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Pavement Treatment Practices and Dynamic Albedo Change of Urban Pavement Network in California

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ABSTRACT

Recognizing the potential for cool pavements to reduce greenhouse gas emissions and improve heat islands and air quality, California local governments are beginning to adopt cool pavement strategies in their Climate Action Plans. Reflective pavement is one cool pavement strategy, using high albedo to reduce temperature. This paper details results of pavement management survey, albedo of different pavement treatment materials, and dynamic modeling of albedo of public pavement for different local governments in California. This information is intended for use in an urban heat island LCA tool and for inputs into climate modeling for the use phase for that tool. Key findings from the study include: (1) Most local governments treat a small portion of the public street pavement network every year, ranging from 1.3% to 20% with an average of 7% for the eight local governments. (2) Slurry seal is the major treatment used by most local governments, ranging from 28% to 82% of mileage treated with an average of 41%. Asphalt Overlay is another major treatment used by most local governments, ranging from 13% to 100% of mileage treated with an average of 37%. (3) Most pavement treatments currently used have relatively low steady-state albedos, ranging from 0.05 to 0.15 with an average of 0.1 for asphalt concrete, and from 0.1 to 0.24 with an average of 0.15 for chip seal. All reconstruction treatments have an asphalt overlay surface and should have similar albedos as asphalt concrete. Albedos for cape seals and slurry seals were measured in the City of Davis and ranged from 0.06 to 0.15, with an average of 0.12. Experimental treatments include asphalt concrete with reflective coating with albedo from 0.2 to 0.3 with an average of 0.25 and concrete with reflective coating ranging from 0.15 to 0.35 with an average of 0.25. (4) Due to the small portion of the typical pavement networks currently treated every year with treatments of relatively low steady-state albedo, the final steady-state albedo increase of pavement network in the 50 year analysis period for the urban heat island tool is relatively low, ranging from 0.03 to 0.14. The 50-year average increase of the pavement network albedo is even lower, ranging from 0.02 to 0.12.

Keywords: Heat island effect, pavement treatment, albedo, albedo change, urban climate, modeling.

INTRODUCTION

Background to the Study

The construction, use, and maintenance of California's roadways and parking lots are responsible for substantial energy and resource consumption and emissions of greenhouse gases (GHGs) and other air pollutants. In addition, pavements—which cover about one-third of a typical U.S. city (*1*)—can have a influence on local temperatures and air quality, with the amount of influence depending on a number of factors, including climate region, urban tree canopy, land use and other factors. When pavement increases the air temperature of an urban area, it can influence the formation of air pollutants. When increased air temperatures occur in areas where air conditioners are used more because of the increased temperatures then more GHG may be produced if the electrical power to run them comes from GHG emitting power sources.

Research is currently focused on identifying opportunities to reduce the environmental impacts of pavements. For instance, "cool" pavements, including reflective pavement (*2; 3*) and permeable pavement (*2; 4; 5*), can reduce ambient temperatures, slow the temperature-dependent formation of smog, decrease air conditioning and peak electricity demand, and induce negative radiative forcing that cools the atmosphere (*1; 6*). Cooler asphalt pavements may be less prone to rutting and cracking, and under certain conditions may also have lower rolling resistance due to viscoelastic energy dissipation under heavy truck loading (*7*).

Recognizing the potential for cool pavements to reduce greenhouse gas emissions and improve heat islands and air quality, some California local governments are beginning to adopt cool pavement strategies in their Climate Action Plans (currently as voluntary initiatives, not mandates). Chula Vista, Vallejo, and Santa Rosa are a few of the local governments that have already identified cool pavements as a strategy for both mitigating and adapting to climate change. Despite this interest, the greenhouse gas, local climate, and air quality impacts of cool pavements remain largely un-quantified.

As California state and local governments investigate approaches to reduce greenhouse gas (GHG) emissions and air pollution and to adapt to climate change, decision-making requires a strong understanding of the life-cycle environmental impacts of conventional and cool pavements. Evaluating the environmental impacts of pavement in California and estimating the potential impact of GHG reduction strategies present an opportunity to reduce greenhouse gas emissions, reduce ambient temperatures in those locations where they cause human discomfort, improve air quality, and protect public health. In California, this will help the Air Resources Board (CARB) determine best methods to meet state law targets for short and long-term greenhouse gas emission reduction targets; and help the state and local transportation agencies determine where the most cost-effective use of limited funding can be best used.

Urban climate modeling is a commonly-used method to simulate the urban climate and examine the effect of different mitigation strategies on the climate change on small or large scale. Currently an average albedo of 0.1 to 0.2 is commonly used for pavement in urban climate modeling. Simulations of increases in the albedo of reflective pavements typically consider average increases in the range of +0.1 to +0.2 (Reference *(1)* as an example where an average change of +0.15 is assumed). With the application of cool pavement strategies on a large scale in an urban area, the average albedo of urban pavement network across space and time is expected to increase. The increased average albedo of urban pavement network will consequently influence the climate change and urban heat island (UHI).

Objectives

The work presented in this paper is part of a larger research project that is developing models to better understand the life cycle environmental effects of implementing reflective pavements in California, considering the materials production and construction to maintain them over a 50 year analysis period, and the use phase impacts on building energy use (heating, cooling and lighting). The results will be used to develop a software tool for local governments in the state to estimate the effects of implementing reflective pavements as part of their pavement management practice. The impact categories to be considered by the tool will be global warming potential, air pollution and energy use.

The Weather Research and Forecasting (WRF) model being used for the project, and for other climate modeling, can only consider relatively large-scale discretization, on the order of 4 km by 4 km areas across the state and surrounding regions and ocean, and cannot consider changes in albedo over the analysis period. Therefore, the objective of the work presented in this paper was to develop the tool, a model was developed for estimating an average city-wide albedo for the 50 year analysis period to be considered in the software tool, taking into account local government pavement management practice and available albedo data.

To achieve this objective, a pavement management survey was conducted, data were collected for albedo of different pavement treatment materials, and dynamic modeling of albedo of publicly owned pavement for different local governments in California was developed. This paper presents:

1) A summary of the method and results of the pavement management survey for urban pavement networks.
2) A summary of the measurement method and albedo of different pavement treatment materials.
3) The dynamic modeling and results of albedo change of publicly owned pavement for different local governments in California.
4) Conclusions and recommendations related to modeling of urban pavement network albedo.

METHODOLOGY

Pavement Management Practice Survey

The pavement management survey was conducted with several local governments in California, to obtain general information on the pavement treatment practices currently used by local governments in California.

Local Governments for Pavement Management Practice Survey

The local governments for the pavement management survey included:

- City of Bakersfield,
- City of Berkeley,
- City of Chula Vista,
- City of Fresno,
- City of Los Angeles,
- City of Richmond,
- City of Sacramento, and
- City of San Jose.

Some local governments provided average data while most local governments provided the a detailed report with statistics for many years. For local governments with statistics for many years, the latest five-years of data available (2009 to 2013 or 2008 to 2012) were obtained from the City of Chula Vista, City of Los Angeles, City of Richmond, and City of Sacramento and used to calculate the average value for this report.

Main Questions for Pavement Management Practice Survey

The main questions included in the pavement management survey for different local governments were:

1) Size of pavement network managed by the local government (any units, lane-miles, square feet, centerline miles, whatever is used).
2) Portion of the network that in a typical year gets any kind of treatment. For example, “treat 7.5 lane-miles per year, or treat 5 percent of network per year”.

