Energy Research and Development Division

FINAL PROJECT REPORT

Solar-Reflective "Cool" Walls: Benefits, Technologies, and Implementation

Appendix F: Effect of Cool Walls on Energy-saving Benefits from Cool Pavements (Task 3.3 Report)

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Appendix F:
Effect of cool walls on energy-saving benefits from cool pavements (Task 3.3 report)

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Note: This task report is a preprint of Rosado and Levinson (2015). A brief element of this report (Section 3.2: Building to roads view factors) was included in Levinson et al. (2017).

Abstract

Solar-reflective “cool” pavements are an urban heat island reduction strategy that increases pavement albedo (solar reflectance) to reduce convective heating of the outdoor air, which has the “indirect” effect of decreasing cooling loads in summer and increasing heating loads in winter. Raising pavement albedo also increases the solar flux incident on walls and windows. This “direct” effect of reflective pavement can increase cooling loads in summer and reduce heating loads in winter. In this study we focus on the direct effect of cool pavements, and quantify its impact on the annual conditioning (heating and cooling) energy uses of buildings in California, USA. The study also measures how modifying wall and window properties alter the direct effect.

We prepared nine code-compliant building prototypes with external horizontal shading surfaces that represent local roads. To quantify the direct effects of cool pavements, we simulated with EnergyPlus the annual cooling and heating energy uses of each prototype, varying the road albedo, wall absorptance, and window solar heat gain coefficient.

We present a physical model that relates each heating and cooling energy use to building properties, and to local road albedo. The results from the building simulations were used to validate the physical model, and to generate relationships that predict the direct effect of pavement albedo change on building energy use.

1 Introduction

Heat island refers to the phenomenon of having higher urban temperatures compared to the temperatures of surrounding suburban and rural areas (Santamouris 2013). In the United States, pavements cover typically up to 30% of the urban fabric (Rose et al. 2003), and as hot, dry surfaces can contribute substantially to the heat island effect.

The use of cool pavements is an urban heat island reduction strategy that increases pavement albedo (solar reflectance) to reduce convective heating of the outdoor air. This lowers the air temperature difference across the building envelope, reducing heat gain via conduction and infiltration. This “indirect” effect of reflective pavement can decrease cooling loads in summer and increase heating loads in winter. Raising pavement albedo also increases the solar flux incident on walls and windows. This “direct” effect of reflective pavement can increase cooling loads in summer and reduce heating loads in winter. The total annual changes in cooling and heating energy loads will depend on the relative magnitudes of the indirect and direct effects. This study explores only the direct effect of cool pavements for buildings in California cities.

The magnitude of the direct effect depends on the design and properties of the building’s walls and windows. We prepared nine code-compliant building prototypes with external horizontal shading surfaces that represent local roads. To quantify the direct effects of cool pavements, we simulated with EnergyPlus the annual cooling and heating energy uses of each prototype, varying the road albedo, wall absorptance (1 – wall albedo), and window solar heat gain coefficient.

We present a physical model that relates each heating and cooling energy use to building properties, and to local road albedo. The results from the building simulations were used to validate the physical model, and to generate relationships that predict the direct effect of pavement albedo change on building energy use.

2 Methodology

2.1 Physical model

We derived a physical model to describe the effect of modifying building envelope properties on conditioning energy use when implementing cool pavements. This physical model describes the cooling and heating energy uses of a building from modifications to local road albedo (ρ_r), exterior wall solar absorptance (α), and window solar heat gain coefficient (σ).

Raising the local road albedo increases the reflected solar flux incident on walls and windows. Reducing the solar absorptance of the walls decreases the reflected solar flux that is absorbed and conducted through the walls and eventually heats the interior. Additionally, reducing the solar heat gain coefficient (SHGC) of windows decreases the reflected solar flux that is direct transmitted through the window to the interior, and that is absorbed by the window and re-radiated to the interior. Thus, the change in cooling or heating energy use E by the change in the local road albedo can be described as

$$\frac{\partial E}{\partial \rho_{\mathrm{r}}} = a_2 \cdot \alpha + a_4 \cdot \sigma \ . \tag{1}$$

Similarly, the change in cooling or heating energy use by a change in the wall absorptance is described as

$$\frac{\partial E}{\partial \alpha} = a_1 + a_2 \cdot \rho_{\mathrm{r}} \tag{2}$$

