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CASE APPLICATION OF PAVENEXT TO ACHIEVE SUSTAINABLE PAVEMENT

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Abstract: Pavement covers 45% of the land in urban regions of the U.S. and produces over 17 million metric tons of greenhouse gases every year. While technology exists to curb emissions, unfortunately, government agencies and private businesses are slow to change business as usual for short-term stability and profits. This paper presents a web-service application, namely PaveNext that enables pavement designers to compare traditional and sustainable pavement design with consideration of performance requirements and economic differences. In particular, the app puts an emerging standard for generating carbon credits with sustainable pavement into practice. The app basis, object model, and implementation are discussed and demonstrated using the $190 million Interstate 64 project in Virginia, Maryland. By replacing HMA with FSB, the app shows the most conservative sustainable design saves, at minimum, 3,300 t CO_2 emissions and is likely eligible for at least $8,500 in carbon credits. The pros and cons of app-based pavement design optimization are also discussed.

1 Introduction

The world overpays – environmentally and monetarily – for traditional hot mix asphalt (HMA) pavement, but continues to use it widely (Magnum 2006, NAPA 2015, EPA 2009). An emerging carbon credit standard for pavement (Cui 2014) could encourage sustainable design, but its methods need to be automated and accessible to HMA project stakeholders: (a) designers need to be able to compare carbon credits alongside material costs and structural numbers for different design scenarios, (b) contractors and owners need to get paid for choosing sustainable materials, and (c) carbon registries need reports to review to award credits. This paper presents a web-based software application (app) that aims to addresses these needs. A case study, the I-64 highway rehabilitation project in Virginia, demonstrates the app.

2 Background Literature

2.1 Traditional vs Sustainable Pavement

Environmentally, in an industry comparison of greenhouse gas (GHG) emissions, Truitt (2009) shows HMA emits 0.48 t of GHG per $1,000 spent, which is approximately three times the amount of GHG emitted per dollar spent on power and communication lines. In addition to GHG emissions, HMA production emits sulfur dioxide (SO_2), nitrogen oxide (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and volatile hazardous air pollutant (HAP) organic compounds (EPA 2009). Despite these problems, HMA is the most widely used pavement material in the world. For example, Canada, the United States, and Europe pay these environmental costs for HMA across 90% of all paved roads, which lay respectively 415,000 km, 4.3 million km, and 5.2 million km long (Mangum, 2006). The United States, alone, produced 317 million metric tonnes (Mt) of HMA in 2014 (NAPA 2015).

A traditional HMA plant predominantly uses crushed, virgin rock in its mix. Miners and drivers expend fossil fuels to quarry this virgin aggregate and transport it to mix plants. From there, a traditional HMA mix plants needs to process the aggregate, mix it with other materials, and heat the entire mix to 163 °C (Cui 2014). A typical HMA mix in Maryland includes 72% crushed rock, 8% sand, 15% reclaimed asphalt pavement (RAP), and 5% bitumen. A sustainable pavement plant, producing foam stabilized base asphalt (FSB) as an alternative example, replaces aggregates in an HMA mix with all RAP. A typical FSB mix includes 96% RAP, 1% cement, 2% bitumen, and 1% water (Schwartz and Khosravifar 2013, Wirtgen 2010). Further, while an HMA plant heats its entire mix to high temperatures, an FSB plant only heat a small amount of bitumen until it is at a viscous state (155 °C) before mixing this bitumen with its RAP at ambient temperatures (Cui 2014). These lower temperatures require less fuel.