3) Approximate breakdown of treatments used, for example:
   a. Slurry seal, 70 percent or 7 lane-miles
   b. Asphalt resurfacing, 20 percent or 2 lane-miles
   c. Reconstruct 10% or 1 lane-mile (such as full depth asphalt, full-depth reclamation, concrete overlay, etc).

Field Measurement of Albedo

The albedo of the main pavement treatment materials were obtained from field measurements with different sources and measurement methods (*3*).

There are two ASTM standard testing methods for determining solar reflectance of a surface: 1) ASTM C1549 Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer (*8*); and 2) ASTM E1918, Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field (*9*).

ASTM C1549 Test Method

Solar spectrum reflectance measurement with this method relies on a testing instrument with an integrated radiation source and four detectors with filters for four specific wavelength ranges. This test method is best suited for use on flat and homogeneous smooth surfaces, such as single-ply membranes and smooth modified-bitumen membranes. The test method also requires that a surface to be tested is dry. However, it is not suited for rough surfaces such as gravel surfacings and some other pavement surfaces (*8*).

Pyranometer Test Method (ASTM E1918)

The device employed in this test method allows for calculation of solar reflectance based on alternate readings of incoming solar radiation and reflected solar radiation on a surface using only one pyranometer. The test procedure is weather-sensitive. It requires a cloudless weather condition and a sun angle to the normal of the test surface of less than 45 degree to obtain valid and repeatable solar reflectance values (*9*).

This test method is suited to measurements over all types of flat surfaces, including textured or irregular surfaces such as gravel surfacing. However, it has only one pyranometer to measure both the incoming solar radiation and reflected solar radiation on a surface. After measuring the incoming solar radiation, the pyranometer has to be flipped over to measure the reflected solar radiation (*9*). This is not convenient and might increase measurement error since the incoming solar radiation and reflected solar radiation are not measured at the same time, especially on cloudy days.

Dual-Pyranometer Test Method

To improve the convenience and reduce the measurement error of ASTM E1918, a dual-pyranometer was selected and used to perform the measurement of solar reflectivity in this study. A dual-pyranometer (also called albedometer) is composed of two star pyranometers. One pyranometer faces upward and the other faces downward. Incident global solar radiation (diffuse and direct solar radiation) with wavelength of 0.3~3 μm is measured by the upward facing pyranometer, while reflected solar radiation from surfaces is measured by the downward facing pyranometer (*10*). Separate outputs are provided for each pyranometer, which can be read from an indicator or recorded together automatically using a datalogger.

Testing in the research project done by the University of California Pavement Center (UCPRC) [see the following description for details] was conducted in accordance with ASTM E1918, following the standard method except using a dual-pyranometer. The Model 240-8140 dual-pyranometer was purchased from NovaLynx Corporation® in July 2011, with a calibration certificate and showing the measurement error of less than 1 W/m^2. The data are recorded automatically using a data acquisition system (DAS) composed of a CR 10X datalogger from Campbell Scientific, Inc.® powered by a battery and connected to a computer. This allows monitoring the solar reflectivity of a surface over long time periods. The whole measurement system is shown in Figure 1.

Figure 1. Albedo measurement system with a dual-pyranometer and DAS.

Data Sources of Pavement Albedo

Lawrence Berkeley National Laboratory (LBNL)

The Lawrence Berkeley National Laboratory (LBNL) Heat Island Group has compiled a pavement albedo database, including a set of measurements done on samples of various cool pavement surface treatments using LBNL's spectrophotometer in the laboratory, and those done in the field using the pyranometer test method (ASTM E1918) and compiled from various sources such as field testing and literature.

Many of the measurements in the laboratory were parts of iterative product development processes with manufacturers, so many of the measurements that are in initial or intermediate status in fact did not make it to market. The results of these measurements in the laboratory are not presented in this report.

The measurements in the field mostly feature measurements done at the LBNL’s UC Davis demonstration site. These field measurements also include information on the age of the pavement that is being measured, so they help to understand how the albedo of certain types of pavements changes over time. The pavement materials in the field measurements include asphalt concrete (AC) or overlay, asphalt overlay with reflective coating, chip seal, portland cement concrete (PCC), and portland cement concrete with reflective coating (*11*-*13*). The albedo measurement sources for the reflective coatings in this paper are mainly from LBNL and partly from a number of other research groups in China (*14*-*19*). It should be noted that some of the portland cement concrete represented in the data set contains carbon black, which is sometimes used to darken concrete pavement for aesthetic reasons.

Federal Highway Administration (FHWA) Project

Some initial data were used from an on-going Federal Highway Administration (FHWA) project, entitled “Quantifying Pavement Albedo”, including asphalt and concrete materials with different ages measured with the pyranometer test method (ASTM E1918).

University of California Pavement Research Center (UCPRC) Project (3)

The on-going study on cool pavements being conducted at the University of California Pavement Center (UCPRC) is devoted to investigation of the thermal behavior and cooling effect of different pavement types (including asphalt, concrete and block paver) and innovative designs (impermeable and permeable designs), and use the field measurement data to validate heat transfer modeling and employ the validated model to simulate the thermal behavior and cooling effect of different pavements under various contexts (climates and surroundings), and examine the effect of cool pavements on human thermal comfort (*20*).

Pavement Materials for UCPRC Albedo Measurement

These nine test sections include three different pavement surfacing materials, namely interlocking concrete pavers (surfacing type A), open-graded asphalt concrete (surfacing type B) and portland cement concrete (surfacing type C). For each pavement surface type, one impermeable pavement design (design 1) and two permeable pavement designs were constructed (designs 2 and 3, note that the industry preferred terms are pervious concrete, porous asphalt and permeable pavers, the word "permeable" is used for all surface types for convenience in this paper). Both of the permeable interlocking concrete paver pavements have the same cross-sections, the difference is in the solar reflectivity of the pavers. Both of the permeable asphalt sections have the same surface material, the difference is in the thicknesses of the layers. The two permeable concrete sections have different thickness and different concrete surface material mix designs, meaning that the aggregate gradations, cement contents and other ingredient proportions are different. The permeable concrete section C2 is darker than C3, resulting in different albedos.

Besides these nine sections, some extra pavement sections with conventional impermeable asphalt and concrete surfacing were also included in the study for field measurement of albedo. In addition, albedo was measured on some other land cover materials, including gravel, soil and grass, for comparison. Some of these materials were different ages when the measurement of solar reflectivity was conducted on them. The overall summary of materials used for albedo measurement in this study and dates of measurement are summarized in Table 1.

More field albedo measurements were performed around Davis, California in May 2014 to include slurry seal, fog seal, cape seal, chip seal and more PCC and AC materials. Eight test sites with different materials were selected and are shown in Table 1.