The change in cooling or heating energy use by a change in window SHGC can be described as

$$\frac{\partial E}{\partial \sigma} = a_3 + a_4 \cdot \rho_r \tag{3}$$

The solutions to the differential equations of these physical models provide a way to calculate the cooling or heating energy uses as a function local road albedo building surface parameters. Combining equations (1) through (3) yields

$$E = a_0 + a_1 \cdot \alpha + a_2 \cdot \rho_{\mathrm{r}} \cdot \alpha + a_3 \cdot \sigma + a_4 \cdot \rho_{\mathrm{r}} \cdot \sigma \tag{4}$$

Equation (4) was used to obtain the solutions that describe the cooling (E_{C}) and heating (E_{H}) energy uses.

2.2 Building prototypes

The EnergyPlus prototypes include seven commercial buildings and two residential buildings. Table 1 lists the nine prototypes and summarizes their dimensions. The commercial prototypes were obtained from the California Energy Commission (CEC); the residential prototypes were obtained from the United States Department of Energy's Building Energy Codes Program (PNNL 2016a,b). All nine prototypes were modified to meet California's 2008 Title 24 commercial (CEC 2008a) and residential (CEC 2008b) building codes for: (a) wall, ground floor and ceiling thermal resistance (RSI) values; (b) window thermal transmittance, SHGC, and visible transmittance; (c) air-conditioning's SEER; and (d) heating's annual fuel utilization efficiency (AFUE).

The CEC established 16 building climate zones (hereafter, "climate zones") in the state, each representing a geographic area of a particular climate. CEC's Title 24 estipulate building construction codes for each of these 16 climate zones. For each building prototype we prepared 16 code-compliant versions, one per climate zone.

2.3 Prototype modifications

The residential and commercial prototypes were modified to include horizontal surfaces to represent local roads. Additional external vertical surfaces were included to represent the shading effect from neighboring buildings.

We obtained the minimum side and front setbacks for different building types from the street design guidelines specified for the city of Sacramento, CA in the Zoning Code of Sacramento County, ZCSC (ZCSC 2015). These setback regulations were used to define the distance between the modelled buildings and the vertical shading surfaces. We also obtained the front setbacks regulations, which we used to define the distance between the modelled buildings and the roads. Table 1 lists the front setbacks.

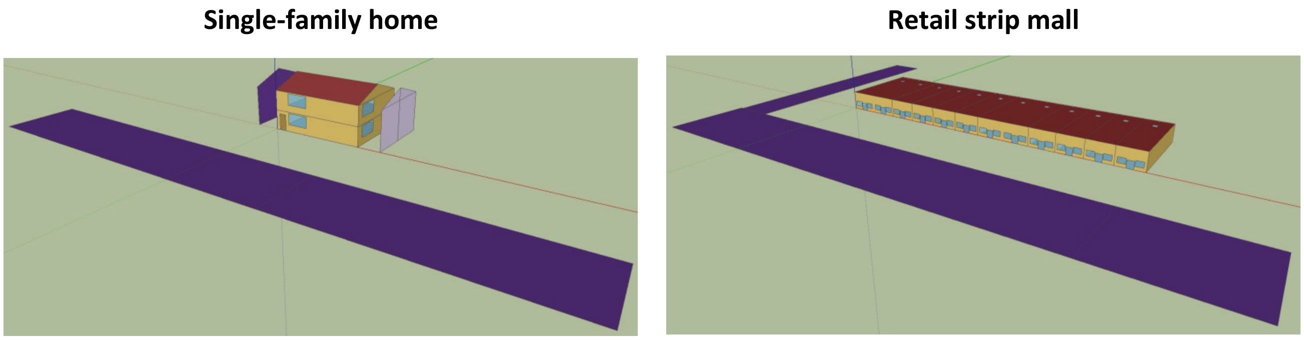
In average, a city block covers a surface area of 10,000 m^2. Hence, unless a large building occupies an entire city block, it is common to have a building facing a paved surface from only one or two sides. We estimated the number of sides each prototype faces a paved surface by comparing its footprint area to the size of a city block.

The road dimensions follow street design configurations and standards used for the city of Sacramento (DoT Sacramento 2009). We used Sacramento's street design dimensions because they are closest to the average street dimensions found in other large California cities (e.g. Los Angeles (Ryan Snyder Associates. 2011) and San Jose (DoT San Jose 2010). Hence, we classified the roads used in the modelling into three types: residential, commercial, and boulevard. The road widths are 9 m, 11 m, and 22 m, respectively. The road type added in each prototype depended on the building use. Table 1 lists the road types used.

