Cool pavement LCA tool: inputs and recommendations for integration

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ABSTRACT: To advance the adoption of strategies to reduce the greenhouse gas and air pollutant emissions and urban heat island effects of pavement systems within California, a collaborative research project was conducted between the University of California Pavement Research Center (UCPRC), Lawrence Berkeley National Laboratory (LBNL), and University of Southern California (USC) to develop a tool for comparing environmental impacts of alternative decisions at the local government level in California. This paper details results of the pavement management survey, albedo of different pavement treatment materials, dynamic modeling of albedo of public pavement for different local governments in California, and life cycle assessment (LCA) models of such materials and common pavement surface treatments to capture their environmental impacts. This information is intended for use in the urban heat island LCA tool and for inputs into climate modeling in that tool's use stage.

1 INTRODUCTION

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 (Akbari et al. 2009) can have a strong influence on local temperatures and air quality.

Research has identified opportunities to reduce the environmental impacts of pavements. Previous research indicated that "cool" pavements with high solar reflectance 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 (Akbari et al. 2009, Rosenfeld et al. 1998). Moreover, 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 (Lenke et al. 1986, Pouget et al. 2012).

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. Chula Vista, Vallejo, and Santa Rosa are a few of the local governments that have already identified cool pavements as an important strategy both for mitigating and adapting to climate change. Despite this interest, the greenhouse gas, local climate, and air quality impacts of cool pavements remain largely unquantified.

As California re-engineers its local government practices to reduce 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, improve air quality, and protect public health. This will help the California Air Resources

Board (CARB) meet its short- and long-term greenhouse gas emissions reduction targets; help regions and the state meet air pollution standards; and help local governments adapt to increasing temperatures.

University of California Pavement Research Center (UCPRC) in a collaboration with Lawrence Berkeley National Laboratory (LBNL) and University of Southern California (USC) conducted a study on benefits and environmental impacts of cool pavements in urban areas in California. The project, funded by California Air Resources Board and Caltrans, was aiming at developing a tool to compare alternative pavement management strategies for reducing urban heat island. With an analysis period of 50 years, the scope of the tool consisted of pavement material production, transportation to the site, pavement construction activities, the changes in urban temperature due to cool pavement strategies implemented, and the resulting changes in building energy consumption throughout the analysis period. In addition to the total primary energy demand GHG emissions, air quality impacts were investigated by comparing smog and particulate matter formation under each scenario. The research project seeks to progress the adoption of strategies to reduce the greenhouse gas and air pollutant emissions and urban heat island effects of pavement systems within California. The following tasks will be completed to achieve this objective:

1. Review the existing literature for cool pavements and pavement LCA, and convene an expert panel that will inform the goal and scope of the LCA analysis.
2. Develop a scenario-modeling tool to analyze, for a wide range of pavement characteristics, the GHG emissions inventories and the air quality, urban heat island (UHI), and building energy use impacts of pavement albedo over a wide range of California city characteristics.
3. Create a pavement strategy guidance tool for local government officials based on the scenario results that can be used to estimate the potential impact of cool pavement adoption.
4. Create clear guidelines for the continual maintenance of the modeling and guidance tools.

This paper covers part of Tasks 2 and 3.

2 PAVEMENT MANAGEMENT PRACTICE

A pavement management survey was conducted with several local California governments to obtain general information about the pavement treatment practices in current use. The main questions included in the pavement management survey for different local governments concerned the following:

1. The size of the pavement network managed by the local government (any units, lane-miles, square feet, centerline miles, etc.).
2. The 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 the network per year.”
3. The approximate breakdown of the treatments used, for example: slurry seal, 70 percent or 7 lane-miles

Table 1 summarizes the results of the pavement management survey and Table 2 shows a summary of the pavement treatment surface materials, the recommended thickness or the user specifies the thickness, and approximate ranges of the expected time between replacements.