Table 1. Summary of Materials and Plan for Albedo Measurement by UCPRC (*3*)

Surface Category	Permeable Type	Binder/Cement/Color Type	Code [a]	Measurement Date (m/d/yy) (Pavement Age at Measurement)
Asphalt	Impermeable	Conventional	B1	9/19/11, 10/13/11, 2/15/12, 5/2/12 [d]
	Permeable	Polymer modified	B2 [b]	9/19/11, 10/13/11, 2/15/12, 5/2/12 [d]
	Permeable	Polymer modified	B3	9/19/11, 10/13/11, 2/15/12, 5/2/12 [d]
	Impermeable	Polymer modified	PMA	10/13/11 (3 years)
	Impermeable	Rubberized	RHMA	10/13/11 (3 years)
	Impermeable	Warm mixed asphalt	RWMA	10/13/11 (2 years)
	Permeable	Polymer modified	OGFC	10/13/11 (1 year)
	Impermeable	Conventional	Aged AC	10/13/11 (5 years)
	Impermeable	Conventional (parking lot)	Aged AC	5/21/14 (5 years)
Concrete	Impermeable	Conventional	C1	9/19/11 10/13/11, 2/15/12, 5/2/12 [d]
	Permeable	Conventional	C2 [c]	9/19/11 10/13/11, 2/15/12, 5/2/12 [d]
	Permeable	White	C3	9/19/11 10/13/11, 2/15/12, 5/2/12 [d]
	Impermeable	Conventional	PCC	10/13/11 (3 years)
	Impermeable	Conventional (parking lot)	PCC	5/21/14 (5 years)
Interlocking Concrete Paver	Impermeable	Conventional- orange	A1	9/19/11 10/13/11, 2/15/12, 5/2/12 [d]
	Permeable	Conventional- champagne	A2	9/19/11 10/13/11, 2/15/12, 5/2/12 [d]
	Permeable	Conventional- orange	A3	9/19/11 10/13/11, 2/15/12, 5/2/12 [d]
Treatment	Impermeable	Conventional	Slurry Seal	5/21/14 (5 years)
	Impermeable	Conventional	Chip Seal	5/21/14 (5+ years)
	Impermeable	Conventional	Cape Seal	5/21/14 (3+ years)
	Impermeable	Conventional	Fog Seal	5/21/14 (0.1 and 3 years)
Gravel	Permeable	Crushed open-graded basalt in blue/gray color	Gravel	10/13/11 (0.5 year)
Soil	Permeable	Native yellow clay	Soil	10/13/11
Grass	Permeable	Yellow lawn	Grass	10/13/11

[a] *Code: A1-3, B1-3, C1-3 are experimental test sections described previously. PMA-Polymer Modified Asphalt; RHMA- Rubberized Hot Mixed Asphalt; WMA- Warm Mixed Asphalt; OGFC- Open Graded Friction Course; AC-Asphalt Concrete; PCC-Portland Cement Concrete.*
[b] *monitored continuously over time.*
[c] *monitored continuously in one day.*
[d] *age for A1-3, B1-3, C1-3: 9/19/11 (1 month), 10/13/11 (2 months), 2/15/12 (6 months), 5/2/12 (9 months).*

Dynamic Albedo Change Modeling for Urban Pavement Network

A model was developed to simulate the dynamic change and the average of urban albedo (mainly public pavement) over 50 years with different pavement management strategies.

Dynamic Model for Urban Albedo

The urban area land cover includes building, pavement, vegetation and bar soil, etc. The pavements include public pavement and private pavement. The public pavement is usually managed by government agency and a portion of the public pavement receives regular treatment to improve the pavement performance. The urban area land cover is illustrated in Figure 2.

Every year a portion (r_t) of the public pavement gets treated with different treatments (i = A, B, C, D, …) with different albedos ($\alpha_{i,t}$). With that the total pavement albedo ($\alpha_{p\,t}$) and consequently the urban albedo (α_t) will change over time. This dynamic process can be modeled with a dynamic albedo model, as shown in Equations 1 through 4. In this paper, we will focus on the pavement albedo with Equations 3 and 4.

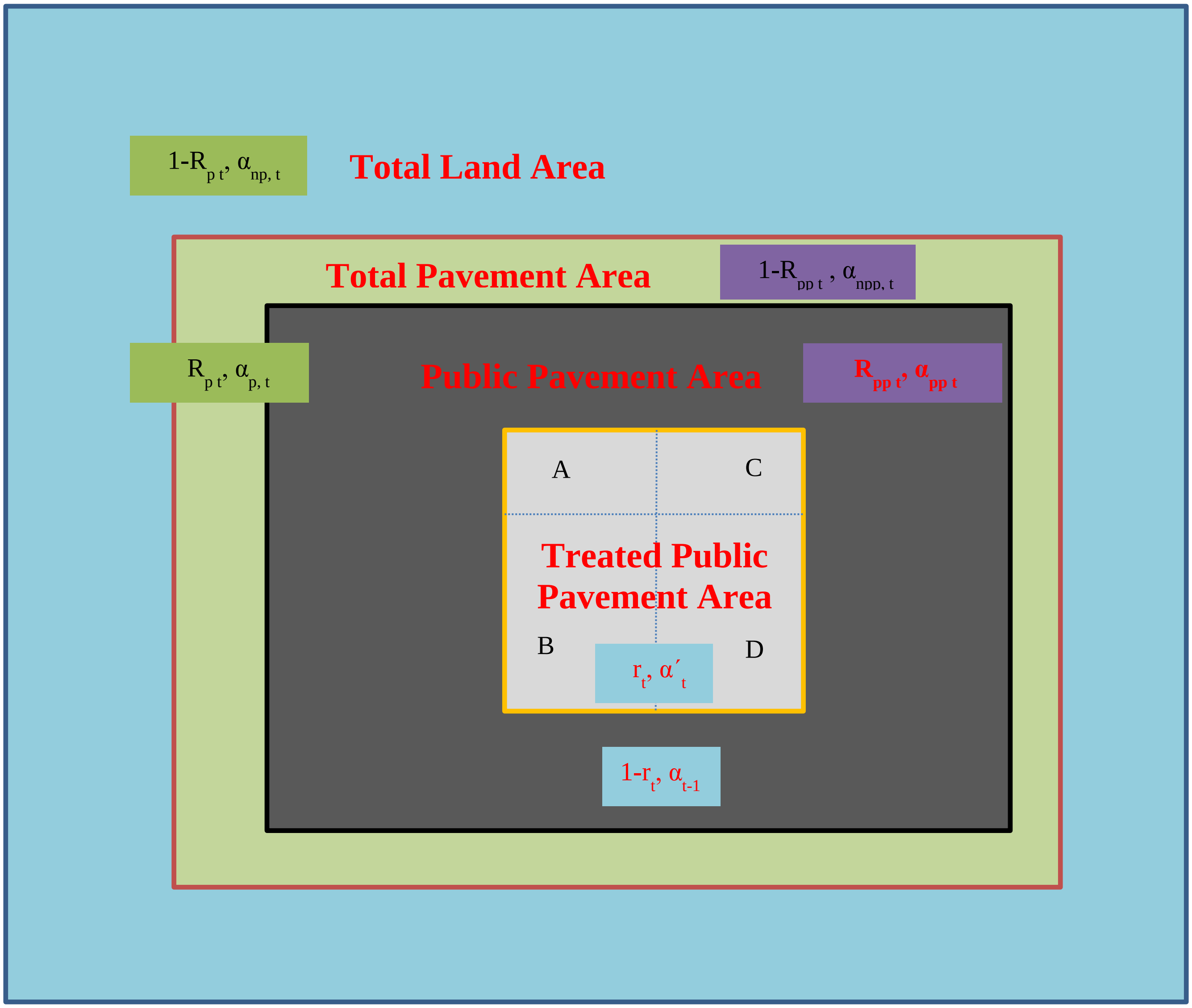


Figure 2. Urban land cover at year t. (refer to Equations 1 through 4 and the variables definition below)

$$\alpha_t = (1-R_{p\,t})\alpha_{np\,t} + R_{p\,t}\,\alpha_{p\,t} \tag{1}$$

$$\alpha_{p\,t} = (1-R_{pp\,t})\alpha_{npp\,t} + R_{pp\,t}\,\alpha_{pp\,t} \tag{2}$$

$$\alpha_{pp\,t} = (1-r_t)\,\alpha_{t-1} + r_t\,\alpha'_t \tag{3}$$

$$\alpha'_t = \sum n_{i,t}\,\alpha_{i,t} \tag{4}$$

where,

$R_{np\,t}$ = total non-pavement area portion in urban land surface at Year t;
$R_{p\,t}$ = total pavement network area portion in urban land surface at Year t;
$R_{pp\,t}$ = total *publicly managed* pavement network portion in urban land surface at Year t;
r_t = portion of pavement network for treatment at Year t;
$n_{i,t}$ = portion of treated pavement network which use treatment i at Year t;
α_t = albedo of total urban area at Year t;
$\alpha_{p\,t}$ = albedo of total pavement area at Year t;
$\alpha_{npp\,t}$ = albedo of non-public pavement area at Year t;
$\alpha_{pp\,t}$ = albedo of public pavement area at Year t;
$\alpha_{i,t}$ = albedo of pavement treatment i at Year t;