Table 1: Summary of prototypes construction, setback distances, and road types.

Prototype building	Road type	Floors	Conditioned floor area [1000 m^2]	Gross wall area [1000 m^2]	Window area [1000 m^2]	Window-to-wall ratio [%]	Front setback [m]	Sides facing road
Single-family home	Residential	2	0.22	0.24	0.03	14.1	10	1
Apartment complex	Residential	3	2.0	1.50	0.25	16.4	11	1
Large hotel	Boulevard, Commercial	6	11.3	4.03	1.21	30.2	15.2	2
Large office	Boulevard, Commercial	13	46.3	11.6	4.64	40.0	40, 11	2
Medium office	Commercial	3	5.0	1.98	0.65	33.0	11	1
Primary school	Residential	1	6.8	2.51	0.88	35.0	11	3
Fast-food restaurant	Commercial	1	0.23	0.19	0.03	14.0	19	1
Retail stand-alone	Boulevard	1	2.3	1.18	0.08	7.1	65	1
Retail strip mall	Boulevard, Commercial	1	2.2	1.18	0.12	10.5	65, 19	2
Sit-down restaurant	Commercial	1	0.51	0.28	0.05	17.1	19	1

Figure 1 shows the single-family home and strip mall retail prototypes. The horizontal purple surfaces are the EnergyPlus shading objects used to represent the "roads". The single-family home also has vertical shading surfaces used to represent neighboring buildings.


Single-family home

Retail strip mall

Figure 1: Modified building prototypes of the single-family home and the strip mall retail.

2.4 Weather files

The building prototypes were simulated using the most recent California weather files developed by White Box Technologies (WBT 2011) for use in Title 24 compliance calculations. They have produced 86 weather files from weather stations throughout the state of California. The files have a period of record of 12 years (1998-2009). From the 86, there are 16 weather stations that the US Department of Energy uses to demonstrate compliance with Title 24 in California's climate zones (CZ). In this study, we focused on the CZ which are most densely populated. Table 2 lists some of the major cities in each CZ.

Table 2: California's mayor cities in the represented climate zones.

Climate zone	Major cities
3	Oakland, Fremont, San Francisco
4	San Jose
7	San Diego
8	Los Angeles, Irvine, Anaheim, Santa Ana
9	Burbank, Glendale, Pasadena
10	Riverside, Rancho Cucamonga, San Bernardino
12	Sacramento
13	Fresno, Bakersfield
15	Palm Springs

2.5 EnergyPlus simulations

All simulations were run with EnergyPlus v8.1 (EnergyPlus 2003), a building energy simulation program that models cooling, heating, ventilation, and other energy flows. The time to run all simulations was reduced using the parametric simulation manager jEPlus (jEPlus 2015).

We ran simulations to perform a parametric analysis that varied the road albedo, window SHGC, and wall solar absorptance. Each prototype was modelled with six different road albedos (0.1, 0.15, 0.2, 0.4, and 0.5), four different window SHGCs (0, 0.2, 0.4, 0.6), and four different wall absorptances (0, 0.2, 0.5, and 0.8).

3 Results

3.1 Comparing contributions from walls and windows

We compared the magnitude of solar flux reflected from the roads that is incident on walls to that incident on windows. To understand the contribution through walls, we performed simulations in which the wall absorptance was either the code-compliant default or zero. These simulations were run for both low and high road albedo. We first calculated the total change in cooling or heating energy use that results from increasing road albedo [Eq. (5)]. This is calculated with the default wall absorptance (α_d).

$$\Delta E_T = E(\rho_{high}, \alpha_d) - E(\rho_{low}, \alpha_d) \ . \tag{5}$$

Similarly, the portion of the energy change not attributed to walls was calculated with the simulations where wall absorpance was set to zero (α_0):

$$\Delta E_{non\_wall} = E(\rho_{high}, \alpha_0) - E(\rho_{low}, \alpha_0) \ . \tag{6}$$

Lastly, the portion in ΔE_T that is attributed to walls is obtained by subtracting the non-wall contribution from the total change:

$$\Delta E_{wall} = \Delta E_T - \Delta E_{non\_wall} \ . \tag{7}$$

Following the same approach described in Equations (5) through (7) but using the simulations where the windows SHGCs were set to zero, we calculated the magnitude of heat load gained through windows (ΔE_{window}).