3 ALBEDO DATA FOR DIFFERENT PAVEMENT TREATMENTS

There are two ASTM standard test methods for determining the solar reflectance of a surface: ASTM C1549 (Standard Test Method for Determination of Solar Reflectance near Ambient Temperature Using a Portable Solar Reflectometer) (ASTM 2009) and ASTM E1918 (Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field) (ASTM 2006). A modified method was developed by UCPRC that is in accordance with ASTM E1918. This modified method essentially follows the standard method except for two differences: it uses a dual-pyranometer instead of a single pyranometer and it uses a data acquisition system (DAS) composed of a datalogger powered by a battery and connected to a computer to record data automatically. These modifications provide a way to monitor the solar reflectivity of a surface over long time periods.

Table 1. Summary of pavement treatment practice currently used by local governments in California

City	Public Pavement Network Lane-Miles (Centerline Miles) [1]	Portion of Network Treated Every Year	Portion of Each Treatment Used in Total Network Treated					
			Slurry Seal	Sand Seal	Chip Seal	Cape Seal	Asphalt Overlay	Recon-struc-tion
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 [2]	(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%*

[1] Use multiplier 2.2 to convert centerline miles to lane-miles. The lane width is assumed 12 ft.
[2] Forty (40) centerline miles asphalt overlay up to 2009, then 20 centerline miles asphalt overlay since 2009.

Table 2. Summary of pavement treatments

Treatment Type	Range of Treatment Life [1]	Thickness (mm) or Application Rate (Asphalt, Aggregate)
Conventional Asphalt Concrete Overlay	2–12 years (1–2 inch) Varies with traffic and design (> 2 inches)	User gives thickness
Rubberized Asphalt Concrete Overlay	2–12 years (1–2 inch) Varies with traffic and design (> 2 inches)	User gives thickness
Asphalt Concrete or Overlay with Reflective Coating	2–12 years (1–2 inch) Varies with traffic and design (> 2 inches)	User gives thickness
Chip Seal	1–10 years	9 mm stone
Slurry Seal	1–10 years	6 mm
Cape Seal	2–15 years	Chip plus slurry
Fog Seal	1–5 years	-
Sand Seal	1–6 years	-
Portland Cement Concrete	Varies with traffic and design	User gives thickness
Whitetopping	10–20 years (3–5 inches) Varies with traffic and design (> 5 inches)	User gives thickness
User Defined Material	User input	User input

[1] Adapted from Treatment Selection for Flexible Pavements. *www.pavementpreservation.org/library/getfile.php?journal_id=941* for local streets, parking lots, etc., not for highways.

Albedo data were collected from three sources: LBNL, the Federal Highway Administration (FHWA), and UCPRC. The LBNL Heat Island Group has compiled a pavement albedo database that includes sets of measurements from laboratory samples of various cool pavement treatments taken using spectrophotometer, from field samples taken using the pyranometer test method (ASTM E1918), and compiled from various sources such as field testing and literature.

An on-going FHWA project, entitled "Quantifying Pavement Albedo" (Solicitation Number: DTFH61-12-R-000050), is measuring the albedo of different pavement materials. Some initial albedo data were provided by the project contractor, Iowa State University, and included asphalt and concrete materials with different ages measured using the pyranometer test method (ASTM E1918).

An on-going study on cool pavements being conducted at UCPRC is devoted to investigating the thermal behavior and cooling effect of different pavement types (including asphalt, concrete, and block paver) and different designs (conventional impermeable and novel permeable designs), to using the field measurement data to validate the heat-transfer modeling, to employing the validated model to simulate the thermal behavior and cooling effect of different pavements in various contexts (climates and surroundings), and to examining the effect of cool pavements on human thermal comfort (Li et al. 2013). Nine test sections were the primary sections for albedo measurements at UCPRC. 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). More details on the materials can be found in reference (Li et al. 2013). Along with these nine sections, several extra pavement sections with conventional impermeable asphalt and concrete surfacing were also included in the study for the field measurement of albedo. For comparison, albedo has also been measured on other land cover materials, including gravel, soil and grass. Some of these materials were of different ages when solar reflectivity measurements were conducted on them. In May 2014, more field albedo measurements were performed around Davis, California, and these included slurry seal, fog seal, cape seal, chip seal, and more PCC and AC materials.