Sustainable mix processes include (a) hot recycling, (b) hot in-place recycling (HIR), (c) cold in-place recycling (CIR), (d) full depth reclamation (FDR), and (e) cold central plant recycling (CCPR). Table 1 compares HMA processes with these processes (Liu et al. 2016). Mix plants performing hot recycling use batch and drum equipment with a larger percentage of RAP along with recycling agents in comparison to what they would with traditional hot mixes. HIR brings hot recycling to the job site. HIR installers strip and pulverize up to two inches of existing material, combine it with HMA and recycling agents, compact it, and add an HMA surface layer as needed. CIR is similar to HIR, but it does not heat the reclaimed material. CIR typically treats three to four inches of pavement. FDR is another in-place process that generally mixes materials at ambient temperatures. FDR instructs installers to pulverize both existing asphalt and some of any underlying base material (together, usually four to 12 in), treat the reclaimed material with additives, add additional aggregate to reach current structural design requirements as needed, compact everything, and apply a surface layer. CCPR is another cold mix process that can be performed either at a central mix facility or on site with a mobile mix plant. For repair and expansion jobs, transportation of reclaimed material to an offsite plant for processing requires fuel to haul material there and back, but it does not require a mobile plant which may not be available, and it remedies poor drainage problems that may limit CIR (Cui 2014). In urban areas, central plants can stockpile RAP from contractors that often have excess amounts of it, then, recycled material can be transported to new construction jobs.

Table 1. Traditional Hot Mix vs. Alternative Mix Methods and Applications

Mix & Application	Mix Temperature*	Mix Location	Example Percentage of Recycled Materials**
Hot mix asphalt (HMA)	Hot (163 °C)	Central plant	Low (0-15%)
Hot recycling	Hot	Central plant	Medium (15-65%)
Hot in-place recycling (HIR)	Hot	In-place	Medium
Cold in-place recycling (CIR)	Cold (ambient)	In-place	High (65-98%)
Full depth reclamation (FDR)	Cold	In-place	High
Cold central plant recycling (CCPR)	Cold	Central plant – onsite or offsite	High

2.2 Sustainable Pavement Drivers and Barriers

The primary driver for sustainable pavement design is cost. RAP both emits less GHG and costs less than quarrying, hauling, and processing virgin aggregate. The Federal Highway Administration (FHWA) currently encourages the use of sustainable pavement through the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), which is web-based self-evaluation tool for pavement projects (FHWA 2017). INVEST lets pavement project stakeholders score their project with ratings based on 81 best-practices for planning, development, operations, and maintenance of highways. In the private sector, two major carbon registries in the US, Verified Carbon Standard (VCS) and the Climate Registry promote carbon reductions.

The fact that HMA production has been business as usual in the United States is the primary barrier to adoption of sustainable pavement. The precise mixes and structural numbers for sustainable pavement have not been standardized. Maryland and Virginia, for example, publish different structural numbers for FSB. Economically and socially, US business need the start-up funds to purchase sustainable pavement equipment, re-tool existing equipment, and train their workforce to adopt new methods. Finally, the federal government does not currently regulate pavement emissions.

