – ignoring the non-linearity of failure rates with increases in temperature and assuming that the difference between pavement temperature (T_p) and air temperature (T_a) is linear with the albedo (â) of the pavement – the lifetime of AC pavements before failure will be approximately proportional to the amount of time T_p is above 105ºF.

Some of the theory has been published by Solaimanian and Kennedy (1993). They show that the difference between the maximum T_p and the maximum T_a is dependent on latitude (which determines the maximum insolation), but that at a given latitude, the changes in T_p are equal to the changes in T_a. They find maximum temperature difference at 38º latitude to be 40ºF. Whereas Solaimanian and Kennedy calculate maximum temperature differences, Dempsey *et al.* (1995) calculate average annual temperature differences. They find that the average annual temperature difference between T_p and T_a in Reno, Nevada is 30ºF and the average difference during the summer months is 40ºF, which agrees with Solaimanian and Kennedy.

We find that in the hot part of the day that $dT_p/d\hat{a}$ = -7ºF/0.1 (Pomerantz *et al.*, 2000b). For a given dâ of 0.2, for example, dT_p = -14ºF. The original pavement would reach 105ºF when T_a is about 30º F lower, on average, or 75ºF. We can find how many hours T_a is above 75ºF over the course of a year by consulting weather records such as those in Olsen *et al.* (1984). They list the number of hours above a given temperature for every large city. They also give the cooling degree hours (CDH) which is a measure of how far and how high T_a goes above some selected base temperature. For example, Phoenix has 585 hours/year above 75ºF between 10am and 12 noon for which the CDH are 8800ºF-hrs/year. The sum of all the hours above 75ºF from 10am to 6pm is 1917/year, and the CDH are 32,900ºF-hrs/year. This is the time during which most damage to pavements occurs. If the T_p could be reduced by 14ºF by increasing the albedo by 0.2, then the air would have to be 90ºF to raise the T_p to the critical value of 105ºF. The amount of time this occurs can be found from the weather data. For Phoenix, again, the total annual hours above 90ºF are 1148 and the CDH are 9,900ºF-hrs/year. The damaging hours are reduced by perhaps (1917-1148)/1917 or 40% and the reduction in CDH is (32,900-9,900)/32,900 or 70%. This suggests that, in Phoenix, the lifetime of AC pavements before failure could be increased by upwards of 40-70% by increasing the albedo by 0.2. (The amount may be greater than 40-70% because the damage appears to increase non-linearly with temperature above the critical temperature in laboratory tests.)

Thus the general equations for determining the increase in AC pavement lifetime before failure due to rutting and shoving from an increase in albedo are:

(equation C-2) For standard AC, $T_p = T_a + 30ºF$

$$\therefore \text{ assuming } T_{p\_critical} = 105ºF = T_{a\_critical} + 30ºF$$
$$\text{then } T_{a\_critical} = 75ºF$$

(equation C-3) For increased-albedo AC, $dT_p/d\hat{a} = -7ºF/0.1$

$$\therefore \text{ given } d\hat{a}=0.1,\ T_{p\_critical} = 105ºF = T_{a\_critical} + (30ºF-7ºF) = T_{a\_critical} + 23ºF$$
$$\text{then } T_{a\_critical} = 82ºF$$

$$\therefore \text{ given } d\hat{a}=0.2,\ T_{p\_critical} = 105ºF = T_{a\_critical} + (30ºF-15ºF) = T_{a\_critical} + 15ºF$$
$$\text{then } T_{a\_critical} = 90ºF$$

(equation C-4)

$$\%\text{ increase in AC lifetime} \approx \%\text{ reduction in CDH above critical temperature}$$

$$\approx \frac{\left(\text{CDH above } T_{a\_critical}\right) - \left(\text{CDH above } T_{a\_critical} \text{ for given } d\hat{a}\right)}{\left(\text{CDH above } T_{a\_critical}\right)}$$

From the weather data available in Olsen et al. (1984), we can find the annual average cooling degree-hours above the critical temperatures of 75ºF (for standard AC), 82ºF (for AC with dâ=0.1), and 90ºF (for AC with dâ=0.2) between 10am and 6pm for the major urban heat islands in the U.S. These values are shown in **Table C-1** below.