The portions of the change in cooling or heating energy use allotted to walls and windows depend on various factors. Low wall solar absorptance decreases the heat gained through walls; similarly, lower windows SHGC reduces the cool pavements' direct effect through windows. But another factor that dictates the magnitude of the direct effect through either walls or windows is the window-to-wall ratio (window area / wall area). Large window-to-wall ratios increases the contribution through windows by increasing their surface area exposed to the incident reflected solar flux.

Since all prototypes had different window-to-wall ratios, we normalized the direct effect contributions through walls and windows by the window-to-wall ratio (largest ratio is 0.40), to allow a fair comparison of their contributions. Figure 2a,b compare the normalized cooling contribution through walls and windows, respectively to the total direct effect. From the regressions' slope, we find that windows contribute nearly 60% to the total direct effect on the cooling energy use, that is, 1.5 times the contribution through walls.

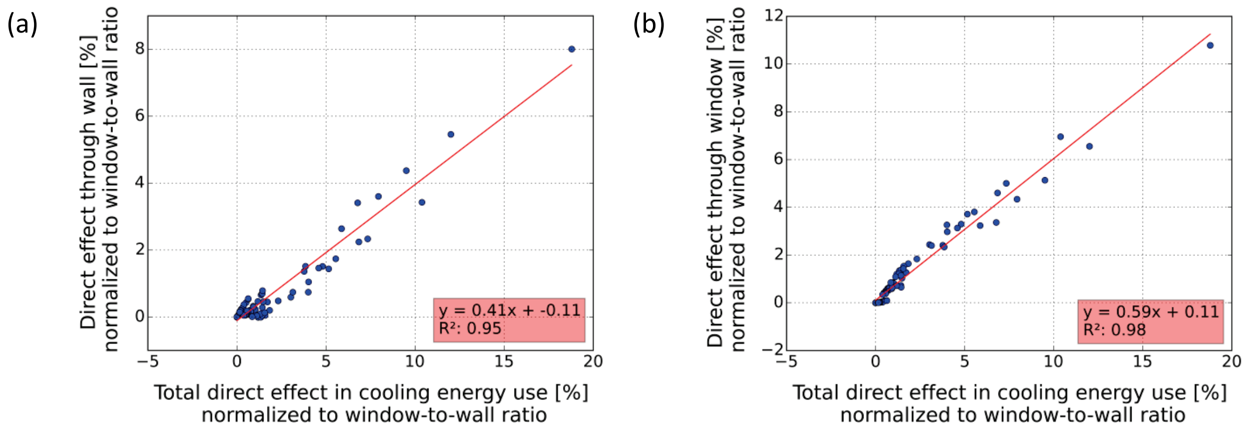


Figure 2: Comparing the fraction of the direct effect in cooling energy use that is gained (a) through the walls and (b) through the windows.

3.2 Building to roads view factors

Assuming unobstructed view from wall to road (e.g. absence of trees), we used standard radiation configurations to calculate the view factors from the prototypes to the roads. We treat the road facing walls of a building as a rectangular surface of height (H_w) and length (L_w), with a setback to the road (W_s). The road is treated as an infinitely long rectangle of width (W_r). To calculate the wall-to-road view factors ($F_{w\text{-}r}$), we employ two standard radiation configurations. One configuration was used to find the view factor from the wall to the portion of the road directly in front of the wall, which we call the central road. The second configuration was employed to calculate the view factor form the wall to the left and right wings of the road. See Figure 3 for the break out of the wall, setback, and road sections used for the view factor calculations.