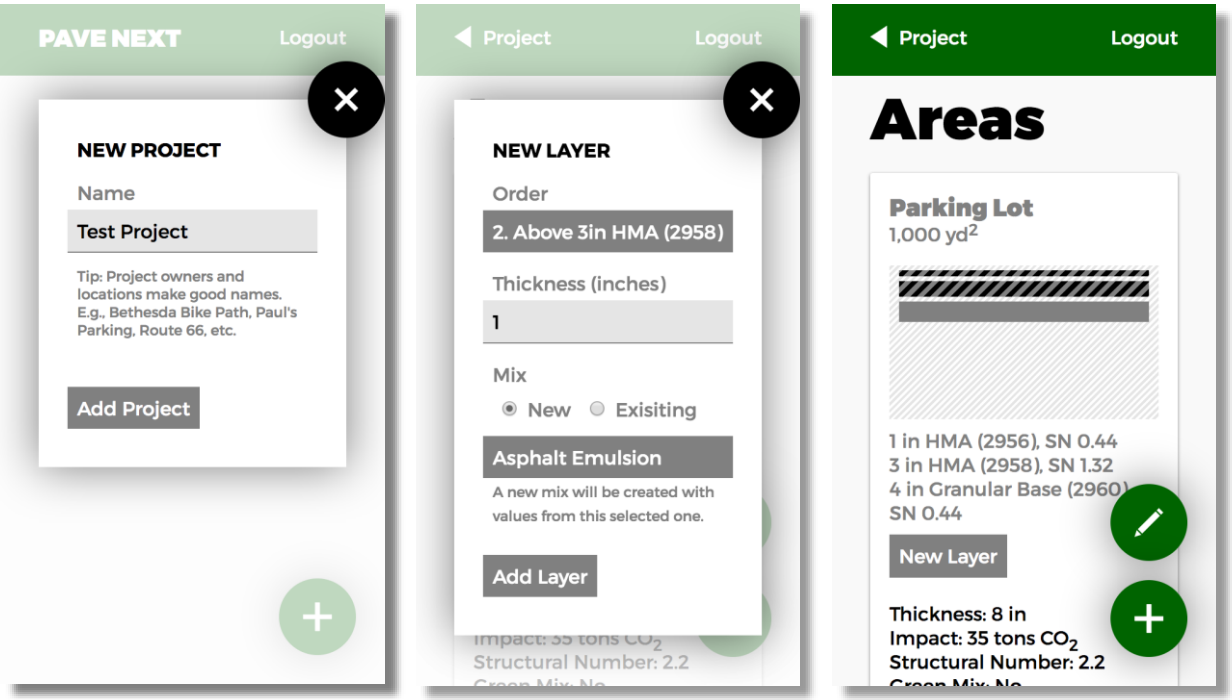
2.3 Pavement Life Cycle Assessment Software

Several pavement life cycle assessment (LCA) software applications exist to measure the environmental impact of pavement, but no service (web-based or otherwise) currently exists to pay users directly for their pavement offset projects. Santos et al. (2017) recently reviewed the most current American and European tools, and Presti and D'Angelo (2017) recently reviewed freely-available tools in Europe. One of the most comprehensive tools, being developed at the FHWA (Senhaji et al. 2017), provides a database of pavement impacts on the environment. While none of the tools tie directly to carbon credit markets as a service, they do go beyond the scope of the app presented in this paper in two main ways: They consider (1) environmental impacts beyond CO_2 emissions and (2) track impacts from cradle-to-grave, beyond installation. The tools generally provide more comprehensive mechanical data, including surface roughness data, than the app presented in this paper.

3 App

3.1 User Story

Designers may approach the app with various amounts of information and motivation to use it. They may already have designs they want to compare. They may only have a traditional design. They may want to estimate the payback for selecting a sustainable pavement design for a new project without any design at all. While the app addresses all of these scenarios, most pavement designers will have a hot mix design ready, or want to use the app to create one. After that, they will likely want to create a sustainable design, compare it to the traditional design, and see how much money they could earn from selecting the sustainable design. For these users, figure one highlights key screen shots of their user story from creating a new project through viewing a contract summary. Figure two shows a high-level dataflow diagram for these processes.



NEW PROJECT

Name: Test Project

Tip: Project owners and locations make good names. E.g., Bethesda Bike Path, Paul's Parking, Route 66, etc.

NEW LAYER

Order: 2. Above 3in HMA (2958)

Thickness (inches): 1

Mix: ● New ○ Exisiting

Asphalt Emulsion

A new mix will be created with values from this selected one.