α_t = average albedo of pavement network at Year t;
α'_t = average albedo of pavement treated at Year t;
i = pavement treatment type, i = A, B, C, D, … ;
t = time i year, t = 1, 2, 3, 4, 5, …, 50;

RESULTS AND DISCUSSION

Local Government Pavement Management Practice

The main results from the pavement management survey with local governments in California are summarized in Table 2. The main findings include:

- Most local governments treat a small portion of the public street pavement network every year, ranging from 1.3% to 20% with an average of 7% for the eight local governments from which a response was received. The survey consisted of responses from cities as opposed to counties.
- The main treatments used by local governments include slurry seal, chip seal, cape seal[1] (chip seal plus microsurfacing or slurry seal), asphalt overlay, sand seal, and reconstruction (including AC, rubberized asphalt concrete [RAC], full depth reclamation [FDR], and cold in-place recycling [CIR]).
- Slurry seal is the major treatment used by most local governments, ranging from 28% to 82% of mileage treated with an average of 41%. Asphalt Overlay is another major treatment used by most local governments, ranging from 13% to 100% of mileage treated with an average of 36.8%. Chip seal makes up on average 6% of the mileage treated, ranging from 0.7% to 46%, while cape seal is used on less than 1 percent on average. Sand seal was used by one city for the majority of their program, and they are the city that treats 20% of their network each year, which is much larger than all other local governments surveyed. Reconstruction is used on average as 6.6% of the total treatment, ranging from 3% to 28%.
- For most of these local governments, it can be seen from the low percentages of pavement being treated each year that pavement maintenance and rehabilitation funding in recent years has not been sufficient to maintain a steady pavement condition index (PCI).

Table 2. Summary of Pavement Treatment Practice Currently Used by Local Governments in California

City	Public Pavement Network Lane Miles (Centerline Miles) [b]	Portion of Network Treated Every Year	Portion of Each Treatment Used in Total Network Treated					
			A. Slurry Seal	B. Sand Seal	C. Chip Seal	D. Cape Seal	E. Asphalt Overlay	F. Reconstruction (AC, RAC, FDR, CIR)
City of Bakersfield	(1,264)	20%	-	75%	-	-	13%	12%
City of Berkeley	453 (216)	7.4%	31%	-	-	-	41%	28%
City of Chula Vista	(461)	3.9%	28.3%	-	46.4%	0.5%	21.8%	3%
City of Fresno [a]	(1,548)	1.3%	-	-	-	-	100%	-
City of Los Angeles	28,000	7.4%	60.7%	-	-		35.4%	3.9%
City of Richmond	576	5.2%	47.1%	-	0.7%	0.5%	45.9%	5.9%
City of Sacramento	3,065	4.3%	82.4%	-	-	-	17.6%	-
City of San Jose	4,264	5%	80%	-	-	-	20%	-
Average	-	***6.8%***	***41.2%***	***9.4%***	***5.9%***	***0.1%***	***36.8%***	***6.6%***

[a] 40 centerline miles asphalt overlay up to 2009, then 20 centerline miles asphalt overlay since 2009.
[b] use multiplier 2.2 to convert centerline miles to lane miles. The lane width is assumed 13.5 ft.

[1] A cape seal is a chip seal covered with a microsurfacing or slurry seal. The benefits from using a cape seal include a very smooth surface with increased durability. The use of a chip seal is generally not popular with the public in urban areas because of the rougher ride and loose stones can cause problems for sewers and street cleaning. With the addition of the top treatment, a microsurfacing or slurry seal, the road ends up with a smooth surface that binds any loose aggregate, reducing stone loss.

Albedo of Pavement Materials

The steady-state albedo of different pavement materials with different data sources are summarized in Table 3. Steady state was defined based on the longer term trend seen the available data for each surface type. Long-term data up to replacement of the surface was available for some treatments, while data for more than one or two years of service was scarce for other surfaces, most notably reflective coatings. The main findings on albedo include:

- Most pavement treatment currently used have relatively low steady-state albedo, ranging from 0.05 to 0.15 with average of 0.1 for asphalt concrete, from 0.1 to 0.24 with average of 0.15 for chip seal. Albedos for slurry seals were measured in the City of Davis and ranged from 0.07 to 0.1, with an average of 0.08. Albedos for cape seals measured in the City of Davis ranged from 0.05 to 0.15, with an average of 0.06. Albedos for fog seals measured in the City of Davis ranged from 0.04 to 0.07, with an average of 0.06. Data are not available for sand seals. For experimental reflective coatings, albedos range from 0.2 to 0.3 after several months after placement with an average of 0.25 for asphalt concrete with reflective coating, and from 0.15 to 0.35 with an average of 0.25 for concrete with reflective coating.
- Although the initial albedo of treatment with reflective coating can be very high (e.g. up to 0.7 or higher), the albedo will decrease very quickly and significantly down to a low steady-state value due to weathering and tracking with current technology.

Table 3. Summary of Steady-State Albedo of Different Pavement Treatment Materials with Different Data Sources

Material Type	Albedo (LBNL)		Albedo (FHWA)		Albedo (UCPRC)		Albedo (Typical)	
	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
Asphalt Concrete or Overlay	0.1 - 0.15	0.12	0.05 - 0.15	0.1	0.06 - 0.15	0.1	0.05 - 0.15	0.1
Asphalt Concrete or Overlay with Reflective Coating	0.2 - 0.3	0.25	-	-	-	-	0.2 - 0.3	0.2
Chip Seal	0.1 - 0.2	0.15	-	-	0.14 - 0.24	0.18	0.1 - 0.24	0.15
Slurry Seal	-	-	-	-	0.07 – 0.1	0.08	0.07 – 0.1	0.08
Cape Seal	-	-	-	-	0.05 – 0.15	0.06	0.05 – 0.15	0.06
Fog Seal	-	-	-	-	0.04 – 0.07	0.06	0.04 – 0.07	0.06
Sand Seal	-	-	-	-	-	-	0.07 – 0.1	0.08
Portland Cement Concrete	0.15 - 0.25	0.2	0.2 - 0.3	0.25	0.18 - 0.35	0.25	0.15 - 0.35	0.25
Conventional Interlocking Concrete Pavement	-	-	-	-	0.25 – 0.3	0.26	0.25 – 0.3	0.26
Permeable Asphalt Pavement	-	-	-	-	0.08 – 0.12	0.1	0.08 – 0.12	0.1
Permeable Concrete Pavement	-	-	-	-	0.18 – 0.28	0.25	0.18 – 0.28	0.25
Permeable Interlocking Concrete Pavement	-	-	-	-	0.25 – 0.3	0.26	0.25 – 0.3	0.26
Gravel	-	-	-	-	0.12 – 0.22	0.18	0.12 – 0.22	0.18
Soil	-	-	-	-	0.21 – 0.23	0.22	0.21 – 0.23	0.22
Grass	-	-	-	-	0.18 – 0.20	0.19	0.18 – 0.20	0.19

- *Not available.*

Dynamic Albedo Change of Urban Pavement Network

Example Simulation of Dynamic Albedo Change

As mentioned previously, the albedo of public pavement is the focus of this paper. For an example simulation of the dynamic albedo of public pavement, the assumptions include:

1) The initial albedo of the public pavement is 0.1.
2) Four treatment types are used, namely A (e.g. slurry seal), B (e.g. chip seal), C (e.g. asphalt overlay with reflective coating), and D (e.g. reconstruction with concrete), with constant steady-state albedo of 0.1, 0.15, 0.2 and 0.3, respectively.