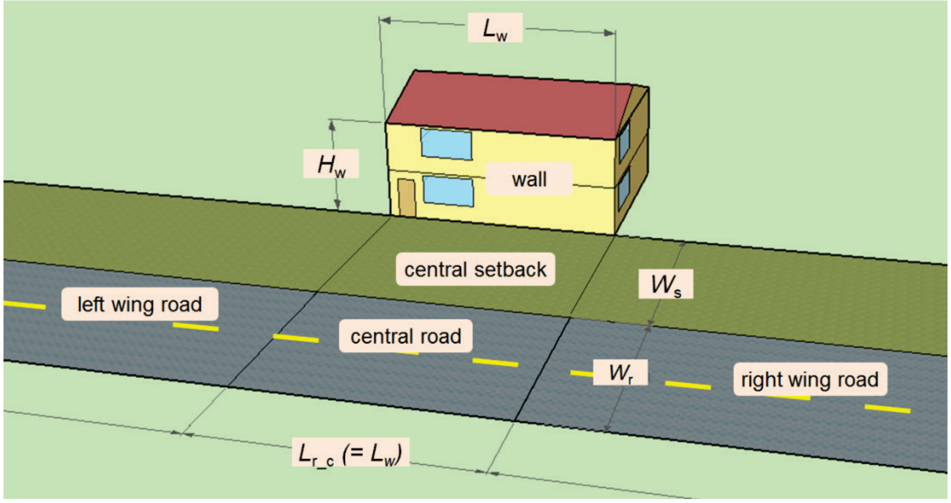


Figure 3: Diagram of single-family home with setback and road.

The first configuration (Incropera 2007) is used for two finite rectangles of same length, having one common edge, and at an angle of 90° of each other. Hence, the view factor from the wall to the central road portion ($F_{\text{w-r\_c}}$) was obtained by subtracting the view factor to the central setback ($F_{\text{w-s\_c}}$) from the view factor to the central setback+road ($F_{\text{w-sr\_c}}$) [Equation (8)].

$$F_{\text{w-r\_c}} = F_{\text{w-sr\_c}} - F_{\text{w-s\_c}} \tag{8}$$

The second configuration (Ehlert and Smith 1993) is commonly used for a rectangle to a rectangle in a perpendicular plane, with all boundaries being parallel or perpendicular. Thus with this configuration we obtained the view factors from the wall to the left ($F_{\text{w-r\_l}}$) and right ($F_{\text{w-r\_r}}$) wings of the road. The total wall-to-road view factor ($F_{\text{w-r}}$) was obtained as

$$F_{\text{w-r}} = F_{\text{w-r\_c}} + F_{\text{w-r\_l}} + F_{\text{w-r\_r}} \tag{9}$$

As explained in Section 4.1, the modified prototypes do not have roads at all four cardinal sides. Using the number of building sides (*N*) facing a road (Table 1), we estimated the overall building-to-road view factor F_{br} as

$$F_{\text{b-r}} = F_{\text{w-r}} \times N/4 \tag{10}$$

Table 3 lists the view factors from the wall to different portions of setback and road. These were calculated using the setback distances listed in Table 1 and the widths of the roads assigned to each prototype.

Table 3: Calculated view factors from wall to setback and road portions.

Prototype	Wall to all setback ($F_{w\text{-}s}$)	Wall to all setback + road ($F_{w\text{-}sr}$)	Wall to road ($F_{w\text{-}r}$)	Building to road ($F_{b\text{-}r}$)
Single-family home	0.373	0.430	0.057	0.014
Apartment complex	0.342	0.406	0.064	0.016
Large hotel	0.277	0.356	0.079	0.040
Large office	0.133	0.246	0.113	0.057
Medium office	0.282	0.372	0.090	0.023
Primary school	0.413	0.45	0.037	0.028
Retail stand-alone	0.422	0.46	0.038	0.010
Retail strip mall	0.434	0.462	0.028	0.014
Sit-down restaurant	0.459	0.472	0.013	0.003

Using the modelling results used for Section 5.1, we obtained a relationship that describes the change in total direct effect as a function of building to road view factor. As before, we normalized the direct effect by the window-to-wall ratio. This relationship is particular to location, which in our case we varied by climate zone. Figure 4 shows this relationship for the direct effect in cooling energy use for climate zones 9 and 12. The slope of the curve varies by climate zone, and for the effects on cooling, it ranged between 15 %/$F_{b\text{-}r}$ and 27 %/$F_{b\text{-}r}$. For the effect on heating energy use, the slopes were opposite in sign, and smaller in magnitude (-25 %/$F_{b\text{-}r}$ to -6 %/$F_{b\text{-}r}$).