Impact: 35 tons CO_2
Structural Number: 2.2
Green Mix: No

Areas

Parking Lot
1,000 yd^2

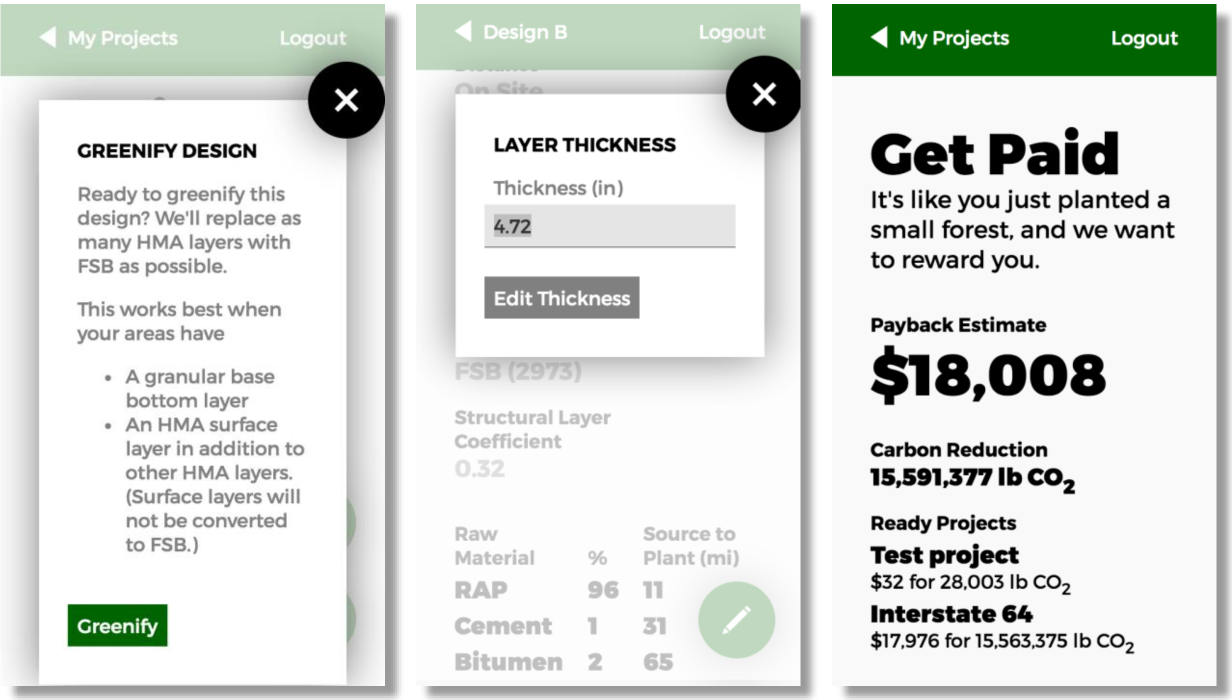
1 in HMA (2956), SN 0.44
3 in HMA (2958), SN 1.32
4 in Granular Base (2960) SN 0.44

Thickness: 8 in
Impact: 35 tons CO_2
Structural Number: 2.2
Green Mix: No

a. Creating a new project

b. Inputting design parameters (for a layer)

c. Reviewing parameters (for an area section)



GREENIFY DESIGN

Ready to greenify this design? We'll replace as many HMA layers with FSB as possible.

This works best when your areas have

- A granular base bottom layer
- An HMA surface layer in addition to other HMA layers. (Surface layers will not be converted to FSB.)

LAYER THICKNESS

Thickness (in): 4.72

FSB (2973)

Structural Layer Coefficient
0.32

Raw Material	%	Source to Plant (mi)
RAP	96	11
Cement	1	31
Bitumen	2	65

Get Paid

It's like you just planted a small forest, and we want to reward you.

