

Carbon Footprint Calculation for a Typical Roadway Section

Pavement infrastructure plays a significant role in modern society by providing transportation and supporting commerce. Pavement has a limited lifespan and must be replaced or rehabilitated every three to twenty years, based on the method. Vast amounts of greenhouse gas emissions are emitted into the atmosphere during pavement construction and maintenance rehabilitation. Pavement construction requires enormous amounts of energy to obtain and process raw materials, transport, mix and apply to the final product of highway. This research evaluates greenhouse gas emissions for pavement utilizing a group of typical pavement sections from Indiana and Oklahoma and identifies a carbon footprint index based on linear foot of pavement. A group of carbon offsets has been determined, using trees, medians, vegetative channels, etc. creating a "shopping list" of carbon offsets, will help owners, designers, and engineers make sustainable determinations. A carbon footprint index allows users to simply quantify benefits of the carbon offsets. The index associates pavement infrastructure materials with their carbon footprint based on the linear foot of pavement.

Key Words: Pavement, Greenhouse Gas (GHG), CO2, Carbon Footprint Index, Typical Section

Introduction

Global climate change has triggered the investigation of strategies to reduce the life cycle greenhouse gas (GHG) emissions associated with the construction and rehabilitation of highway infrastructure (Santero and Harvath 2009). The primary GHG emissions include those from the raw material acquisition and manufacturing phase, and the pavement construction phase. The secondary emissions include emissions due to vehicular use and maintenance operations during the service life of the pavements. The carbon footprint of the highway pavement projects was calculated in terms of CO_2 equivalents (CO_2e) of GHG emissions.

The GHG associated with the construction and maintenance of a pavement is characterized by gases like carbon dioxide (CO2), nitrous oxide (N2O) and methane (CH4). Carbon footprints were calculated in equivalents of carbon dioxide from the GHG emissions, and a tool was developed that could be used to benchmark and estimate footprints to effectively reduce emissions in future projects. Since the 1980s, transportation infrastructure management has been a topic of importance due to government expenditures, user costs and the size of the projects (ASCE 2009). GHG emissions have become significant environmental impacts due to pavement management decisions (Santero and Horvath 2009, Sathaye et al. 2010). However, relatively little work has been done towards understanding the interrelationship between monetary costs and environmental emissions (Zhang et al. 2010).

Previous studies include an examination of the carbon footprint of asphalt and concrete pavements for typical residential, collector, and freeway pavements constructed in Ontario, Canada. Brown (2009) reviewed the carbon footprint of an equivalent asphalt freeway pavement built as a Perpetual Pavement. Both the carbon footprint of the initial construction and the maintenance activities over a 50-year life cycle were evaluated and compared. Mosier et al. (2014) has provided a carbon footprint cost index for various pavement preservation options, proposing criterion that integrates sustainability with initial cost to justify investing in higher cost treatments on a basis of enhanced sustainability. The carbon footprint cost index provides a simple way to enhance pavement sustainability by utilizing an Analytical Hierarchical Process (AHP). The AHP assists owners in determining budget requirements for pavement preservation and sustainability requirements in the decision-making process, using initial cost, life cycle cost, and carbon footprint. The carbon dioxide equivalency for bridge design has been developed (Gopi et al. 2017) with a process to find the embodied CO2e in a particular bridge design to estimate the performance of the deck from a sustainability perspective. A ranking scale was identified by establishing a mathematical relationship between a bridges' CO2e and its structure for parametric estimating of its embodied CO2e to gauge a bridge's sustainability.