The steady-state (the final stable albedo value remained after a certain time of weathering and trafficking) albedo of the different pavement materials summarized across all data sources are shown in Table 3.

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
Cape Seal	-	-	-	-	0.05–0.15	0.06	0.05–0.15	0.06
Chip Seal	0.1–0.2	0.15	-	-	0.14–0.24	0.18	0.1–0.24	0.15
Conventional Interlocking Concrete Pavement	-	-	-	-	0.25–0.3	0.26	0.25–0.3	0.26
Fog Seal	-	-	-	-	0.04–0.07	0.06	0.04–0.07	0.06
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
Portland Cement Concrete	0.15–0.25	0.2	0.2–0.3	0.25	0.18–0.38	0.25	0.15–0.35	0.25
Sand Seal	-	-	-	-	-	-	0.07–0.1	0.08
Slurry Seal	-	-	-	-	0.07–0.1	0.08	0.07–0.1	0.08

The main findings on albedo include:

- The most commonly used pavement treatments currently have relatively low steady-state albedo, ranging from 0.05 to 0.15 with average of 0.1 for asphalt concrete, and 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 were not available for sand seals. For experimental coatings, albedos ranged from 0.2 to 0.3 with average of 0.25 for asphalt concrete with reflective coating, and from 0.15 to 0.35 with average of 0.25 for concrete with reflective coating.

- Although the initial albedo of treatments with reflective coatings can be very high (e.g., up to 0.7 or higher), albedo will decrease very quickly and significantly to a low value due to weathering and tracking with current technology.

4 DYNAMIC ALBEDO CHANGE MODELING FOR URBAN PAVEMENT

Urban area land cover is a term used to include buildings, pavements, vegetation, and bare soil, etc. Urban area land cover is illustrated in Figure 1. Urban area pavements include both public and private ones. Public pavements are usually managed by a government agency, and some portion of them receives regular treatment to improve pavement performance. A number of treatments are used on these public pavements each year, and many of these treatments have different albedos. Because of this, the total pavement albedo and consequently the urban albedo change over time. This dynamic process can be modeled with a dynamic albedo model, as shown in Equations (1) through (4). This report will focus on the pavement albedo using Equations (3) and (4). Figure 2 shows an example dynamic albedo of public pavement with the assumptions that 10 percent of the network is treated annually and 50 percent of the slurry seal and asphalt overlay are replaced with reflective materials.

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

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

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

$$\alpha'_t = \sum n_{i,t}\ \alpha_{i,t} \quad (4)$$

Where:

$R_{np,t}$ is the total non-pavement area portion in urban land surface in year t;

$R_{p,t}$ is the total pavement network area portion in urban land surface in year t;

$R_{pp,t}$ is the total *publicly managed* pavement network portion in urban land surface in year t;

R_t is the portion of pavement network for treatment in year t;

$n_{i,t}$ is the portion of treated pavement network which use treatment i in year t;

α_t is the albedo of total urban area in year t;

$\alpha_{p,t}$ is the albedo of total pavement area in year t;

$\alpha_{np,t}$ is the albedo of total non-pavement area in year t;

$\alpha_{npp,t}$ is the albedo of non-public pavement area in year t;

$\alpha_{pp,t}$ is the albedo of public pavement area in year t;

$\alpha_{i,t}$ is the albedo of pavement treatment i in year t;

α_t is the average albedo of pavement network in year t;

α'_t is the average albedo of pavement treated in year t;

i is the pavement treatment type (A, B, C, D, …); and

t is the year (1, 2, ..., 50).