Payback Estimate
$18,008

Carbon Reduction
15,591,377 lb CO_2

Ready Projects
Test project
$32 for 28,003 lb CO_2
Interstate 64
$17,976 for 15,563,375 lb CO_2

d. Requesting the app to create a sustainable design

e. Adjusting generated values

f. Viewing the contract summary for carbon credit payback

Figure 1. User Story Interface Examples

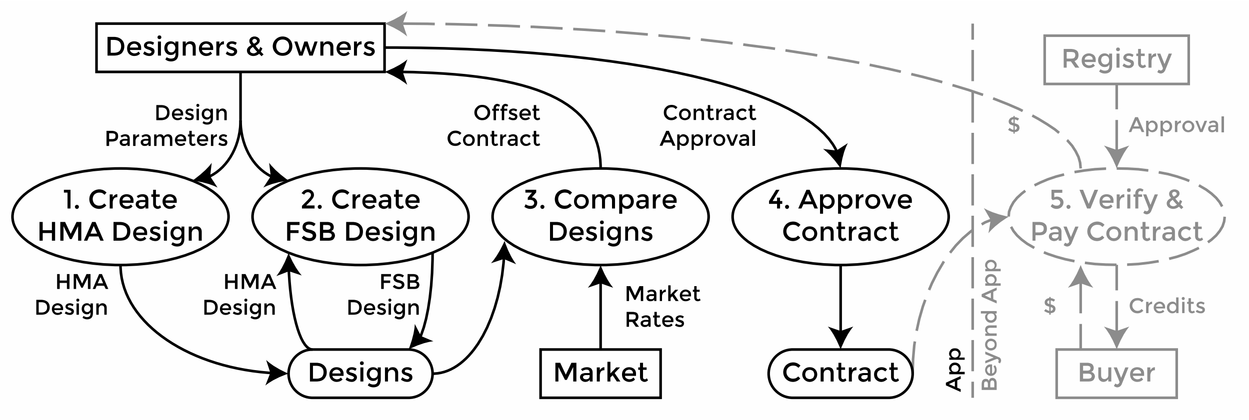


Figure 2. Dataflow Diagram. The app currently addresses functions to the left of the dashed line.

3.2 Object Model

Table two details the generally hierarchal object relationships, and their attributes from the user story.

Table 2. App Object Relationships and Attributes

Object	Relationships	Attributes
User	Child projects	Account and profile information
Project	Parent user Child designs	Geographic location Default project mix plant to job site distance
Design	Parent project Child area sections	Default design mix plant to job site distance Template****
Area section	Parent design Child layers	Size Template****
Layer	Parent area section Child equipment** Child mix	Thickness Position Equipment operating hours Plant to site distance
Mix	Parent Layers Child base Mix*** Child raw materials Child energy source	Density (weight / volume) Structural layer coefficient Raw material proportions and source to plant distances Energy source consumption amounts Amount of mix produced per period Plant energy measurement period Mix plant to job site distance Default mix****
Raw material	Parent mixes	Emission factor (amount of emissions / amount of raw material) Density (weight / volume)
Mix plant energy source	Parent mixes	Consumption units Emission factor (amount of emissions / consumption units)
Installation equipment	Parent layers	Emission factor, Emission rate (amount per hour), Horsepower, Equipment type, Equipment size, Manufacturer, Engine maker, Website

Users: The user object stores account and profile information and may have multiple child projects. Child projects are, at the time, exclusive to individual users but may become nonexclusive in the future with the development of a team object. Note that while table two shows that all other objects can be indirectly related to a user object through parent objects, all other objects are also directly associated to the user that created them; table two does not show this ownership relationship, but it has proven itself useful for tracking objects during development and testing, and helps organize default and template objects by assigning them to an administrative user.

Projects: The project object has attributes for geographic location and a default project mix plant to job site distance. The purpose of the default project to mix plant job site distance is to save designers from repeatedly entering values where multiple mixes may come from the same plant. Descendent designs and subsequently mix objects inherit any default values specified and can override them with their own values. A designer may assign a default value of 20 miles, for example, to a project, and a default value of zero to a particular in-place design within that project. In this case, emission calculations for layers not in this design will use the default distance of 20 miles unless overridden. Emission calculations for layers in the in-place design will use a plan to job site distance of zero.

