OVERVIEW OF PAVEMENT LIFE CYCLE ASSESSMENT USE PHASE RESEARCH AT THE MIT CONCRETE SUSTAINABILITY HUB

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ABSTRACT

In 2009, the US cement and concrete industries established the Concrete Sustainability Hub at the Massachusetts Institute of Technology. A primary thrust of MIT's activities has been improving the Life Cycle Assessment practices to better quantify the environmental impacts over the life of a pavement. In their research, the MIT CSHub determined that the "use phase" can dominate the materials, construction and maintenance phases of a pavement LCA and that two of the important factors in the use phase are Pavement Vehicle Interaction (PVI) and Albedo. PVI describes the excess fuel emissions / energy from vehicles due to excess rolling resistance between the pavement and the vehicle. Albedo is the fraction of solar energy reflected by the Earth's surface, with lighter color, higher albedo surfaces reflecting more energy than lower albedo, darker surfaces. This paper will summarize the CSHub Use Phase research findings to date.

INTRODUCTION

In 2009, the United States cement and concrete industries established the Concrete Sustainability Hub (CSHub) at the Massachusetts Institute of Technology (MIT) to carry out a multi-year research program to evaluate and improve the environmental and economic impact of concrete in pavements and buildings. The goal of the effort is to develop breakthroughs that will lead to more sustainable and durable pavement infrastructure and buildings by (1) providing scientific basis for informed decisions; (2) demonstrating the benefits of a life-cycle view; and (3) transferring research into practice.

With respect to pavements, one focus area of MIT's research has been on improving the Life Cycle Assessment (LCA) practices to better quantify the environmental impacts, energy consumption, material use, etc. throughout the life-time of a pavement. Some of the impacts that a LCA can calculate include Carbon Dioxide (CO2) and Green House Gas (GHG) emissions, Global Warming Potential (GWP), nitrogen oxides (NOx), particulate matter ($PM_{2.5}$ and PM_{10}), energy consumption, water use, eutrophication potential, and many others. While LCA's can be used to evaluate the environmental impact of a single product (e.g., a pavement) to reduce the impact of that product, they can also be used to compare two different options for a product (e.g. concrete and asphalt in pavement design) in the same way that life cycle cost analysis (LCCA) is used to compare costs. As such, it is important that the process be as comprehensive as possible to truly reflect the environmental impacts of a given pavement design.

While the mechanics of performing an LCA for a pavement are not terribly difficult, it is extremely data intensive and it is essential that a standardized LCA framework that includes the raw material production (extraction, processing, and manufacturing), construction, use, maintenance, and disposal or end of life phases be used. (Santero, Loijos, Akbarian, & Ochsendorf, 2011; Santero, Masanet, & Horvath, 2011). This framework ensures that short term gains in the early stages do not come at the expense of long-term deficits at later stages.

In doing their research, and in reviewing LCCA results from others, MIT determined that the LCA results will always vary based on the context for the given scenario and are dependent on the pavement structural design (thickness and materials); the maintenance and rehabilitation treatments used to maintain it; the anticipated traffic that will use it; and the environment that the pavement will be located. Having said that, MIT did determine that while the overall impact varies based on context, the "use phase" almost always plays a major role (MIT, 2014; EAPA/EUROBITUME, 2004), and is often times much larger than the other phases. MIT also found that most of a use-phase environmental impacts come from the following two sources:

1. The emissions by vehicles using the pavement due to excess rolling resistance between the pavement and the vehicle, which increases the fuel usage. This is known as pavement-vehicle interaction or PVI
2. The albedo, or reflectance of the pavements. Albedo is the measure of the fraction of solar energy reflected by the Earth's surface. Lighter color surfaces reflect light and have a high albedo (maximum of 1); while darker surfaces absorb light and have a low albedo (minimum of 0).

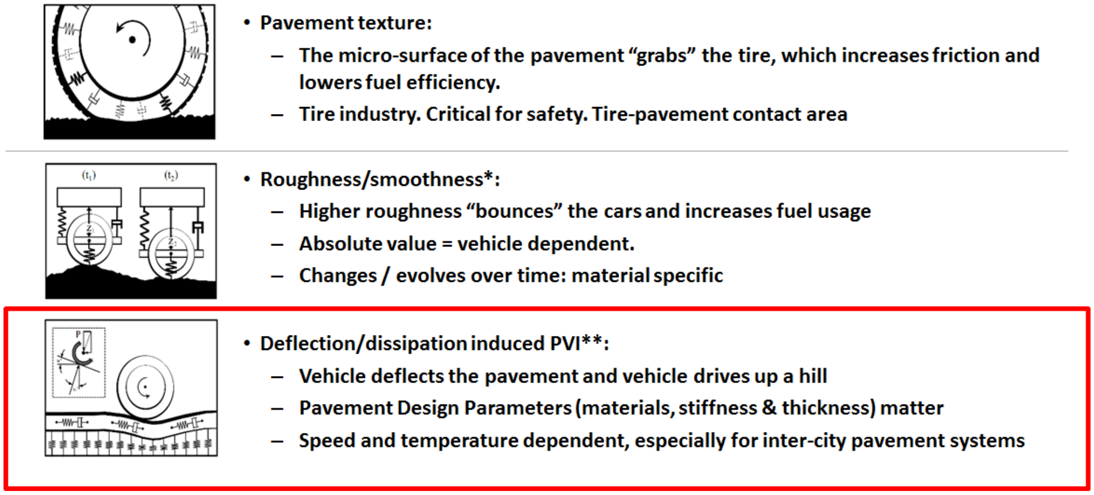
The goal of the paper is highlight MIT's research findings for these two topics over the last 9 years. The primary reason is that while the impact of PVI and Albedo have been shown to be large, there has also been a significant amount of uncertainty associated with them; which made it difficult to apply them in project and network level LCA's. MIT's research intent has been to increase the understanding of each of these so that pavement PVI and albedo could be directly compared with the life cycle GHG emissions from the other pavement life cycle phases such construction and maintenance in a more confident manner.