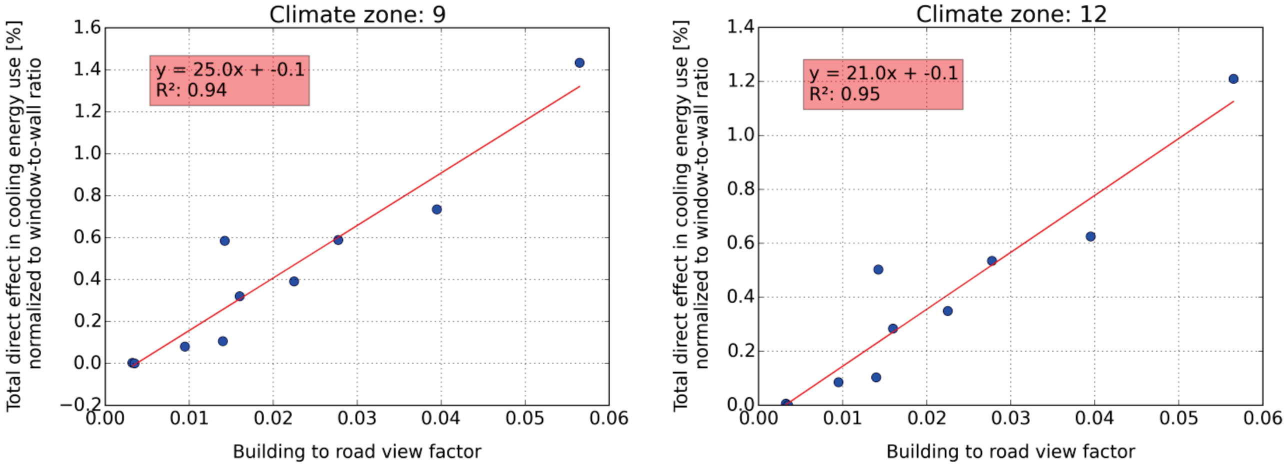


Figure 4: Direct effect in cooling energy use from cool pavements vs building to road view factors, for CZ 9 and CZ 12.

3.3 Coefficients to physical model solutions

Using multiple linear regression analysis on the EnergyPlus simulations, we calculated the coefficients to the physical model solutions described in Equation (4) for cooling and heating energy uses. The coefficients describe annual site energy uses and are particular to each prototype and to each climate zone. This leads to 81 (9 prototypes x 9 climate zones) different physical model solutions for any type of conditioning energy use. As an example, Table 4 show the cooling and heating coefficients for prototypes in climate zone 12, specifically for sit-down restaurant, retail strip mall, and single-family home. The coefficients labelled **e** represent electric energy use in units of MWh/y, and the coefficients **g** are for gas energy use in units of therms/y. Values can be converted to units of MJ by multiplying MWh × 3600, or therm × 105.5.

Table 4: Coefficients for physical model solutions for prototypes sit-down restaurant, retail strip mall, and single-family home, in CZ 12.

Prototype	**Use**	**e0**	**e1**	**e2**	**e3**	**e4**	**g0**	**g1**	**g2**	**g3**	**g4**
Sit-down restaurant	cooling	20.129	0.825	0.002	3.33	0.008	0	0	0	0	0
	heating	0	0	0	0	0	2725.8	-177.3	-1.428	-519.6	0.021
Retail strip mall	cooling	41.552	4.279	0.264	16.74	0.042	0	0	0	0	0
	heating	0	0	0	0	0	1510.1	-135.6	-6.982	-762.7	0.764
Single-family home	cooling	0.483	0.447	0.021	2.28	0.135	0	0	0	0	0
	heating	0	0	0	0	0	205.7	-34.8	-2.143	-168.6	-2.605

3.4 Modify wall and window to counter direct effect

Here we present how changes to wall absorptance and window SHGC can counter the direct effect of cool pavements. For purposes of the analysis, we used a road albedo of 0.10 to represent the base case, and 0.35 for the modified case; these represent typical albedo values of an aged asphalt and new standard gray cement concrete, respectively (ACPA 2002). For wall absorptance, the base case and modified case values were 0.70 and 0.45. For the windows SHGC, values were 0.35 and 0.30 respectively; these values meet the requirements in 2008 Title 24 Standards for all building climate zones and building types. Table 5 summarizes these values.

Table 5: Base case and modified case values for the varied road and building properties.

Property	Base case	Modified case
Road albedo (ρ_r)	0.10	0.35
Wall absorptance (α)	0.70	0.45
Window SHGC (σ)	0.35	0.30

3.4.1 Annual cooling site energy

Considering the case of modifying the road albedo by 0.25 while keeping the building envelope unchanged, the prototypes suffered cooling site energy penalties of no more than 1.3% of their annual use; the largest penalties occurring at climate zones with low cooling degree days at 18 °C (CDD18C). The penalties varied by building and location, but it averaged 0.4%.