Project objects have a method to estimate an amount of "cash back" available to them. This method checks to see if a traditional and green design exist, requests the carbon emissions for the design objects, and calculates the maximum difference between the designs with the highest and lowest emissions. It then multiplies the amount of carbon saved by a constant that represents the number of dollars a business is willing to pay for the carbon reduction credit rights. While projects are not ready for cash back until a user creates at least one traditional and one green design, the app enables users to execute an automatic traditional to sustainable pavement routine, called "greenification," for projects without a sustainable design. The algorithm duplicates a given HMA design, and in it, replaces middle layers of HMA with a single layer of FSB. It then iterates the thickness of the FSB layer until the structural number of the sustainable area matches that of the traditional design.

Designs: Design objects, like project objects, include default mix plant to job site distances which override any project value and can be overridden by any child mix value. Design objects include the ability for app administrators to them to mark them as templates. Once templates, users can copy these designs as new ones. The design for a major arterial highway is one example of a design template. Designs can contain one or more area sections and have a method to sum the emissions for individual areas.

Areas sections: Area objects belong exclusively to their parent designs, and like designs, can be made by app administrators into templates. The app uses areas to calculate volumes and amounts of material. Areas have methods to report total thicknesses, impact, and structural numbers from child layers. Finally, although hidden from the user while viewing a particular area, areas objects have the child methods used to "greenify" designs. These methods combine and replace traditional layers with sustainable layers in the iterative algorithm summarized above.

Layers and Mixes: Layers objects belong exclusively to their parent areas and have exactly one mix. Users can assign a thickness, a layer position, and a single mix to any layer. Sustainable pavement layers require mix plants to supply the distances drivers haul raw materials to the plants, the fuel sources they consume, and their production rates. They also require pavement installers to estimate the type and number of operating hours of installation equipment.

3.3 Layer Emissions

The app calculates carbon credits using the equations from the emerging carbon credit standard for pavement (Cui 2014). To calculate carbon emissions in HMA designs, the standard uses two benchmark ratios of CO_2 emitted per amount of HMA installed. These baseline ratios were derived from typical hot mix and warm mix projects. The standard instructs pavement engineers to choose which of the two ratios to use based on the distance of the mix plant to the installation job site. Engineers use a ratio of 134.5 $kgCO_2$/Mt-HMA for projects within 64 km distance of the mix plant; others use 170.0 $kgCO_2$/t-HMA. These ratios are for project designs that would be complete in 2017 if sustainable pavement materials and installation methods are not used. The standard provides annually adjusted ratios to account for increasing energy efficiency trends. The benchmark ratios for 2020 are, therefore, slightly lower: respectively 134.2 and 167.7 $kgCO_2$/t-HMA.

Compare to the two simple inputs needed to estimate the carbon emissions in a traditional HMA design – amount of mix and project to plant distance – the standard requires several inputs, constants, a database of materials, a database of energy sources, and a database of pavement equipment to estimate the carbon emissions for a sustainable pavement designs. Inputs are given to calculate emissions associated with five items: (1) raw materials, (2) raw material source to mix plant hauling, (3) plant energy required to create a mix, (4) mix plant to job site hauling, and (5) installation.

1. Raw material emissions equal the sum of emissions for each raw material in the mix:

[1] $e_1 = a \cdot t \cdot \rho_{layer} \cdot \sum_i (ef_i \cdot p_i)$

Where a is the layer area, t is the layer thickness, ρ_{layer} is the mix density in amount of mix per unit area, ef_i is the emission factor of material i in amount of CO_2 per amount of material, and p_i is the proportion of material i in the mix.

2. Raw material source to mix plant hauling emissions equal the sum of the hauling emissions for each raw material. For each raw material, hauling emissions equal the number of trips necessary to transport the material multiplied by the source-to-plant distance multiplied by the truck emission factor, where the number of trips equals two trips times the weight of the material divided by the track capacity, rounded up to exclude partial trips. Truck capacity and truck emission factors are constant:

[2] $e_2 = \sum_i \left(2d_i \cdot \left\lceil \frac{w_i}{c_{truck}} \right\rceil\right) \cdot e_{truck}$

Where e_{truck} the emission factor of a truck in amount of CO_2 per mile traveled (constant), w_i is the weight of material i, d_i is the source to mix plant distance for material i, and c_{truck} is the weight of a truck (constant).