OVERVIEW OF PAVEMENT-VEHICLE INTERACTION

Previous research has shown that the three primary factors that contribute to PVI are (1) surface texture, (2) roughness or smoothness, and (3) deflection or dissipation of the pavement as shown Figure 1. In the US, roughness and deflection are considered the main contributors to pavement vehicle interaction. As there has been considerable study on roughness (I. Zaabar, 2010; M. W. Sayers, 1986; T. D. Gillespie, 1980; Chatti, 2012; Louhghalam, Tootkaboni, & Ulm, 2015; Louhghalam, Akbarian, & Ulm, 2015), the MIT CSHub research focused on the deflection and the impact that the structural and material properties of the pavement – and how they change over time – can have on fuel consumption and ultimately to GHG emissions. This would then allow PVI Deflection to be used in project specific LCAs so that use phase PVI impacts could be compared to the other phases in an LCA trade-off analysis.

PAVEMENT DEFLECTION MODELLING AND ITS IMPACTS ON EXCESS FUEL CONSUMPTION

Pavement deflection refers to the small dent that a vehicle creates in the pavement as it drives on a roadway. This deflection creates a slight, but perpetual uphill climb under the tire that results in a resisting force to the vehicle's motion. To maintain a constant speed, the vehicle has



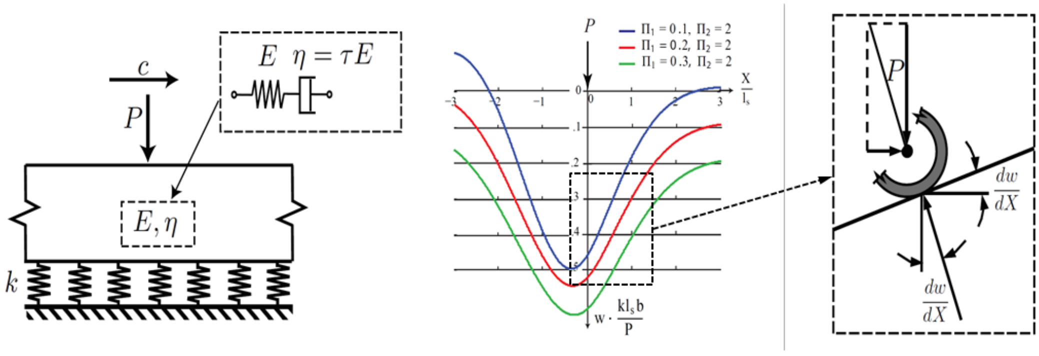
- **Pavement texture:**
  - **The micro-surface of the pavement "grabs" the tire, which increases friction and lowers fuel efficiency.**
  - **Tire industry. Critical for safety. Tire-pavement contact area**
- **Roughness/smoothness*:**
  - **Higher roughness "bounces" the cars and increases fuel usage**
  - **Absolute value = vehicle dependent.**
  - **Changes / evolves over time: material specific**
- **Deflection/dissipation induced PVI**:**
  - **Vehicle deflects the pavement and vehicle drives up a hill**
  - **Pavement Design Parameters (materials, stiffness & thickness) matter**
  - **Speed and temperature dependent, especially for inter-city pavement systems**

Figure 1: Factors that affect Pavement Vehicle Interaction (PVI) - Pavement | Surface Texture, Roughness, & Pavement Structure (Stiffness)

to compensate for the added resistance by consuming excess fuel, whose magnitude depends on the steepness of the hill and is a function of the condition and structure of the pavement and the weight of the vehicle. Note that excess fuel consumption (EFC) is defined as the additional fuel consumption compared with a pavement that is perfectly smooth, rigid, and does not bend (i.e. non-dissipative).

It is important to note is that while the effect of PVI on an individual vehicle is small, its impact within a full pavement life cycle can be significant due to the large number of vehicles that travel over pavements. This is especially true for high volume, heavy traffic roadways where PVI can easily surpass the energy consumption and emissions due to the materials, construction and maintenance phases of the roadway over its lifetime.

MIT's final PVI model shows that the dissipated energy in a viscoelastic pavement is directly related to the slope under the moving wheel (Akbarian M., 2012) (Louhghalam, Akbarian, & Ulm, 2013), (A. Louhghalam, 2014) and is conceptually a 2-step model like shown in Figure 2. The first part determines the slope of a pavement system based on its structure and material properties (the *stiffness* of the system) and the second part relates the rolling resistance (i.e. dissipated energy) needed to drive up this slope to EFC. To quantify the slope under a moving



(a) (b) (c)