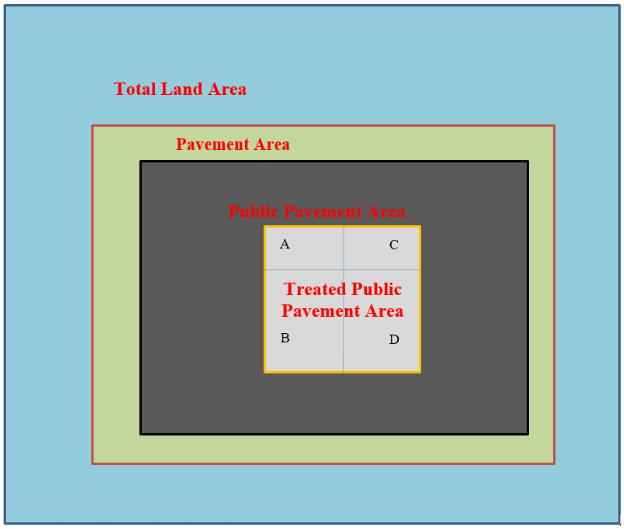


Figure 1. Urban land cover at year t

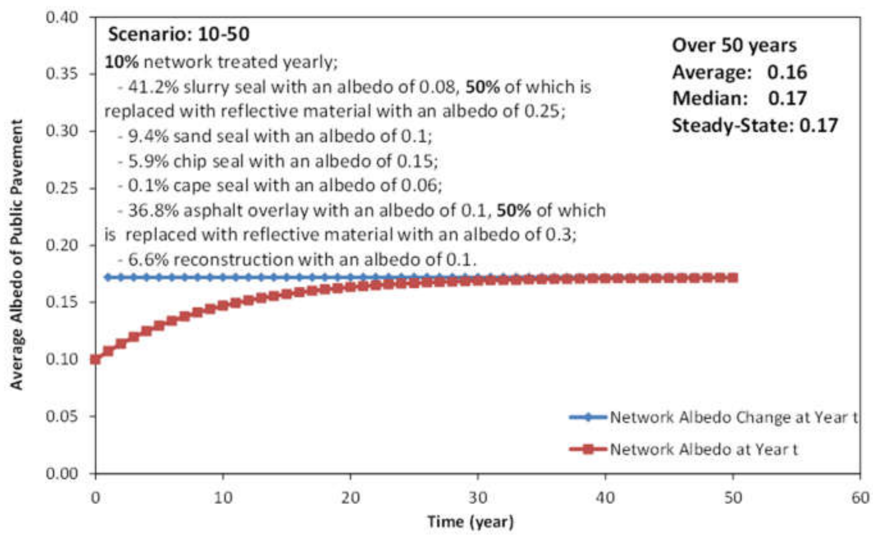


Figure 2. Example dynamic albedo of public pavement with assumptions that 10 percent of the network is treated annually and 50 percent of the slurry seal and asphalt overlay are replaced with reflective materials

5 LIFE CYCLE INVENTORY FOR PAVEMENT TREATMENTS

LCA models were either developed or taken from GaBi software for the construction materials, energy sources, transport modes, and surface treatments. Table 4 and Table 5 show the list of the items included in the database. These models were calibrated to better represent local practice in California in terms of electricity grid mix, plant fuel mixes, and construction processes. Model for materials are cradle to gate. Surface treatment models include material production, transportation to the site (assumed to be 50 miles, the average hauling distance in California), and construction activities. Extensive literature survey was conducted to identify common reflective coatings currently in practice around the world and to determine the components of each. This was used to develop the life cycle inventories (LCI) of the reflective coatings (Li & Saboori 2014). Mix design and construction process for each of the surface treatments were taken from Caltrans' Maintenance Technical Advisory Guide (MTAG) (Caltrans 2007) or through field investigations and inquiries from local experts.

Following California's implementation of the Renewables Portfolio Standard (RPS), it was decided that the LCA models in this study should also be developed taking into account the state's projected grid mix for the year 2020. The new grid mix was developed based on projections in reports from the California Public Utility Commissions (CA PRS website). All the models of materials and treatments were updated based on the new electricity grid mix, resulting in two separate datasets, one based on 2012 grid mix and one based on 2020.

Furthermore, the whole database developed under this study and previous LCA studies at UCPRC were verified by a 3rd party committee. The details of all the assumptions and final results are available in the documentation of the UCPRC LCI database (Saboori et al., in prep.).