Table C-1. Annual average cooling degree-hours above given temperatures between the hours of 10am and 6pm for selected U.S. cities

	CDH's above given temperature		
	75ºF	**82ºF**	**90ºF**
Phoenix	32,900	20,800	9,900
Los Angeles	1,100	400	200
Houston	15,900	5,800	400
Sacramento	11,900	5,400	1,300
New Orleans	13,100	3,900	100
Salt Lake City	9,900	3,900	500
Atlanta	7,300	1,400	0
Miami	18,500	4,700	0

Calculating the percent difference in cooling degree-hours above these critical temperatures yields city-specific estimates of increased AC pavement lifetime before failure due to rutting and shoving from increases in albedo of 0.1 and 0.2, respectively. These estimates are listed in **Table C-2**.

Table C-2. Ratios of annual average cooling degree-hours above 75ºF, 82ºF, and 90ºF for selected U.S. cities

	Δâ = 0.1 [(CDH>75ºF)-(CDH>82ºF)]/(CDH>75ºF)	**Δâ = 0.2** [(CDH>75ºF)-(CDH>90ºF)]/(CDH>75ºF)
Phoenix	37%	70%
Los Angeles	64%	82%
Houston	64%	97%
Sacramento	55%	89%
New Orleans	70%	99%
Salt Lake City	61%	95%
Atlanta	81%	100%
Miami	75%	100%

For this study, we present four options to increase the albedo of AC pavements: 1) the use of high-albedo sealcoating technologies ("sealcoat method"), 2) the use of high-albedo chip seals in conjunction with new AC and AC overlays ("chipseal method"), 3) "chipping" new AC and AC overlays with high-albedo chips ("chipping method"), 4) and the use of high-albedo aggregates in full-depth AC and AC overlays ("aggregate method"). In the sealcoat, chipseal, and chipping methods, we assume that the high-albedo surfaces are applied during the construction of AC pavements and overlays such that the durability benefits of increased albedo begin to be realized immediately. The aggregate method cannot be treated in the same way. Since the high-albedo aggregates are initially coated in binder, AC pavements using the aggregate method begin their service lives nearly black with albedos around 0.05. Therefore, the lifetime extension mechanisms described above do not affect AC pavements with high-albedo aggregates right away. While Pomerantz *et al.* (1999b) showed that AC albedos eventually approach about 70% of the albedo of the constituent aggregate, it was necessary to estimate the lag time between newly laid AC and AC sufficiently weathered to expose high-albedo aggregate. We hypothesize that AC albedos initially change nonlinearly in the first few years of service life and then level off to approach ~70% of the albedo of the aggregate (see **Figure C-1**).

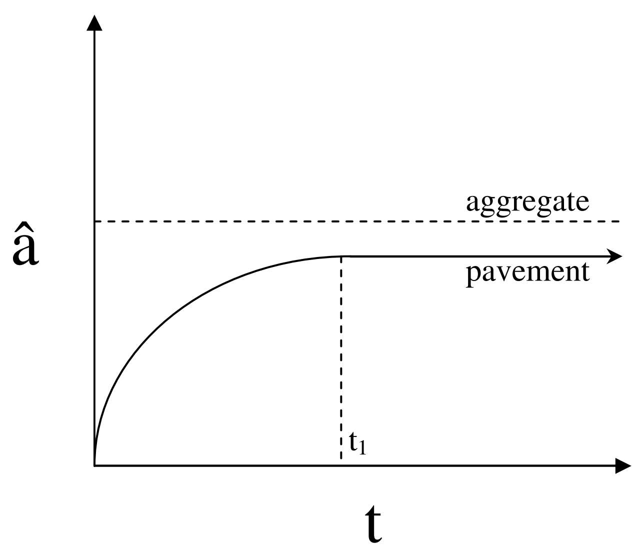

Figure C-1. Hypothetical albedo-time relationship for AC pavements

In order to ensure that our estimates of AC lifetime extension due to increases in albedo are conservative, we apply our lifetime extension formula only to the remaining pavement service life after the albedo begins to level off. To do this, we estimated the point t_1 on the above curve using data from Pomerantz et al. (2000b) by finding the linear trend line with the highest correlation coefficient (R^2) for data between year 0 and each successive year. We chose to use linear trend lines, as opposed to nonlinear trend lines, due to the limited number of observations available. The best fit occurred for data between year 0 and year 6, with an R^2 value of 0.83 as shown in **Figure C-2**.