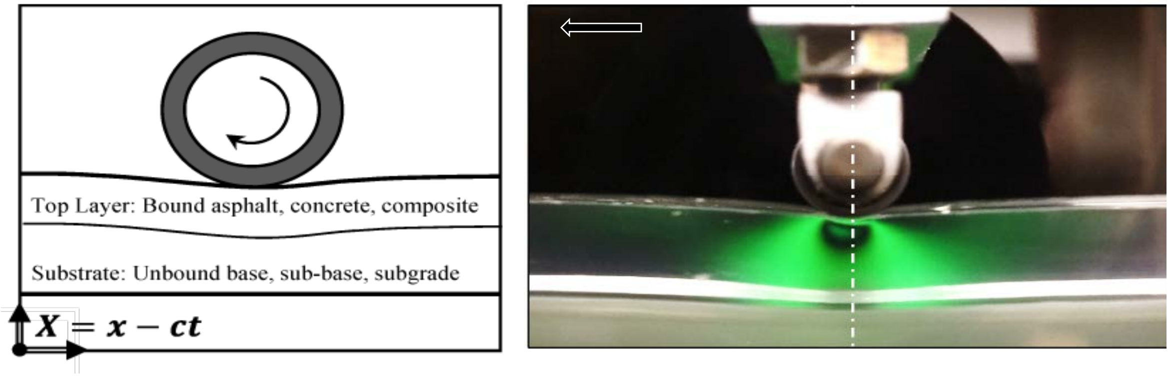
Figure 2: Overview of MIT Deflection-induced PVI Excess Fuel Consumption Model.

wheel, the pavement is modelled through an infinite viscoelastic beam over an elastic foundation (Figure 2(a)). A Maxwell model is used to describe the viscoelastic material's stress and strain relationship, where E is the Young's modulus, τ is the relaxation time of the viscoelastic top layer that accounts time of loading and temperature dependencies (i.e. cool vs hot, slow vs fast), and η is the material viscosity.

Figure 2(b) shows the pavement deflection basin, where the maximum deflection is behind the moving wheel due to the delayed viscoelastic response. The deflection basin's depth (w) and wavelength (Ls) that define the grade slope are a function of the load and the pavement structure / material properties at the time of loading. Once the gradient slope is determined, the EFC of the vehicle is in direct relationship with the resistance, or excess energy, δE, that the vehicle must overcome to travel up the slope as shown in Figure 2(c).

Once MIT developed their theoretical model, they developed a small-scale, desk-top experiment that allowed them to partially calibrate and validate their model by isolating the interaction of the wheel and the pavement structure. The pavement system, a two-layered viscoelastic beam on an elastic subgrade, (Figure 3(a)) was experimentally represented through a two-layered silicone elastomer pavement shown in Figure 3(b). This experimental setup allowed for a range of top layer thicknesses, elastic moduli, viscoelastic properties, and loading conditions to be tested. The use of polymers also allowed MIT to visually observe the pavements' response to the moving wheel and the resulting resisting horizontal force through technique called photoelasticity. The asymmetry of stresses inside the material shows that the wheel is always moving "up a hill."

In total, MIT ran nearly 200 experimental configurations, equivalent to 290 km (180 miles) of road testing, to investigate the impact of key PVI parameters on excess energy dissipation with varying loads, speeds, pavement modulus values, pavement thicknesses and viscoelasticities (relaxation time). Once the testing was completed, the scaling relationship between the theoretical deflection-induced PVI model were compared to the scaling of the dissipation forces from PVI desk-top model and the results were found to be consistent. This confirmed the contribution of pavement structure to EFC and that an increase in pavement stiffness minimizes the impact of deflection-induced PVI. It also verified that deflection-induced PVI impacts can be captured and can have a significant impact on life cycle energy use and emissions.



(a) (b)

Figure 3: Link between the (a) Theoretical Model and (b) Desktop Experiment and photoelasticity showing the wheel moving left

For additional details on the model, calibration, and validation, see (Mack, Akbarian, Ulm, & Louhghalam, 2018), (Mack, M. Akbarian, & Louhghalam, 2017), (A. Louhghalam, 2014), (Louhghalam, Akbarian, & Ulm, 2013), (Akbarian, 2012).

APPLICATION OF PVI AT THE PROJECT LEVEL

If an agency or designer wants to lower the PVI EFC/GHG emissions of a pavement system at the project level; they have two primary strategies that can be used:

1. Build and Maintain Smoother Pavements either by improving the maintenance activities that keep a pavement smooth over its life time, or by building pavements that stay smoother longer
2. Build stiffer, or stiffen the existing pavement so that it deflects less