Table 4. Indicators and flows to be used in the final tool

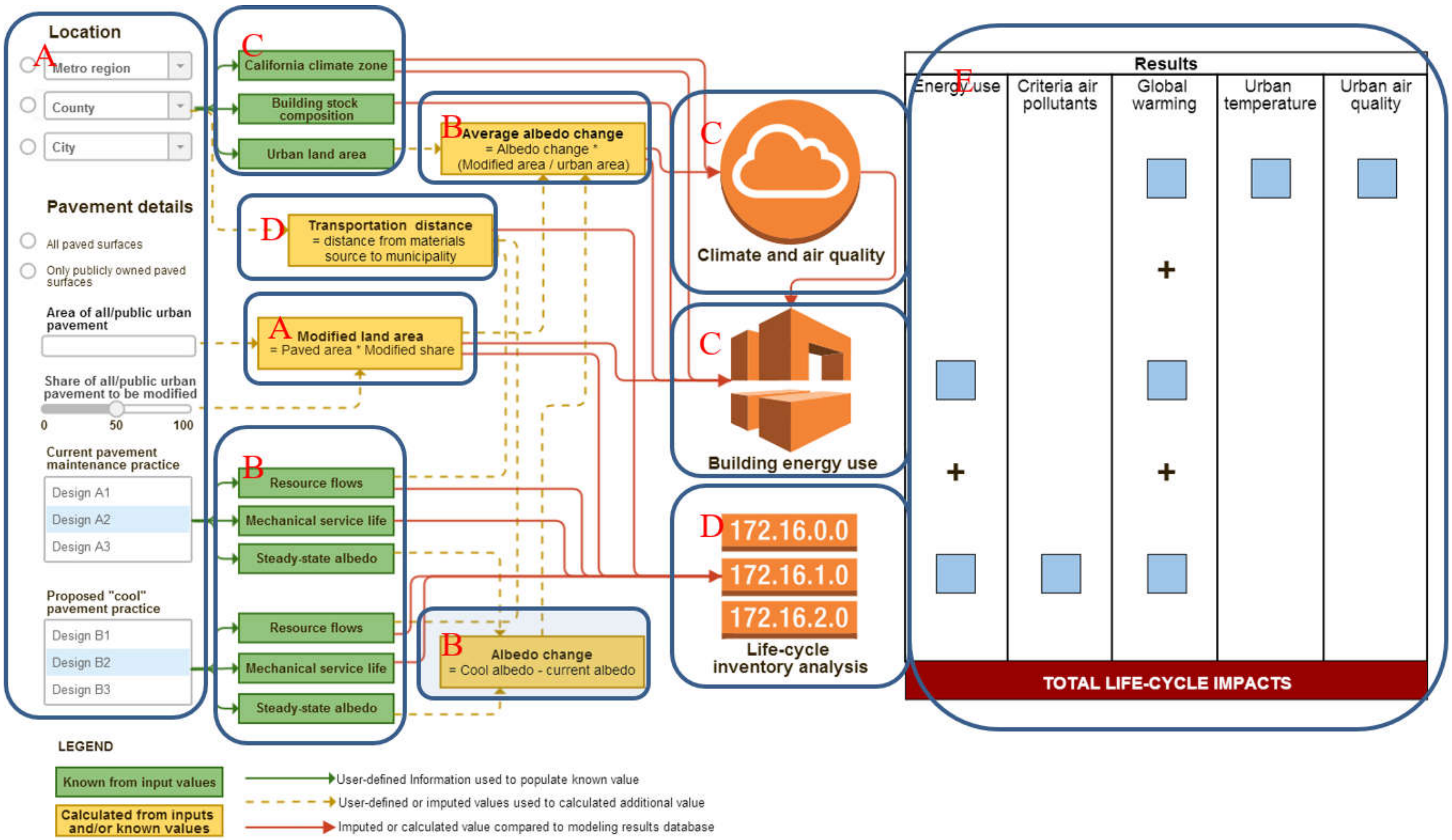
Impact Category/Inventory	**Abbreviation**	**Unit**
Global Warming Potential	GWP	kg of CO_2e
Photochemical Ozone Creation (Smog) Potential	POCP	kg of O_3e
Particulate Matter, less than 2.5 micrometers in diameter	PM2.5	kg
Primary Energy Demand from Renewable & Non-Renewable Resources (net calorific value excluding feedstock energy)	PED (total)	MJ
Feedstock Energy	FE	MJ