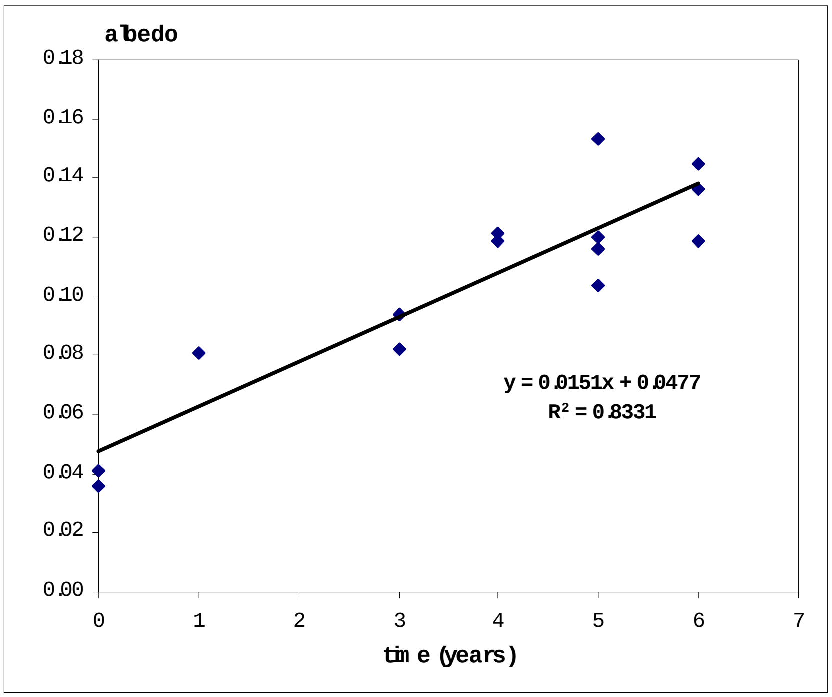

Figure C-2. Best linear fit of albedo vs. AC pavement age data collected by LBNL

The hypothetical albedo vs. time curves applied in our LCCA scenarios for AC pavements can then be portrayed as shown in **Figure C-3**. The general formula describing the application of our increased lifetime estimates, including the 6-year lag time, for AC pavements with high-albedo aggregates is therefore:

(equation C-5) $$L_r = (L_s - 6) \bullet (1 + \%\text{ increase in lifetime from increased } \hat{a}) + 6$$

where L_r = lifetime of increased-â AC pavement
and L_s = lifetime of standard AC pavement

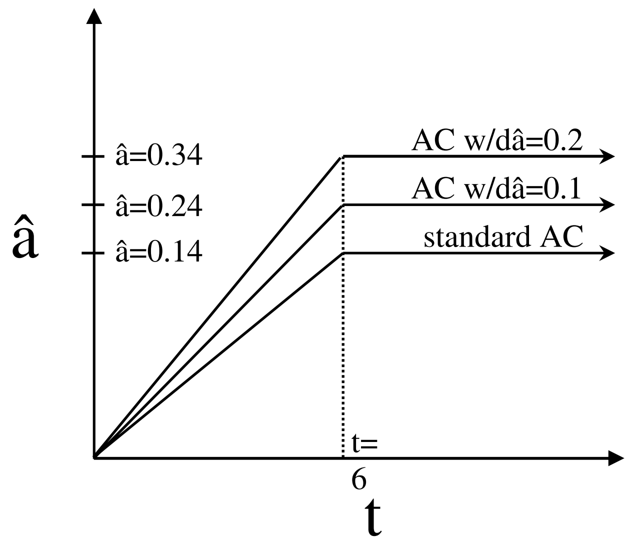

Figure C-3. Albedo-time relationship assumed in this study for standard AC pavements and AC pavements using high-albedo aggregates

An example estimate for Los Angeles using the weather data listed previously would be:

(example C-1) $L_r = (L_s - 6) \bullet (1 + 0.64) + 6$, for dâ=0.1

and

(example C-2) $L_r = (L_s - 6) \bullet (1 + 0.82) + 6$, for dâ=0.2