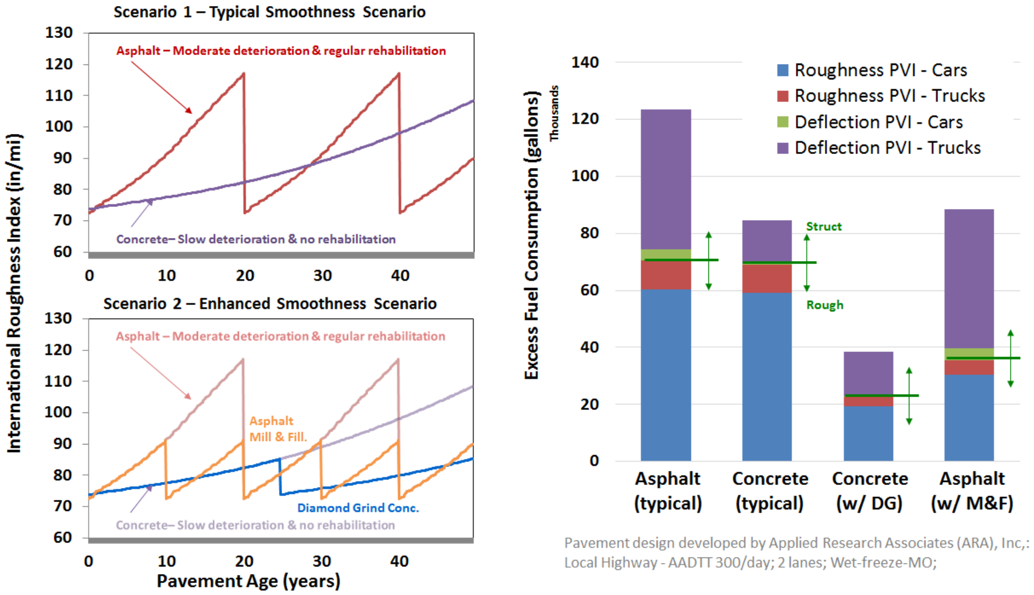
In general, the relative importance "smoothness" and "stiffness" depends on the roughness conditions, traffic volumes and the specific pavement structures being evaluated. Improving the smoothness has a greater impact when the road is old, rough, and/or in need of repair, while stiffness is a fairly constant value and has a larger relative impact when the pavement is new or smooth, and when there is a large amount of trucks (light vehicles such as cars do not weigh enough to cause a large deflection). It is also important to note that smoothness impacts (eg PVI roughness impacts) are only a function of pavement type in respect to how slowly or quickly that specific pavement deteriorates.

On the other hand, stiffness impacts are dependent on pavement type and will be essentially constant for that given pavement design, material properties, and traffic volume. For concrete pavements, which are very stiff, PVI deflection is not a major factor in any traffic mix or pavement condition. However, for asphalt and composite structures, the PVI deflection impacts can be more than 2 orders of magnitude (100 times) higher when compared to concrete (Mack, Akbarian, Ulm, & Louhghalam, 2018). It is important to note that while the magnitude of the PVI deflection impacts for asphalt and composite pavements will change as the visco-elastic properties of the asphalt material changes, the overall trend does not.

Often times, it is stated that if agencies just keep their pavements smooth, they will reduce EFC and have more sustainable pavements. While keeping the pavements smooth does help, the fact is that both smoothness and structure play a major role in lowering PVI impacts and for a given roadway condition (smoothness level) requirement, it will be the deflection PVI component that differentiates pavements use phase PVI GHG emissions.

As an example, Figure 4 shows a comparison of two equivalent asphalt and concrete pavements and the lifetime EFC for two different scenarios. The first scenario is a "typical smoothness scenario" and the second is an "enhanced smoothness scenario." On the left side of Figure 4 are the projected IRI;s for a local highway in Missouri using the AASHTO Pavement ME Design Procedure (MIT, 2014) for both scenarios (typical is top and enhanced is bottom). In the top, typical scenario, the asphalt (red line) has moderate deterioration and is rehabilitated every 20 years to keep the road at a low level of roughness. The concrete pavement (purple line) has a slow rate of deterioration and provides a similar level of lifetime smoothness as the asphalt without rehabilitation. In the bottom graph, to maintain an even higher level of smoothness, the pavements are rehabilitated by applying a diamond grinding (blue line) to the concrete pavement at year 25, or a mill-and fill asphalt overlay (orange line) to the asphalt pavement every 10 years in order to lower the IRI.

On the right is the projected EFC for each pavement and scenario based on the PVI source of the EFC (roughness from cars, roughness from trucks, deflection from cars, and deflection from



Pavement design developed by Applied Research Associates (ARA), Inc,: Local Highway - AADTT 300/day; 2 lanes; Wet-freeze-MO;

Figure 4: Contributions to EFC from roughness and deflection based PVI for Local highway in Missouri. Equivalent Asphalt and Concrete Pavement Designs, AADTT 300/day; 2 lanes; wet-freeze.

trucks). If one looks only at the roughness based PVI impacts on the typical scenario, one can see that they are basically the same for both pavements. However, once PVI structural EFC is included, there is a dramatic difference in the overall EFC for the concrete and asphalt structures due to concrete's increased stiffness. Likewise, on the enhanced smoothness scenario, one can see that while the roughness PVI EFC, and overall PVI are decreased substantially, the EFC from the deflection PVI impacts are unaffected by the IRI changes. In fact, for this case, the overall EFC emissions of the asphalt are higher than the concrete without diamond grinding solely due to the structural PVI impacts. The takeaway is that structure/deflection also plays a major, if not dominant role, when the pavement is already smooth and if one ignores the structural PVI impacts, the conclusions about the sustainability of the different scenarios could be flawed.

PAVEMENT ALBEDO, CLIMATE, AND URBAN HEAT ISLANDS

Albedo is the measure of the fraction of solar energy reflected by the Earth's surface. Lighter color surfaces reflect light and have a high albedo (maximum of 1) while dark surfaces absorb light and have a low albedo (minimum of 0). A pavement's albedo can affect global warming potential by two major mechanisms (Figure 5):

1. Radiative Forcing (RF) – accounts for the direct reflectance of the incoming solar radiation
2. Building Energy Demand (BED) – accounts for increased ambient temperature (aka Urban Heat Island - UHI) effects and the amount of incident radiation reflected from pavements to the buildings, both of which impacts building cooling and heating requirements.