Table 5. List of materials, energy sources, transport modes, and surface treatments for which LCA models were developed

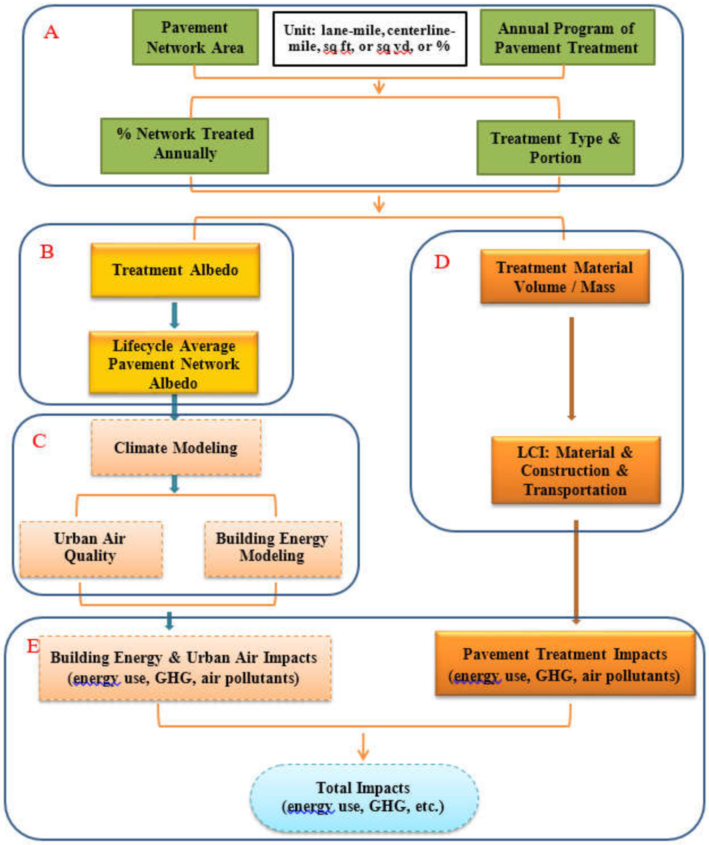
Materials and Energy Sources	Aggregate – Crushed		Surface Treatments	Cape Seal
	Aggregate – Natural			Chip Seal
	Bitumen			Fog Seal
	Bitumen Emulsion			Conventional Asphalt Concrete (mill and fill)
	Crumb Rubber Modifier (CRM)			Conventional Asphalt Concrete (overlay)
	Dowel & Tie Bar			Conventional Interlocking Concrete Pavement
	Energy Sources	Diesel Burned in Equipment		Permeable Asphalt Concrete
		Electricity		Permeable Portland Cement Concrete
		Natural Gas Combusted in Indust. Equip.		Portland Cement Concrete
	Limestone			Portland Cement Concrete w. SCM
	Quicklime			Reflective Coating - BPA
	Paraffin (Wax)			Reflective Coating - Polyester Styrene
	Portland Cement	Regular		Reflective Coating - Polyurethane
		Slag Cement (19% Slag)		Reflective Coating - Styrene Acrylate
		Slag Cement (50% Slag)		Rubberized Asphalt Concrete (mill and fill)
	Portland Cement Admix-tures	Accelerator		Rubberized Asphalt Concrete (overlay)
		Air Entrainer		Sand Seal
		Plasticizer		Slurry Seal
		Retarder		Thin White Topping
		Superplasticizer	Transpo	Barge Transport
		Waterproofing		Heavy Truck (24 tonne)
	Styrene Butadiene Rubber (SBR)			Ocean Freighter

6 INTEGRATION OF RESULTS INTO COOL PAVEMENT LCA TOOL

Figure 3 shows the proposed integration of the pavement management practices along with the life-cycle inventories and impact calculations developed in this project. Figure 3(a) shows the integration of all the elements in the user interface. Figure 3(b) shows the recommended flow of calculations for using the results of this study in calculating the life-cycle flows and impacts of interest for the complete life-cycle—including the materials production, construction, and use stages, where the use stage includes building energy use.