We chose to decrease the wall absorptance by 0.25 to match (in magnitude) the road albedo increase. During the cooling season, we observed that this was generally enough to outweigh the direct cooling penalty from the cool pavements. As an example, the benefits from lower wall absorptance in the residential buildings outweigh the cool pavement penalties by more than a factor of 3 in most CZ. The single-family home and apartment complex experienced cooling savings that range between 5-19% and 2-7% respectively. These results are similar to the ones found in the commercial buildings with similar window-to-wall ratio (retail strip mall and retail stand-alone). However, lowering the wall absorptance had no effect over the cooling site energy in the prototypes with high window-to-wall ratio (medium and large office).

When considering the case of modifying the road albedo and the window SHGC, the prototypes also experienced cooling savings (average of 2.8%). Hence, the penalties from the direct effect of cool pavements during the cooling season can be far outweighed by performing small modifications to the wall absorptance and window SHGC. Figure 5 show the cooling savings from modified pavements and surface properties, as a function of CDD18C, for the single-family home and retail strip mall. The figures demonstrate how the magnitudes of the savings reduce with increasing CDD18C.

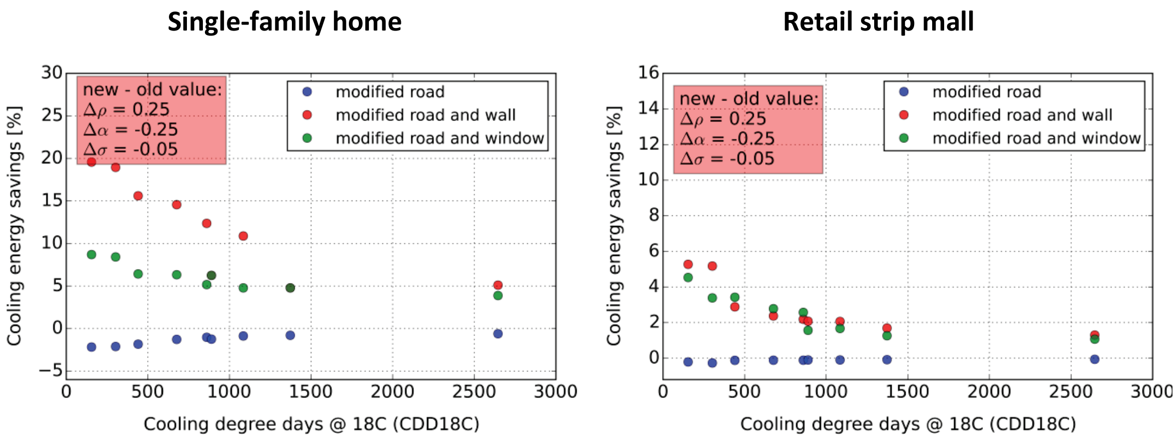


Figure 5: Cooling site energy savings vs CDD18C for single-family home and retail strip mall.

3.4.2 Annual heating site energy

As expected, the heating season experienced the opposite response from the cooling season. The single-family home experienced the largest annual heating savings from cool pavement (0.67%), but the mean savings across buildings and climate zones was 0.1%.

In magnitude, the fraction of heating penalties from modified wall absorptance and window SHGC were similar than cooling benefits. In average, modifying the roads and walls alone had a penalty of 4%. For the case of road and windows SHGC, the penalties were 3.2%.

Figure 6 show for the single-family home and retail strip mall, the heating penalties from modified pavements (negative values mean savings), walls and windows, as a function of HDD18C. In the heating season, magnitudes of the penalties did not show any obvious correlation with HDD18C.