Although there are some conglomerations of construction items available (Hammond and Jones, 2011), there are very few applications of materials. There is some very specific research on the construction material carbon footprint (Chevotis and Galehouse 2010 and Hammond and Jones 2011). Carbon offsetting has been a controversial topic. However, when trying to get a clear understanding of how many trees to plant to offset GHGs as CO2 equivalents (CO2e), the construction, maintenance and longevity of the trees themselves must be a factor (Strohbach et al. 2012). This research highlights how to use trees or alternative materials to reduce the carbon footprint rather than a purchased carbon offset or carbon tax. An index was created by pavement infrastructure materials with their carbon footprint based on the linear foot of pavement. This allows a comparison of current bid price per linear foot of pavement to carbon footprint along linear feet. From carbon footprint emission data, the owner or engineer can create and compare the cost budget to the sustainability requirements.

Pavement Sustainability

The asphalt cement or bitumen used in asphalt pavement has high carbon content. The average carbon content of asphalt cement is about 82 percent, and about 5 percent of an asphalt cement is used in the asphalt pavement, with the rest being aggregates. Currently in North America, at least 95 percent of the asphalt pavement removed from the road is either reused in new asphalt pavements or recycled as base or shoulder material (Asphalt Pavement Alliance, 2010). The material not reused or recycled is still not burned and thus the embodied carbon is never released into the atmosphere.

Cement Industry of Canada Sustainability Report (2010) analyzed the difference in carbon footprint calculation between asphalt and concrete pavement. For every 1,000 kg of portland cement, approximately 730 kg of carbon dioxide is produced. Heating the aggregate and clay used to produce portland cement to a temperature of around 1,450°C in the kiln causes the disassociation of the limestone and the production of about 60 percent of the carbon dioxide, which is released to the atmosphere. While comparing 50-year life-cycle GHG production, concrete pavement produced about 1610 CO_2e tons/km and asphalt pavement produced about 500 CO_2e tons/km (Cement Industry of Canada 2010 and Asphalt Pavement Alliance 2010).

A recent study on permeability in asphalt concrete from Oklahoma Department of Transportation determined an average density of compacted asphalt of 144.8 pcf (Cross and Bhusal 2009). The Asphalt Institute provides a range of densities from 135-155 pcf (2001) for Hot Mix Asphalt (HMA). The bulk specific gravity of compacted asphalt ranges from 2.29 to 2.35 (Leng et al. 2011). As specific gravity for HMA is based on the unit weight or solid density of the compacted mix, the Rice value or Gmm is used as a basis for the specific gravity. The Asphalt Institute also provides guidance on specific gravities, pointing to 2.5 being a typical value (2017). For this research, we utilize an estimated specific gravity of compacted asphalt to be 2.32 which multiplied times the density of water (62.4 pcf) provides a density of 144.77 pcf which is rounded here for simplicity to 145 pcf. The density or unit weight of Portland Cement Concrete Pavement (PCCP) is well known. However, an average value has been identified for this work. The unit weight of concrete is commonly known to be between 140-150 pcf (Johnston 2014). For this work the value of 145 pcf will be used.

Soil & Subbase Treatments

Subgrade treatment consists of providing, placing and compacting one or more layers of soil along with chemical additives and water to achieve a stable subgrade. Chemical additives used to stabilize or modify the subgrade are either cementitious additives; fly ash or cement kiln dust, or lime additives. Aggregate base material may also be used instead of a chemical soil modification. Depending on the type of soil of a geographical location, the preferred option is determined for the subgrade stabilization. Oklahoma City typically depicts clayey soil for the counties under its vicinity. Soil average specific gravity value of 2.73 and density of 170 pcf is taken for all calculations of the carbon footprint in this paper.

Cement Kiln Dust (CKD) is one of the most common additives used for soil stabilization purposes. The density of portland cement is 1860 kg/m3 (Hammond and Jones 2011) which converts to 115.87 pcf. The specific gravity of CKD typically ranges from 2.6-2.8 (Collins and Emery 1983). Using the average specific gravity of 2.7, the weight is approximately the same as soil or 170 pcf. An application rate of 5% by weight have been used. Hammond and Jones simplify the calculations by providing a CKD soil stabilized base carbon footprint of 0.06 kg/kg which converts to 0.386 kg/sf/in of stabilization (2011).