(a) User interface of cool pavement LCA tool



(b) Flowchart for cool pavement LCA tool development
Figure 3. Cool pavement LCA tool development

7 SUMMARY AND RECOMMENDATIONS

This study includes these key findings:

- Based on responses from eight of the California local governments surveyed, most local governments treat a small portion of the public street pavement network every year, ranging from 1.3 percent to 20 percent with an average of 6.8 percent. The survey consisted of responses from cities as opposed to counties.
- The main treatments used by these 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 percent to 82 percent of the pavement miles treated and an average of 41 percent. Asphalt overlay is another major treatment that most local governments use, ranging from 13 percent to 100 percent of mileage treated with an average of 36.8 percent. Chip seals makes up on average 5.9 percent of the mileage treated, ranging from 0.7 percent to 46.4 percent, 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. On average, reconstruction is used for 6.6 percent of the total treatments, ranging from 3 percent to 28 percent.
- Most pavement treatments currently used have relatively low steady-state albedo, with a range from 0.05 to 0.15 and 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 AC. 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. Data were unavailable for sand seals. Experimental treatments include asphalt concrete with reflective coating, which had albedo ranging from 0.2 to 0.3 with an average of 0.25, and concrete with reflective coating, which ranged from 0.15 to 0.35 with an average of 0.25.

- Although the initial albedo of treatments with reflective coating can be very high (e.g. up to 0.7 even 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.
- Due to the small portion of pavement network treated every year with treatments of relatively low steady-state albedo, the final steady-state albedo increase of the 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.

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9 REFERENCES

Akbari, H., Menon S., & Rosenfeld A. 2009. Global Cooling: Increasing World-Wide Urban Albedos to Offset CO2. *Climatic Change*, Vol. 94, No. 3, pp. 275-286.

ASTM, 2006. ASTM E1918-06 Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field. American Society for Testing and Materials.

ASTM, 2009. ASTM C1549-09 Standard Test Method for Determination of Solar Reflectance near Ambient Temperature Using a Portable Solar Reflectometer. American Society for Testing and Materials.

CA RPS webpage available at: *http://www.cpuc.ca.gov/PUC/energy/Renewables/*

Caltrans Maintenance Technical Advisory Guide (MTAG) 2007. California Department of Transportation, Sacramento, CA.

Lenke, L. & Graul, R. 1986. "Development of runway rubber removal specifications using friction measurement and surface texture for control." The Tire Pavement Interface, ASTM STP 929, MG Pottinger ans TJ Yagger, Eds, American Society of Testing and Materials: 72-88.

Li, H., Harvey, J.T. & Kendall, A. 2013. Field Measurement of Albedo for Different Land Cover Materials and Effects on Thermal Performance. *Building and Environment*, Vol. 59, No. 2013, pp. 536-546.

Li, H., Saboori, A., & Cao, X. 2014. Reflective Coatings for Cool Pavements: Information Synthesis and Preliminary Case Study for Life Cycle Assessment. *2014 Pavement LCA Symposium*, University of California Davis, Davis, CA.

Pouget, S., C. Sauzéat, H. Benedetto, and F. Olard., Viscous Energy Dissipation in Asphalt Pavement Structures and Implication for Vehicle Fuel Consumption. Journal of Materials in Civil Engineering, Vol. 24, No. 5, 2012, pp. 568-576.

Rosenfeld, A.H., Akbari H., Romm J.J., & Pomerantz, M. 1998. Cool Communities: Strategies for Heat Island Mitigation and Smog Reduction. *Energy and Buildings*, Vol. 28, No. 1, pp. 51-62.

Saboori, A. in prep. Documentation of the UCPRC Life Cycle Inventory (LCI) Used in CARB/Caltrans LBNL Heat Island Project and other Caltrans' LCA Studies. University of California Pavement Research Center, Davis, CA.