3. Plant energy emissions released while creating a mix equal the ratio of material produced for the layer to the material produced for the plant period, multiplied by the emissions produced during the plant period:

[3] $e_3 = \frac{w}{m} \cdot \sum_i (ef_i \cdot c_i)$

Where w equals the weight of the layer calculated from the layer area (a), thickness (t), and mix density (ρ_{layer}). The variable m equals the weight of the mix produced during a reported plant period, ef_i equals the emission factor of the energy source i used at the plant per energy source units (e.g. watts, gallons of fuel), and c_i equals the consumption per period of energy source i in energy source units per unit of time. In this calculation, the standard provides a table of emission factors for energy sources, and mix plants are required to provide the amount of mix created and amount of energy expended for a particular period. Pavement engineers can calculate these values based on operation hours, mix yield, energy bills, and fuel receipts from the plants.

4. Similar to raw material hauling emissions, mix plant to job site hauling emissions equal the distance trucks need to travel times the truck emission factor. The distance trucks need to travel depends on the number of truck trips, which depends on the layer mix weight and the truck capacity:

[4] $e_3 = d \cdot n \cdot e_{truck} = d\left(2 \cdot \left\lceil \frac{w}{c_{truck}} \right\rceil\right) \cdot e_{truck}$

Where d equals the plant to site distance, n equals the number of trips, e_{truck} equals the same truck emission factor in amount of CO_2 per mile traveled (constant) as used in equation two, w equals the weight of the layer calculated from area (a), thickness (t), and mix density (ρ_{layer}) as in equation three, and c_{truck} equals the same constant weight of a truck used in equation two.

5. Installation equipment emissions equal the sum of their emission rates multiplied by the number of hours they are used. The standard provides a table of emission rates for several types of equipment including backhoes, cold recyclers, dump trucks, milling machines, pavers/spreaders, three different types of rollers, sweepers/scrubbers, tack distributors, and water trucks.

[5] $e_3 = \sum_i (er_i \cdot t_i)$

Where er_i equals the given emission rate of equipment i in amount of CO_2 per unit time, and t_i equals the number of service hours for equipment i per unit time. The unit time for these variables is usually reported in hours.

The total emissions released for a sustainable pavement layer equals the sum of these five emissions (equations one through five). In the case of in-place recycling, the emissions from mix plant to job site hauling are zero. In the case of CCPR, where a mobile plant is used, pavement designers can conservatively use the maximum distance across the projects area, or more accurately calculate an average a distance trucks must travel at the job site based on a site plan.

3.4 Software Stack

In order to make the service widely accessible, the app employs a web platform. It relies on WordPress, the most widely used content management system on the web, for user management, and it uses a relatively new Javascript framework, React, for the user interface (figure 1). WordPress runs on an Apache and NGiNX hybrid webserver. A managed platform provides development and production environments, automatic security updates, SSL encryption, and enforcement of strong user passwords. PHP code defines app objects classes (table 2) and a MySQL database stores project data.