While physical mechanisms that underlies albedo are well understood, evaluating the impacts of pavement albedo in an LCA is complicated because local changes in pavement albedo can potentially have local, regional and global impacts that are difficult to predict due to climatic feedback loops. As such, the impacts of albedo in pavement LCA's are often ignored or quantified using very simple models. The MIT CSHub research was specifically undertaken to analyze the

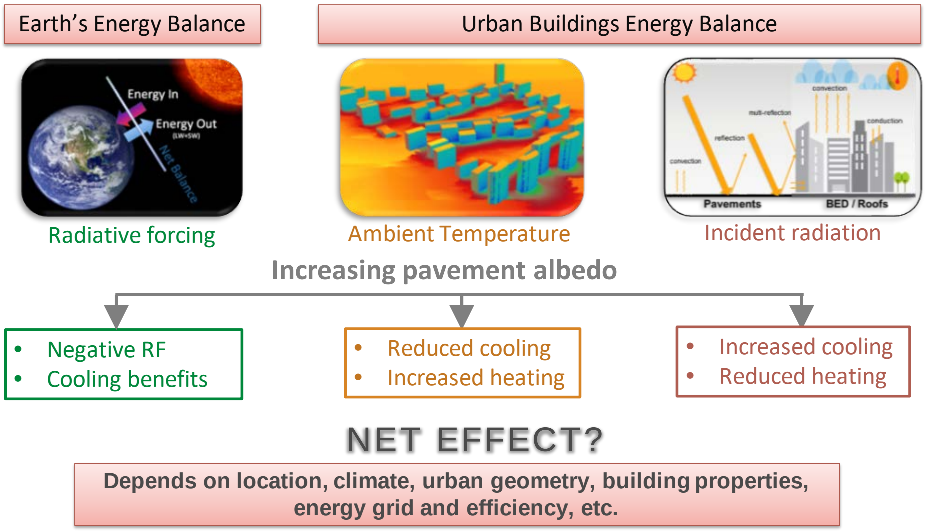


Figure 5: Albedo effects on Radiative Forcing & Building Energy Balance

impacts of changing pavement albedo using a variety of different modelling approaches to develop models to quantify the impacts of changes in pavement albedo on GHG emissions so that they can be compared in an LCA with the GHG emissions from other phases.

QUANTIFYING RADIATIVE FORCING IMPACT OF PAVEMENT ALBEDO

The term "radiative forcing" (RF) is defined as the change in net (down minus up) irradiance (solar plus long-wave radiation) at the top of the atmosphere (TOA) due to some imposed change from items such as greenhouse gases, aerosols, ozone, land-use change, solar irradiance, etc. (Figure 6). Increased pavement albedo impacts RF because it means that more solar radiation will be reflected back into space and less will remain on the earth. Studies have demonstrated that enhancing albedo can improve RF without the downside of environmental damage because it can, to some extent, mitigate or delay some of the consequences of warming from CO_2 emissions. For example, researchers at the Heat Island Group at the Lawrence Berkeley National Laboratory have estimated that for every square meter of urban area, 2.55 kg of emitted CO_2 is offset for each 0.01 increase in albedo. (Akbari, Menon, & Rosenfeld, 2009).

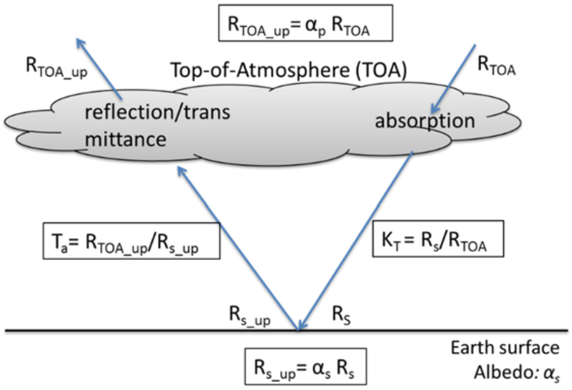


Figure 6 Schematic diagram describing Radiative Forcing

MIT created an adaptive model that characterized the effects of solar intensity, precipitable water, solar zenith angle and cloudiness on atmospheric transmittance and albedo effects. This adaptive approach combined the results from two different modeling approaches (Simple symmetric model and Model-based parameterization) to estimate the upper and lower bounds of the location-specific GWP savings of pavement albedo changes on radiative forcing. In addition, most models implicitly assume that 100% of the downward solar radiation transmitted through the atmosphere will strike the pavement with no recognition of shading by buildings or trees. In urban areas, MIT accounted for this effect by introducing an urban canyon transmittance factor that accounted for building height and the effect of shading. For rural areas where the FHWA Roadside Design Guide requires a clear zone or horizontal clearance, which specifies a minimum unobstructed distance beyond the edge of the travel way, MIT assumed no shading effects.

With their new adaptive model, MIT then applied it to 14 cities across the US to estimate the ranges of GWP savings from a 0.01 increase in pavement albedo. These cities where chosen to cover the seven major temperature climate zones defined by the International Energy Conservation Code, which range from being ‘very hot’ to being ‘very cold’ as well as along with the sublimate zones based on moisture content (moist, dry and marine). Figure 7 shows the location-specific estimate of global warming mitigation potential of increasing pavement albedo by 0.01. The upper bounds and lower bounds represent results calculated using the two different models described above (symmetric model and parameterization model) and reflect the uncertainty associated with the climate condition. The red triangles represent the cloud transmittance factors (higher values mean less clouds/more clear sky).