3) The total yearly portion of public pavement network treated is set as a constant of 8% in the analysis term of 50 years.
4) The portions of treatments A, B, C and D used for total public pavement network treated are set as constants of 60%, 15%, 15% and 10%, respectively.

Pavement Surface Treatment Scenario

The assumed scenario of pavement management with surface treatments is illustrated in Figure 3.

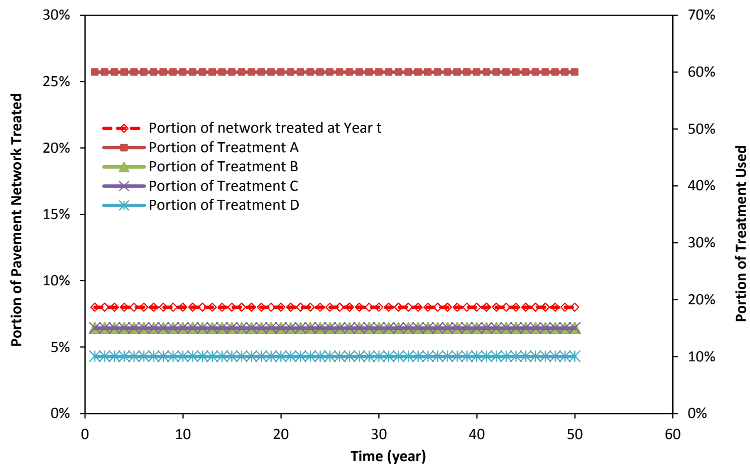


Figure 3. Pavement surface treatment scenario.

Public Pavement Albedo

The dynamic albedo of public pavement over the 50 years is illustrated in Figure 4. Since 8% of the public pavement network gets treated with treatments of different albedos every year, the average albedo of the whole public pavement changes dynamically over time, as shown in Figure 4. The average albedo increases gradually from 0.1 up to 0.14 over the 50 years. It takes approximately 30 years to reach the steady state with a stable albedo of 0.14, with a 50-year average of 0.13.

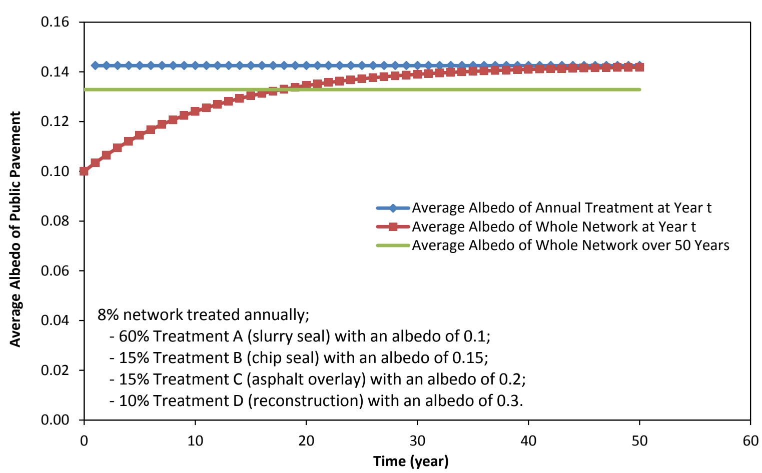


Figure 4. Dynamic albedo of public pavement with treatments at Year *t* over 50 years.

Albedo of Public Pavement Network for Different Local Governments with Current Treatment Practices and Technologies

Pavement Treatment Practices

The pavement treatment practices and albedos for treatments currently used by local governments in California are summarized in Table 4. The local governments for the albedo modeling include City of Bakersfield, City of Berkeley, City of Chula Vista, City of Fresno, City of Los Angeles, City of Richmond, City of Sacramento, and City of San Jose. The assumptions include,

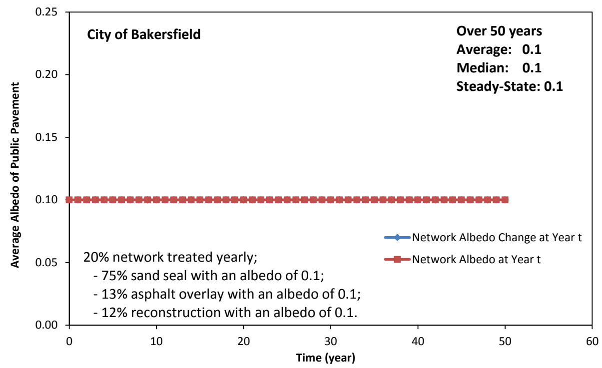
1) The initial albedo of the public pavement is 0.1.
2) Six main treatment types are used, namely slurry seal (A), sand seal (B), chip seal (C), cape seal (D), asphalt overlay (E), and reconstruction with asphalt (F), with constant steady-state albedos of 0.08, 0.1, 0.15, 0.06, 0.1 and 0.1, respectively.
3) The total yearly portion of public pavement network treated is set as constant values from Table 4 for each city in the analysis term of 50 years.

Table 4. Summary of pavement treatment practice and albedo currently used by local governments in California.

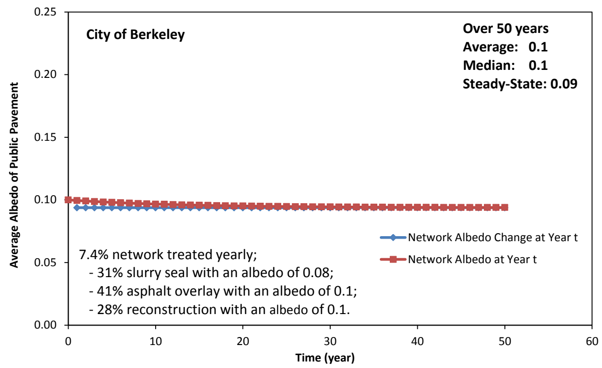
City	Portion of network treated every year	Portion of Each Treatment in Total Treatments (albedo)						Steady-State Albedo in 50 Years (Initial Albedo = 0.1)
		A. Slurry Seal (0.08)	B. Sand Seal (0.10)	C. Chip Seal (0.15)	D. Cape Seal (0.06)	E. Asphalt Overlay (0.10)	F. Reconstruction (AC, RAC, FDR, CIR) (0.10)	
City of Bakersfield	20%	-	75%	-	-	13%	12%	**0.1**
City of Berkeley	7.4%	31%	-	-	-	41%	28%	**0.09**
City of Chula Vista	3.9%	28.3%	-	46.4%	0.5%	21.8%	3%	**0.12**
City of Fresno	1.3%	-	-	-	-	100%	-	**0.1**
City of Los Angeles	7.4%	60.7%	-	-	-	35.4%	3.9%	**0.09**
City of Richmond	5.2%	47.1%	-	0.7%	0.5%	45.9%	5.9%	**0.09**
City of Sacramento	4.3%	82.4%	-	-	-	17.6%	-	**0.09**
City of San Jose	5%	80%	-	-	-	20%	-	**0.09**
Average	***6.8%***	***41.2%***	***9.4%***	***5.9%***	***0.1%***	***36.8%***	***6.6%***	***0.1***