4 I-64 Case Study

4.1 Case Study Parameters

Virginia is one of twelve states in the US that employ recycled material on interstate highways projects, and the Interstate 64 (I-64) project is one of the few multi-process recycling projects currently proposed in the country. Interstate 64 consists of a jointed plain concrete pavement (JPCP) design commonly laid down in the 1950s in the United States and Canada. The highway spans two travel lanes in each direction of travel (four lanes total), and stretches 7.08 miles in each direction across Newport News, James City and York Counties in Virginia. It carries over 3,000 trucks per day in each direction. The project proposes a $190 million budget to (a) construct a new travel lane and 12 ft. shoulder consisting of a cement treated aggregate (CTA) foundation, a CCPR base, and traditional hot mix asphalt surface layers, and (b) reconstruction of existing lanes with a FDR foundation, a CCPR base, and asphalt surface layers. Traffic will move from the old lanes to the new lanes while installers reconstruct the old lanes. These designs are based on the successes of Interstate 81 and National Center for Asphalt Technology test track trials. Diefenderfer (2016) estimates the sustainable design will save over $10 million in materials and reduce greenhouse gases by up to 50%. Work on I-64 should begin in this year (2017). Table three compares traditional and sustainable designs for the project.

Table 3: Case Study App Input: I-64 Traditional and Sustainable Designs Above Subgrade

	Traditional Design		Sustainable Design	
Layer	Material	Thickness (in)	Material	Thickness (in)
1	HMA Surface	2	HMA Surface	2
2	HMA Intermediate	2.5	HMA Intermediate	2.5
3	HMA Base	4	CCPR	6
4	Stabilized drainage layer	2	Stabilized drainage layer	2
5	CTA	8	FDR	12

4.2 Case Study Results & Discussion

The app can currently accommodate all of the layers in Table 3 except the stabilized drainage layer without creating custom mixes. Because this layer is the same thickness and material for both the traditional and recycled designs, this study removed it for the purposes of calculating carbon emission reductions. The app estimates a carbon reduction of 3,336 t CO_2 from 19,197 t CO_2 to 15,861 t CO_2 and an increase in structural numbers from 4.94 for the traditional design to 5.1 for the sustainable design.

Interestingly, applying the “greenification” methods to the traditional HMA design given, the app creates an alternative two-layer design to sit on the subgrade consisting of the same 2.0 in. HMA top layer in the sustainable design planned, and a 12.69 in. bottom layer of all FSB. This alternative design has an equal structural number of 4.94 to its traditional design, demonstrating the efficiency of the model algorithm to iterate thickness until a structural target is achieved, but leaving an uneven number of inches that would most likely be rounded to 13 in. in practice. In terms of carbon emissions, the alternative generated design yields almost a double the amount of emission reductions: 7,059 t CO_2 compare to 3,336 t CO_2, and yields a final emission amount of 12,138 t CO_2 compare to 15,861 t CO_2 from the original sustainable design. Assuming a rate of $5/t to $10/t of CO_2 reduced, this project could be eligible for $17,000 to $34,000 for the sustainable design provided, or up to $35,000 to $70,000 if the final design ends up being more like the generated one. These amounts would bring to an additional 0.2% to 0.7% savings on top of the estimated $10 million in material savings. In the most conservative case, if an investor pays only 50% of the lowest valued sustainable design scenario, the project owner would receive a minimum of $8,500.

5 Conclusions

The pavement industry still faces challenges to adopt sustainability. The app presented in this paper will help encourage it. The app enables designers to compare traditional and sustainable designs with both economic and environmental criteria. It then estimates, in a novel way for the pavement industry, an economic incentive for choosing sustainable materials based on carbon credits. Given the United States produces 317 Mt of HMA per year, the market potential for the app using only a 20% share of this 317 Mt of HMA is 2.8 Mt of carbon offsets, or over $20 M in revenue (at a conservative rate of $7.50/t-CO2). In addition to this new source of revenue for carbon credits, contractors could be saving an additional $20/t in material savings for HMA replaced by FSB. These material savings amount to an additional $1.3 G for this 20% market share of 317 Mt of HMA.

Near-future versions of the app could address the two main limitations in the current version: (1) The app could incorporate raw material costs to further encourage adoption of FSB over HMA. (2) The app could consider a more complete cradle-to-grave carbon life cycle analysis, including pavement repair and maintenance. Looking ahead, the app could eventually become a marketplace where carbon brokers could bid and invest in pavement emission reduction prospectuses.

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