Fly ash is another frequently utilized additive for stabilizing soil for highway constructions. The specific gravity of flyash varies widely, from 2.0-2.6 (ACAA 2003). The density of fly ash has been taken as 144 pcf (Hammond and Jones 2011). As per ODOT (2009), the soil stabilization mix design states an optimum replacement level of 14% in stabilization of soil subbase in Oklahoma, which typically applies to all soil types except A7 under the AASHTO soil classification method.

Subgrade stabilization using lime additive which is preferred for soil types which are categorized under the AASHTO M145. Soil classification of A6 and A7 soil where the density is taken as 75 pcf for the carbon footprint calculation is (Hammond and Jones 2011). A range of application rates for lime has been established between 3%-6% by weight (Solanki et al. 2002). An application rate of 5% by weight will be used here.

Additional subbase improvements may include No. 8 and No. 53 aggregate base material. Aggregate base varies in density based on the material and compaction. A variety of densities have been identified for aggregate base materials from 100 pcf to 180 pcf. Hammond and Jones (2011) provide a density and carbon footprint in their Inventory of of Carbon and Energy. The density provided by ICE is 2,240 kg per cubic meter which converts to 139.8 pcf rounded to 140 pcf for simplicity herein.

Non-Pavement Roadway Construction

Understanding the carbon footprint is important, but equally important is understanding potential carbon offsets. Substituting flyash or slag for PCCP can reduce associated GHG emissions (Collins 2010). Warm Mix Asphalt or Recycled Asphalt Paving can be used to reduce the carbon footprint as well. A review of the roadway design elements behind the curb is also required. Many roadway projects include a variety of landscape elements to reduce the carbon footprint. VicRoads, a state authority in Australia, provided details on a trial carbon-neutral construction project, planting 7,463 trees upon completion to achieve carbon neutrality. The trees were expected to absorb carbon from the atmosphere over their life removing carbon generated by the extraction, manufacturing, and placement of the material used, as well as the transportation of the materials to and on the site (2014).

Trees may provide a carbon offset on average of 19 kilograms per year at maturity, which is between 12 and 18 inches in trunk diameter and typically over 30 feet in height (Nowak 1994 and Akbari 2002). Further other evidence provides carbon storage in trees and shrubs in grams per square meter based on land use. It is taken as a given that trees sequester carbon during growth. However, some amount of loss due to lack of maintenance and death. Other benefits are associated with trees in urban areas. Trees are known to provide shade. Additional benefits include evapotranspiration cooling and wind speed reduction (McPherson and Simpson 1999).

Turf grass and shrubs can also be used in carbon footprint calculations. Similar to trees, there are some other considerations by using turf grass as a carbon offset. Fertilizer, irrigation and other maintenance like mowing of turf grass must be included as additional emissions, not offsets (Townsend-Small and Czimczik 2010). In areas where other types of grasses or wild flowers are used, assumptions would change. Depending on the density and the life stage, shrubs may provide carbon offsets as well. Shrubs can provide 0.13–12.93 g/m2 of carbon storage based on density of shrubbery (McHale et al. 2016).

For a 24’ roadway, the statutory right-of-way in Oklahoma is 66’. Although this is “shared” space by the property owner and the state, a clear zone is required in the first 7’-10’ either side of the roadway section. Along with highway signs, some low planting occurs in this area, including turf grass. Indigenous plants and xeriscaping would provide the best outcomes with the least amount of carbon emissions associated with installation and care. It is worth noting that in the locations of interest, OKC and Fishers, xeriscaping is not indigenous and not considered here. However, there is plenty of research identifying the carbon sequestration value of native soils and xeriscaping. Bouchard et al. (2013) provides some insight into the ditch area on a section with no curb. As the vegetation acts as a filter and swale, it also provides some carbon footprint reduction. This can be appropriately compared to an underground utility pipe.