Dynamic Albedo of Public Pavement Network in 50 Years for Different Local Governments with Current Treatment Practices and Technologies

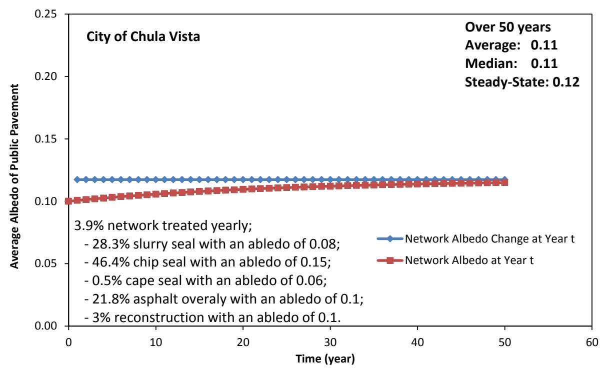
With the pavement treatment practice and albedo currently used by local governments in California listed above in Table 4, the dynamic albedo molded for different local governments are presented in Figure 5 (a) through (h). Most of the current pavement materials are asphalt concrete (including asphalt overlay) with an albedo of 0.1, which is the initial value of current pavement network albedo. The current treatment practices used by most local governments are dominated by slurry seal which has a lower albedo of 0.08. With the current treatment practice and technologies, the average albedos of the public pavement network for most local governments remain constant or decrease by a small amount over the 50 years. Only the cites (e.g. City of Chula Vista) that are using a larger portion of chip seal with a higher albedo of 0.15 present an increasing albedo by a little amount over the 50 years. As shown in Figure 5 (a) through (h) and summarized in Table 4, the steady-state albedo change of pavement network in the 50 years is relatively low, ranging from -0.01 to 0.02 from the initial value of current pavement network albedo of 0.1. The average steady-state albedo of the pavement network in the 50 years across local governments still remains close to the initial value of current pavement network albedo, which is 0.1.



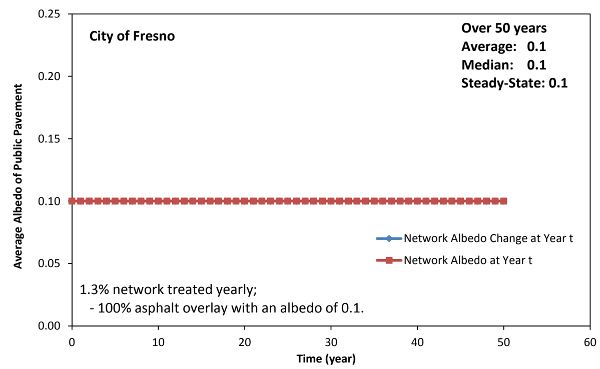
(a) City of Bakersfield



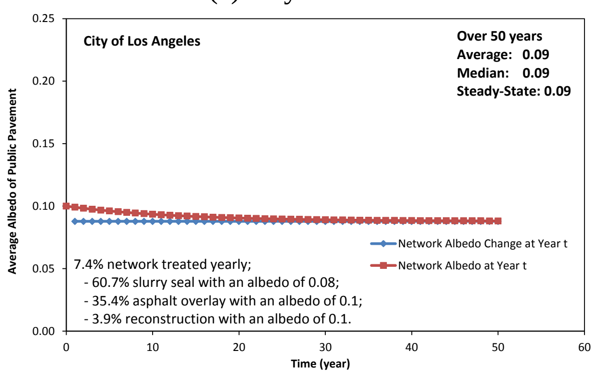
(b) City of Berkeley



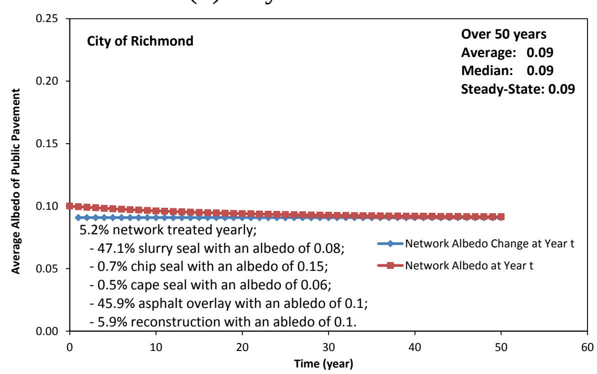
(c) City of Chula Vista



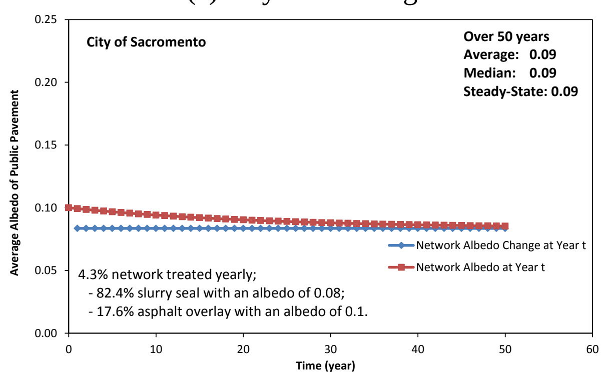
(d) City of Fresno



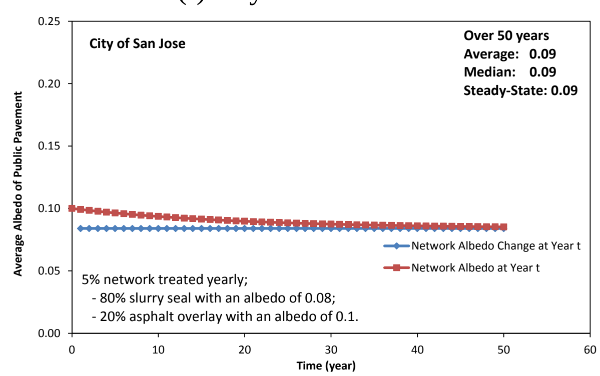
(e) City of Los Angeles



(f) City of Richmond



(g) City of Sacramento



(h) City of San Jose

Figure 5. Dynamic albedo of public pavement with currently treatment practice in different cities in California.

Albedo of Public Pavement Network for Different Local Governments with Assumed Treatment Practices and Technologies

Pavement Treatment Practices

The scenarios for changing pavement treatment practice for local governments in California to include more reflective surfaces (higher albedo) assumed are summarized in Table 5. The assumptions on the treatment practices and technologies for local governments include:

1) The initial albedo of the public pavement is 0.1, which is the average steady-state albedo in 50 years under current practice (see Table 4).
2) The portion of network treated each year is 5%, 10%, and 20% as constant values in the analysis term of 50 years.
3) Six main treatment types are used, namely (current practice on average, see Table 4),
    - 41.2% slurry seal with an albedo of 0.08;
    - 9.4% sand seal with an albedo of 0.1;
    - 5.9% chip seal with an albedo of 0.15;
    - 0.1% cape seal with an albedo of 0.06;
    - 36.8% asphalt overlay with an albedo of 0.1;
    - 6.6% reconstruction with an albedo of 0.1.
4) Reflective treatment replacements include: 20%, 50% and 100% of slurry seal is replaced with reflective material with albedo of 0.25, and 20%, 50% and 100% of asphalt overlay is replaced with reflective material with albedo of 0.3.