As can be seen, the uncertainty is closely correlated with the cloudiness of the area, which affects the transmittance of the solar radiation. Uncertainty is smallest for Phoenix as it is mostly clear throughout a year. For Miami, LA and Seattle, uncertainty arises from many cloudy and humid days, aerosols, and/or smog.

Next MIT took their adaptive model and did a nationwide analysis of cloud transmittance and GWP savings due to a 0.2 increase in pavement albedo at the state level to determine the annual GWP savings from for all urban and rural roads across the U.S. (Figure 8). Overall, increasing the albedo of all urban and rural roads in the US leads to GHG savings equivalent to removing nearly 9.4 million passenger vehicles, or roughly 8% of all passenger vehicles on the road each year. In general, states in the south of U.S. have larger potential for CO2 savings from

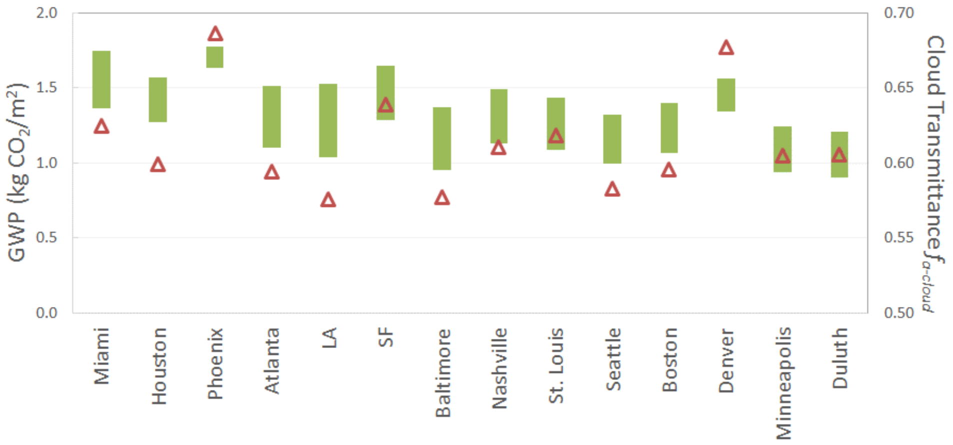


Figure 7 GWP savings from RF due to 0.01 increase in pavement albedo
for selected 14 locations over 50 years

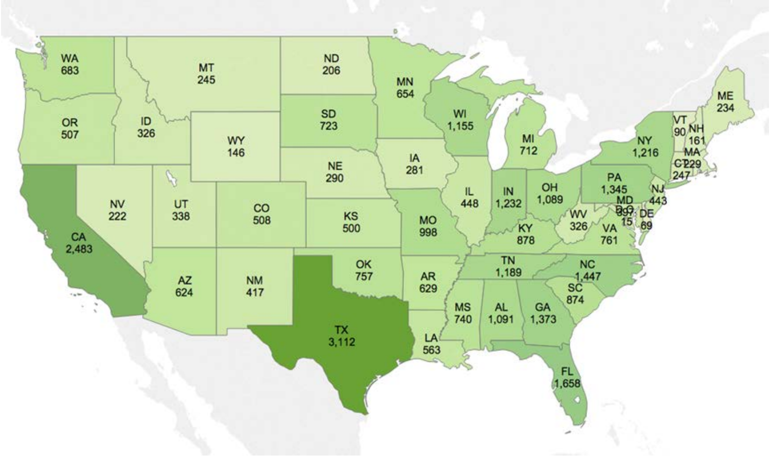


Figure 8: Annual GWP savings from RF due to 0.2 albedo increase in all urban and rural asphalt roads across the U.S.

RF due to pavement albedo enhancement, mainly because these states receive more solar radiation and have more roads exposed to sunlight. Texas exhibits the greatest GWP savings if all roads were converted into a higher albedo pavement. The relative lower GWP savings in California compared to other states at a similar latitude is probably due to the climate condition particularly the cloudiness effect.

IMPACT OF PAVEMENT ALBEDO ON URBAN ENERGY DEMAND

As shown in Figure 5, the net effect of increased incident radiation and reduced ambient temperature on building energy due to pavement albedo increase is not intuitive. Increasing the albedo of road surfaces has a direct impact on adjacent buildings by increasing incident radiation, resulting in changes in building energy consumption; but it also reduces the ambient temperature within the canyon, altering BED in an opposite way to the increased incident radiation.

Currently, most existing building energy models consider individual buildings as stand-alone entities, without any neighborhood contextualization (Han, Taylor, & Pisello, 2017). These models simulate the energy balances on building envelope and indoor air, excluding the outdoor energy balance, and are effective for evaluating different energy efficiency improvement strategies. Similarly, the urban energy balance models in the meteorological community, usually consider an urban grid cell as a 1-D or 2-D canopy consisting of a single building and canyon floor, which is an oversimplified representation of the urban morphology (the spatial configuration of the buildings, streets, and other components of the city) (Monaghan, Hu, Brunsell, Barlage, & Wilhelmi, 2104). In reality, the components of the outdoor environment (buildings, streets, vegetation, etc.) have complex interactions with each other, which suggests a much more sophisticated system than that of an individual building envelop or simple urban canopy; and no single model exists that can address the complex physical phenomena in the urban climate.