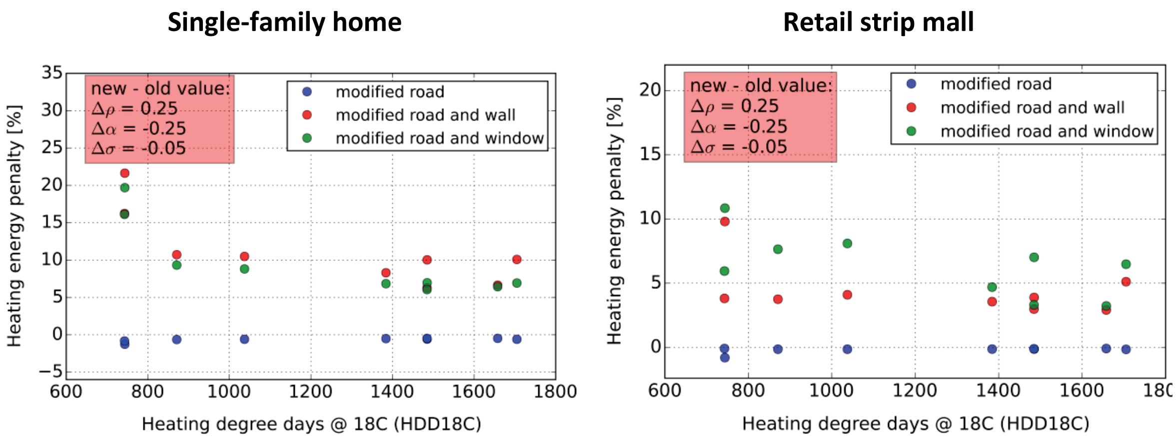


Figure 6: Heating site energy penalties vs HDD18C for single-family home and retail strip mall.

3.4.3 Annual conditioning source energy

In order to properly compare cooling and heating savings/penalties, the cooling and heating site energy uses were converted to source energy. Site energy savings are converted to source energy savings using the site-to-source conversion factors in Table 6.

Table 6: USA average source-to-site energy ratios.

	Electricity	Natural gas
Source-to-site energy ratio	3.34[a]	1.047[a]

[a] *US average (EnergyStar 2013).*

All buildings suffered a net conditioning source energy penalty when we only modified the road. But when combined with modified wall and windows, all prototypes experienced net source energy savings, ranging from 0.68% (sit-down restaurant) to 5.82% (apartment complex). Table 7 summarizes the base conditioning source energy intensity and the savings percent (mean savings / base) for all prototypes. Values represent the average for the nine CZ.

Table 7: Summary of conditioning source energy savings averaged over all CZ.

Prototype	Source mean conditioning (cooling + heating) energy intensity savings				
	Base [MJ/m²y]	Savings from road [%]	Savings from road + wall [%]	Savings from road + window [%]	Savings from road, wall, window [%]
Single-family home	146.5	-0.59	4.17	1.64	5.82
Apartment complex	121.6	-0.50	2.20	3.11	5.31
Large hotel	705.0	-0.40	1.14	0.68	1.82
Large office	241.5	-0.80	-0.19	2.94	2.75
Medium office	398.2	-0.29	0.35	2.58	2.93
Primary school	261.3	-0.35	0.59	2.48	3.07
Retail stand-alone	309.6	-0.07	2.00	1.59	3.60
Strip mall retail	350.2	-0.09	1.75	1.39	3.13
Sit-down restaurant	903.6	0.01	0.36	0.32	0.68

4 Summary

In this study, we focused in the direct effect of cool pavements, and quantified their impact on the annual building conditioning energy use for nine prototyped buildings in California. The prototypes were modelled varying road albedo, wall absorptance and window SHGC. The simulation results were used to generate relationships to predict the direct effect of pavement albedo change as a function of the road albedo and wall and window properties.

The study analyzed how the location and dimension of the road with respect to the building affects its direct effect on the building energy use. For this, we compared the building-to-road view factors to their direct effect. We observed a relationship in which the direct effect on cooling increases linearly with the view factor; the direct effect on heating is a linear decrease.

The direct effect from cool pavements had a slightly larger contribution through windows than walls. Their individual contributions depend heavily on the window-to-wall ratio, as well as other construction properties. In our case, the latter was similar across prototypes. Hence, after normalizing to a window-to-wall ratio of 0.40, we found windows contribute 1.5 times more to the direct effect than walls (for the base case values of wall absorptance and window SHGC).

Although increasing the pavement albedo by 0.25 caused net conditioning energy penalties that were as much as 0.80% (large office averaged over all CZ), when reducing the wall absorptance by 0.25 most prototypes experienced net conditioning energy savings (as much as 4.2%). Similarly, when window SHGC was reduced by 0.05, all prototypes experienced net conditioning energy savings ranging between 0.32% and 3.11%. Hence, the study suggests small modifications to a building's envelope can outweigh the small cooling penalties associated with the direct effect of cool pavements.

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