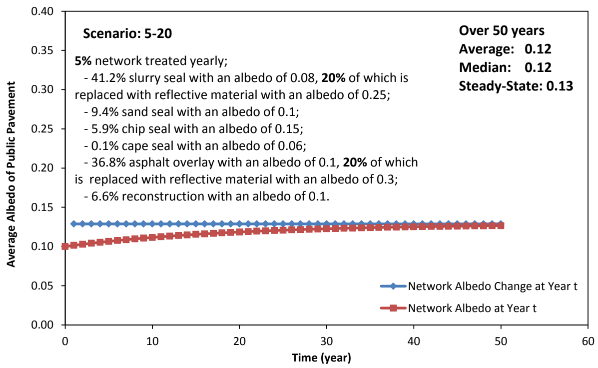
Table 5. Summary of pavement treatment practice and albedo assumed for local governments in California.

Scenario [a]	Portion of Network Treated Every Year	Replacement Ratio of Reflective Treatment		Albedo of Reflective Treatment		Network Albedo for 50 Year Period (Initial Albedo: 0.1)		
		A2. Reflective Slurry Seal	E2. Reflective Asphalt Overlay	A2. Reflective Slurry Seal	E2. Reflective Asphalt Overlay	Average	Median	Steady-State
1 (5-20)	5%	20%	20%	0.25	0.3	0.12	0.12	0.13
2 (5-50)	5%	50%	50%	0.25	0.3	0.15	0.15	0.17
3 (5-100)	5%	100%	100%	0.25	0.3	0.19	0.21	0.23
4 (10-20)	10%	20%	20%	0.25	0.3	0.12	0.13	0.13
5 (10-50)	10%	50%	50%	0.25	0.3	0.16	0.17	0.17
6 (10-100)	10%	100%	100%	0.25	0.3	0.22	0.23	0.24
7 (20-20)	20%	20%	20%	0.25	0.3	0.13	0.13	0.13
8 (20-50)	20%	50%	50%	0.25	0.3	0.17	0.17	0.17
9 (20-100)	20%	100%	100%	0.25	0.3	0.23	0.24	0.24

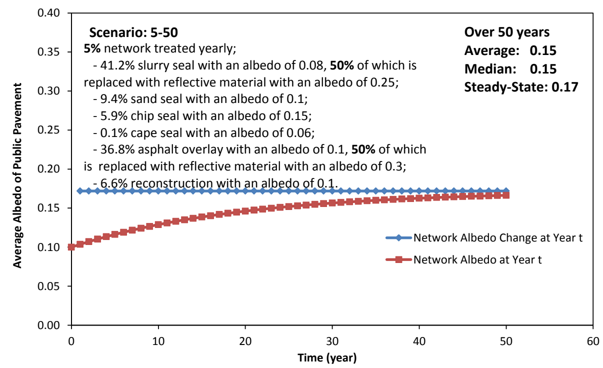
[a] Scenario i (x-y): x% network gets treated yearly and y% of slurry seal and asphalt overlay are replaced with reflective materials.

Dynamic Albedo of Public Pavement Network in 50 Years for Different Local Governments with Assumed Treatment Practices and Technologies

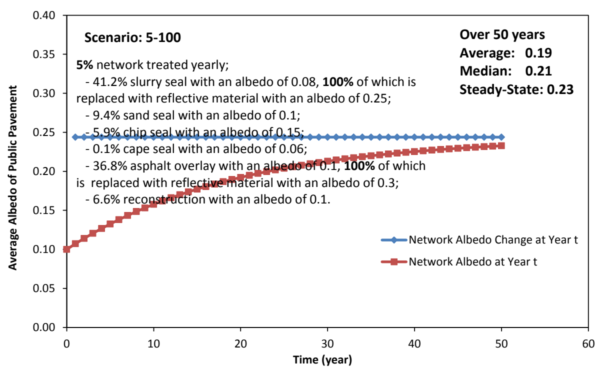
With the scenarios of pavement treatment practice and albedo assumed for local governments in California listed above in Table 5, the dynamic albedo of the public pavement network modeled under the different scenarios are presented in Figure 6 (a) through (i). Since a constant and considerable portion of the public pavement network gets treated with treatments of different albedos every year, the average albedo of the whole public pavement changes dynamically over time for each city, as shown in Figure 6 (a) through (i). The average albedo increases gradually from the initial value of 0.1 up to 0.12, 0.15, 0.19, 0.12, 0.16, 0.22 0.13, 0.17, and 0.23 over the 50 years for the nine scenarios, respectively. It takes approximately 10 to 50 years to reach the steady state with a stable network albedo. Due to the small portion of pavement network currently treated each year with treatments of relatively low steady-state albedo, the steady-state albedo increase of pavement network in the 50 years is relatively low, ranging from 0.03 to 0.14. The 50-year average increase of the pavement network albedo is even lower, ranging from 0.02 to 0.12.



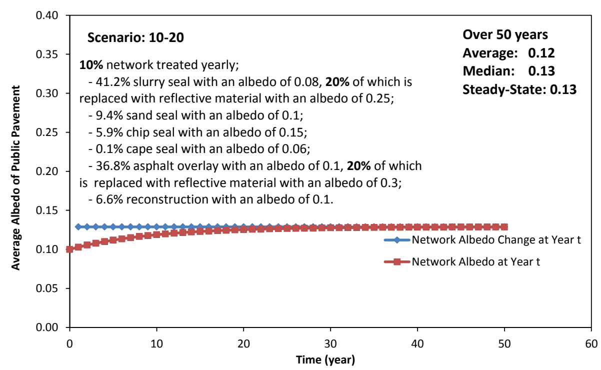
(a) Scenario 1 (5-20)



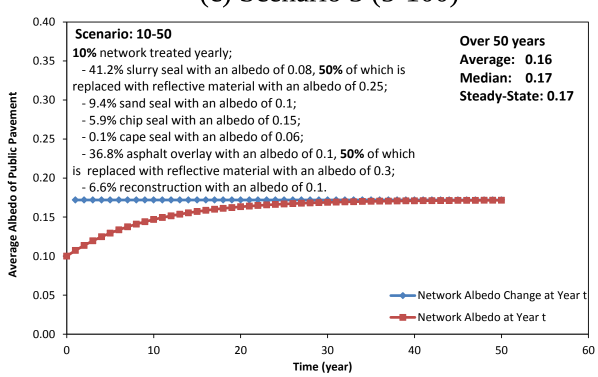
(b) Scenario 2 (5-50)



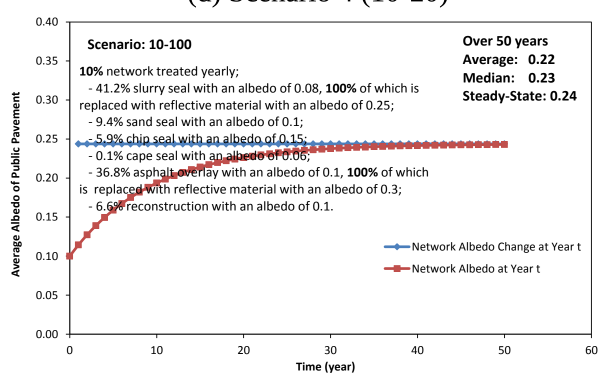
(c) Scenario 3 (5-100)



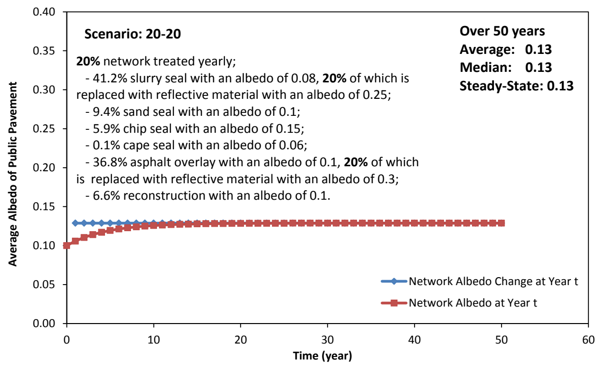
(d) Scenario 4 (10-20)