To quantify how density, building shapes and building typology influence building energy performance, MIT CSHub researchers created a model to quantify the impacts of pavement albedo on building energy demand, that incorporates the effects of changes in ambient temperatures and incident radiation on BED as a function of local climate and urban morphology at the neighborhood scale. Neighborhood characterization is accomplished by assigning a local climate zone (LCZ) based on the 10 urban microclimate categorization schemes developed by Stewart &

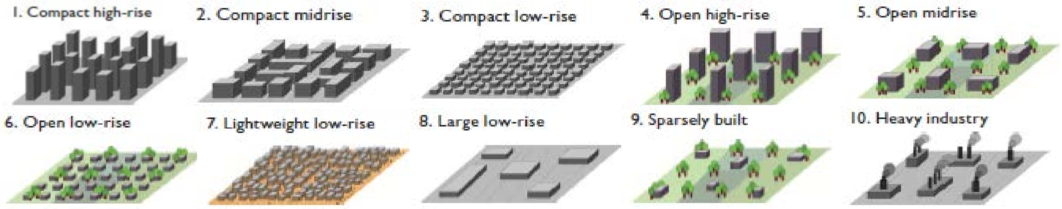


Figure 9: Categorization of urban neighborhoods using local climate zones (LCZs)

Oke (Stewart, Oke, Stewart, & Oke, 2012) shown in Figure 9. MIT then used a parametric approach called design of experiments to generate individual cases with different combinations of building height, canyon street width, canyon aspect ratio, building density, pavement density and others to evaluate the changes in BED for each LCZ due to a 0.2 increase in pavement albedo.

Finally, MIT researchers used GIS data from the cities of Boston and Phoenix representing a cold and hot climates respectively to quantify the contradictory impacts of RF and BED in specific neighborhoods throughout two cities with different climates to determine the overall GWP changes (Figure 10). As expected, the magnitude of RF and BED in urban areas depends on context, but usually RF is more significant and leads to net benefits from increasing pavement albedo. In dense, urban downtown neighborhoods, the GWP due to BED was larger than RF due to shading, so there was a net GWP burden. In all other neighborhoods the GWP due to RF was larger than BED, leading to a net GWP savings.

One item to note is that using increased albedo for pavements in new or renovation projects to reduce the impacts of UHI and climate change is a relatively low-cost and low-risk endeavor. That is, albedo adjustments in new or retrofit projects have minimal cost implications when compared with modifications of existing surfaces because the pavements are already being created to carry traffic, so any cost associated with albedo modification is minor in comparison, if it is necessary at all.

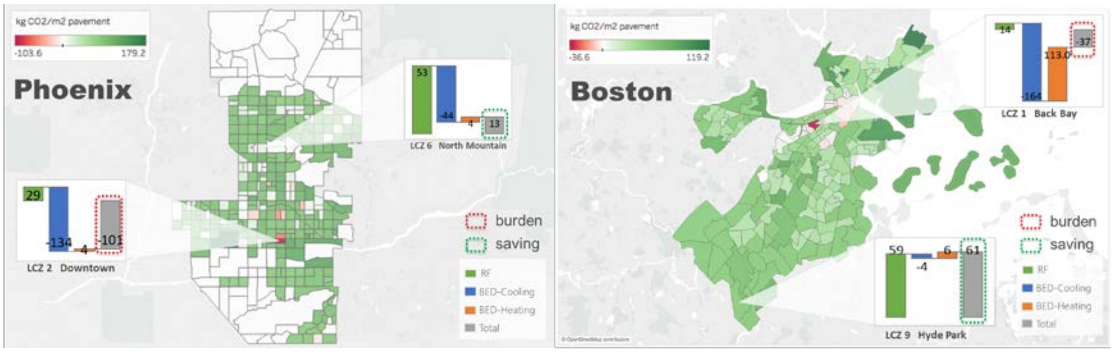


Figure 10: Net GWP savings from BED and RF due to 0.2 increase in pavement albedo for 50 years for Phoenix and Boston. Local climate zones (LCZ) 1 and 2 are for dense, urban areas, whereas LCZs 6 and 9 are residential areas.

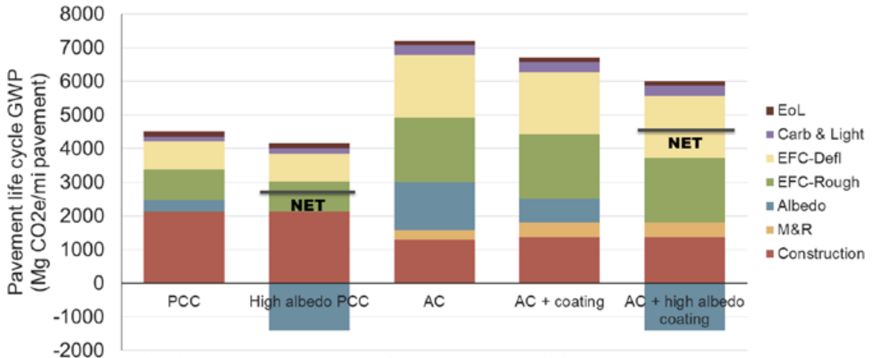
PAVEMENT LCA WITH CONTEXT-SPECIFIC IMPACTS FOR PVI AND PAVEMENT ALBEDO

While guidance and standards have been developed for conducting pavement LCA's, it has not been widely implemented for supporting environmentally conscious pavement designs, partially due to the limitations in models for quantifying the impacts in the use phase, such as PVI and Albedo. With their new context specific models for RF, BED and PVI, MIT investigated five pavement designs scenarios to examine the life cycle impacts of reflective pavements strategies for urban conditions and quantify their impacts on reducing GHG emissions, mitigating the UHI effect, and improving the air quality. Two of the scenarios are baseline PCC and AC designs, while the rest are reflective pavement designs, with different surface treatment techniques to increase the pavement albedo.

MIT's analysis used a probabilistic life cycle assessment (LCA) model that included the full scope of material production, construction, use, and end-of-life. The use phase included impacts due to changes in albedo, excess fuel consumption from PVI, carbonation, and lighting. The pavement designs considered were functionally equivalent flexible (asphalt) and rigid (concrete) pavement designs and maintenance schedules that were created using the AASHTO Pavement-ME software models. High albedo concrete was achieved through the use of white cement, and high albedo asphalt was achieved through the use of reflective coatings.

Figure 11 presents the results of the pavement LCA using a 30-year design life and 50-year analysis period for the five pavement design scenarios in Boston. In this figure, each color represents a life cycle component of a pavement design. From the figure, it is obvious that materials and construction contribute to a large percentage of total life cycle GWP impact for PCC designs. However, for AC designs, use phase impact, especially the excess fuel consumption from roughness and the impact of albedo, drives the total GWP.

With respect to albedo, it can be seen that the relative magnitude of pavement albedo is comparable to that of the PVI impact in the use phase and that that reflective pavement surface materials exhibit greater GWP savings as compared to their conventional counterparts. Among the reflective designs, PCC pavements with high-albedo materials has the lowest life cycle GWP impact. For the AC pavements, pavements with high-albedo (0.5) coating do exhibit greater GWP savings, which makes reflective coating an attractive option for AC pavement designs if high-albedo can be achieved and maintained without costing too much (note that in this exercise, the reflective coating's life was assumed to be 10 years). Ordinary coatings for AC pavements with an albedo of 0.25 do not improve the life cycle impact of AC pavements significantly and are not as good as conventional concrete.



Albedo impacts relative to baseline of average earth albedo (0.3)
M&R=maintenance & rehabilitation; EFC= excess fuel consumption; Defl=deflection; Rough=roughness; Carb&Light= carbonation & lighting; EoL= end-of-life

Figure 11: Pavement life cycle global warming potential for Portland Cement Concrete (PCC) and asphalt concrete (AC) designs and rehabilitation scenarios in a residential neighborhood in Boston

In this case, implementing the lowest GHG footprint pavement designs that mitigate UHI impacts across the city of Boston would save approximately 26 ktons CO2-eq/year, which is equivalent to removing approximately 5,500 passenger vehicles from the road for a year.

SUMMARY

In 2009, the US cement and concrete industries established the Concrete Sustainability Hub at MIT to find breakthroughs that will lead to more sustainable and durable pavement infrastructure and buildings. With regards to pavements, MIT found that the "use phase" plays a substantial role in the environmental impact of given pavement design, and that these impacts are often higher than the impacts associated with the pavement materials and construction. MIT also found that most of a use-phase environmental impacts come from Pavement Vehicle Interaction and the impact of pavement albedo on both radiative forcing and building energy demand.

With respect to PVI, MIT developed a mechanistic based PVI deflection model to determine excess fuel consumption of a pavement system based on its structure and material properties (the *stiffness* of the system), and then used a small-scale, desk-top experiment to partially calibrate and validate the PVI-Deflection (structure) model. MIT then applied the model at the project level and determined that while both smoothness and structure play a major role in lowering PVI impacts; for a given roadway condition (smoothness level) requirement, it will be the deflection PVI component that differentiates pavements use phase PVI GHG emissions.

Albedo is the measure of the fraction of solar energy reflected by the Earth's surface. Lighter color surfaces reflect light and have a high albedo (maximum of 1), while darker surfaces absorb light and have a low albedo (minimum of 0). Changes in pavement albedo affect the climate directly through radiative forcing (RF) (altering the radiative balance at the top-of-atmosphere), and indirectly by affecting the ambient temperature (changing the amount of heat transferred to the atmosphere). In urban environments, pavement albedo changes also influence the amount of incident radiation from pavements to buildings, which affects building energy demand (BED). The combination of ambient temperature changes and incident radiation will either increase or decrease electricity and natural gas use, which impacts greenhouse gas (GHG) emissions.

In order to understand the net impacts of implementing higher albedo pavements, CSHub researchers analyzed the impacts of changing pavement albedo using a variety of different modeling approaches and analytical scopes. The key findings of this research were that increasing pavement albedo has significant potential as a climate change mitigation mechanism. For example, increasing the albedo of all urban and rural roads in the US by 0.2 leads to GHG savings equivalent to removing nearly 9.4 million passenger vehicles, or roughly 8% of all passenger vehicles on the road. They ales found that the relative magnitude of RF and BED in urban areas depends on context, but usually RF is more significant and leads to net benefits from increasing pavement albedo. In dense, urban downtown neighborhoods the global warming potential (GWP) due to BED was larger than RF due to shading (net GWP burden) while in all other neighborhoods the GWP due to RF was larger than BED, leading to a net GWP savings.

While albedo and PVI can be a significant fraction of pavement life cycle GHG emissions, the selection of pavement designs should consider all elements of the full life cycle. In the LCA case study of a pavement in a residential neighborhood in Boston, the concrete scenarios had higher construction impacts than the asphalt scenarios, but lower use phase impacts, including impacts due to changes in PVI and albedo.

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