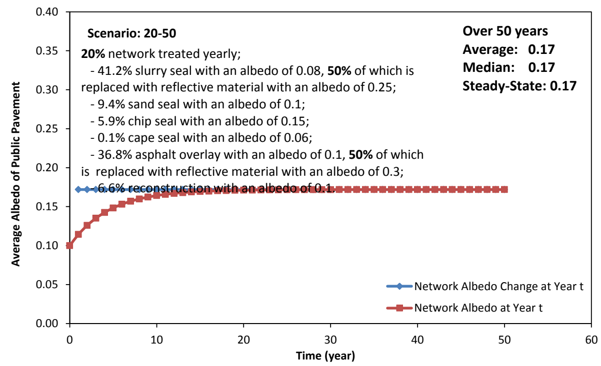


(e) Scenario 5 (10-50)

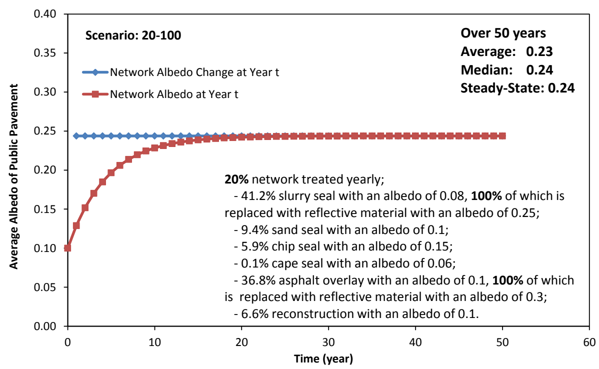


(f) Scenario 6 (10-100)





(g) Scenario 7 (20-20) (h) Scenario 8 (20-50)



(i) Scenario 9 (20-100)

Figure 6. Dynamic albedo of public pavement with different assumed scenarios on replacement with reflective materials.

(Note: Scenario i (x-y): x% network gets treated yearly and y% of slurry seal and asphalt overlay are replaced with reflective materials.)

LIMITATIONS OF THIS PAPER

This paper focuses on the dynamic albedo change of the whole urban pavement network due to the cumulative impacts of annual pavement maintenance practices over 50 years. A portion of the urban pavement network will be treated annually with different maintenance practices with various albedos. For simplification and due to the lack of data, and due to the nature of the information needed for the WRF climate models, the aging-related pavement albedo changes over the long term were not explicitly considered, and the treatment albedo is assumed to be constant after reaching a fairly steady condition until a new treatment is applied. The steady state albedos were estimated from the data available for each treatment, and the data, though reasonable, are sparse enough to preclude rigours statistical modeling of the albedo aging. Instead, the dynamic albedo change of the whole urban pavement network due to major treatment-related impacts were captured over 50 years, to reflect the albedo impact of various pavement treatment practices in each year. Therefore, the limitation of the model is that the aging effect was not explicitly considered. Development of albedo aging models and their inclusion in the dynamic modeling of aging for the network will be included in the revised model when adequate data are available.

SUMMARY AND RECOMMENDATIONS

This paper details results of pavement management survey, albedo of different pavement treatment materials, and dynamic modeling of albedo of public pavement for different local governments in California. Key findings from the study include:

Pavement Management Practice

- Most local governments treat a small portion of the public street pavement network every year in recent years, ranging from 1.3% to 20% with an average of 6.8% for the eight local governments from which a response was received. The survey consisted of responses from cities as opposed to counties. It is clear that for many of these cities, the treatment program is not adequate to maintain the pavements in their network.
- The main treatments used by local governments include slurry seal, chip seal, cape seal (chip seal plus microsurfacing or slurry seal), asphalt overlay, sand seal, and reconstruction (including asphalt concrete (AC), rubberized asphalt concrete (RAC), full depth reclamation (FDR), and cold in-place recycling (CIR)).
- Slurry seal is the major treatment used by most local governments, ranging from 28% to 82% of mileage treated with an average of 41%. Asphalt Overlay is another major treatment used by most local governments, ranging from 13% to 100% of mileage treated with an average of 36.8%. Chip seal makes up on average 6% of the mileage treated, ranging from 0.7% to 46%, while cape seal is used on less than 1 percent on average. Sand seal was used by one city for the majority of their program, and they are the city that treats 20% of their network each year, which is much larger than all other local governments surveyed. Reconstruction is used on average as 7% of the total treatment, ranging from 3% to 28%.

Pavement Albedo

- Most pavement treatments currently used have relatively low steady-state albedo, ranging from 0.05 to 0.15 with average of 0.1 for asphalt concrete, from 0.1 to 0.24 with average of 0.15 for chip seal. Albedos for slurry seals were measured in the City of Davis and ranged from 0.07 to 0.1, with an average of 0.08. Albedos for cape seals measured in the City of Davis ranged from 0.05 to 0.15, with an average of 0.06. Albedos for fog seals measured in the City of Davis ranged from 0.04 to 0.07, with an average of 0.06. Data are not available for sand seals. Experimental treatments include asphalt concrete with reflective coating with albedo from 0.2 to 0.3 with average of 0.25 and concrete with reflective coating ranging from 0.15 to 0.35 with average of 0.25.
- Although the initial albedo of treatments with reflective coating can be very high (e.g. up to 0.7 or higher), the albedo will decrease very quickly and significantly down to a low value due to weathering and tracking with current technology. This information represents currently available technologies.
- With the pavement treatment practice and albedo currently used by local governments in California, most of the current pavement materials are asphalt concrete (including asphalt overlay) with an albedo of 0.1, which is the initial value of current pavement network albedo. The current treatment practices used by most local governments are dominated by slurry seal which has a lower albedo of 0.08. With the current treatment practice and technologies, the average albedos of the public pavement network for most local governments keep constant or decrease by a little amount over the 50 years. Only the cites (e.g. City of Chula Vista) that are using a larger portion of chip seal with a higher albedo of 0.15 present an increasing albedo by a small amount over the 50 years. The steady-state albedo change of pavement network in the 50 years is relatively low, ranging from -0.01 to 0.02 from the initial value of current pavement network albedo of 0.1. The average steady-state albedo of the pavement network in the 50 years across local governments still keeps close to the initial value of current pavement network albedo, which is 0.1.
- With the scenarios of pavement treatment practice and albedo assumed for local governments in California, a constant and considerable portion of the public pavement network gets treated with treatments of different albedos every year, and the average albedo of the whole public pavement changes dynamically over time for each city. The average albedo increases gradually from the initial value of 0.1 up to 0.12, 0.15, 0.19, 0.12, 0.16, 0.22 0.13, 0.17, and 0.23 over the 50 years for the nine scenarios, respectively. It takes approximately 10 to 50 years to reach the steady state with a stable network albedo. Due to the small portion of pavement network currently treated

every year with treatments of relatively low steady-state albedo, the final steady-state albedo increase of pavement network in the 50 years is relatively low, ranging from 0.03 to 0.14. The 50-year average increase of the pavement network albedo is even lower, ranging from 0.02 to 0.12.

Recommendations

It is recommended that albedo data for typical pavement treatments at various ages be collected to improve the database available for the Heat Island tool, especially considering urban pavement treatments. The aging-related pavement albedo changes over long term should be explicitly considered when adequate data of the aging effect is available. It is also recommended that realistic pavement management scenarios be considered in climate modeling so that realistic expectations of the effects of changing albedo and its effects are considered in decision-making.

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