Although vegetation is one consideration, utilities make up another consideration. Many utilities are outside the traditional project scope of government entities and are self-performed by others. Some utilities may be provided by local government, like storm sewer, water lines and sanitary sewer lines. An in-depth analysis of these utilities is not provided here, but some discussion is merited. An Inventory of Carbon and Energy (ICE), has been developed by (Hammond and Jones 2011) specific to construction materials. A comparison of steel, concrete, plastic, PVC and vitrified clay pipe can be performed as well to make determinations as to the least carbon footprint. Like any other comparison, the pipe cannot be considered as a manufactured product alone, the transportation, setting and bedding activities must be analyzed as well.

Methodology

Typical standard pavement sections from Fishers, IN and Oklahoma City (OKC), OK were analyzed to calculate GHG emissions. Both municipalities publish typical sections online. This is unique to smaller government entities. The two municipalities have similar roadway sections. Starting from the roadway sections, an area per linear foot was determined. Roadways are typically bid per linear foot. Using the area per linear foot, an easy correlation can be made to cost. The area per linear foot also allows the different materials to be indexed for comparison. For HMA sections, tack coat is not included as the pay item for tack coat is frequently in gallons and not in linear foot.

Additionally, a standard for the carbon footprint or GHG emissions should be determined. Greenhouse gases are frequently measured in terms of energy used in Btu, Joules or megajoules (MJ). Another way to measure the carbon footprint is through the embodied energy (carbon) of a production cycle. Hammond and Jones propose using a common idea of cradle to gate, which indicates the production energy prior to leaving the factory (2011). Shipping would be accounted for separately. Chevotis and Galehouse use a similar approach specifying an expected travel circuit (2010). For this research, the calculations are presented in one set of units. Because the carbon offset of trees are presented in kg/tree, the appropriate choice of units is the carbon emission of the materials in question or kg of carbon per unit.

For OKC, a typical 24' HMA section with a ditch, the section consists of 3" Type B HMA over 6" Compacted Subgrade, and over 6" Stabilized Aggregate Base or 10" Stabilized Soil. The similar section for Fishers is noted as Main St./Secondary St. and consists of 1.5" Type A HMA Surface over 2. 5" Type A HMA Intermediate and 2. 5" Type A HMA Base, over 3" Type A HMA Base and 14" Stabilized Subgrade or 6" Compacted Aggregate Base No. 53 on 14" Stabilized Subgrade. The narrative description is tabulated in Table 1 with the associated carbon footprint.

An itemized list of carbon footprints has been put forward by Chevotis and Galehouse (2010) and the "Inventory of Carbon and Energy" (ICE) by Hammond and Jones. (2011), both of which focus on typical items utilized in construction. What has not been previously identified is the carbon footprint of a linear foot of typical roadway construction. A carbon footprint per linear foot of construction is necessary to help engineers and owners determine if not only are they making the best budget choices, but also the best choice based on carbon footprint or GHG emissions. Reviewing Table 1, Carbon Footprint for 24' HMA Roadway with No Curb, the carbon footprint for HMA, aggregate base, compacted soil or stabilized soil is not difficult to determine.

By calculating the carbon footprint for each of the individual layers of material based on depth and width of the overall section, a carbon footprint in kg/lf can be determined. The carbon footprint for the roadway section minus the stabilization method for the 24' wide section with no curb is tabulated in Table 1.

TABLE 1 Carbon Footprint for 24' HMA Roadway with No Curb

OKC	CO_2 (kg/lf)		Fishers	CO_2 (kg/lf)
OKC Typ HMA Section 102 - 24'			Main St/Secondary St	
3" Type "B" Asphalt	21.67		1.5" Type A HMA Surface	10.83
6" Compacted Subgrade	1.48		2. 5" Type A HMA Intermediate	15.43
*6" Stabilized Aggregate Base	11.43		2. 5" Type A HMA Base	15.43
			3" Type A HMA Base	18.52
			14" Stabilized Subgrade	30.23
Or			Or	
*10" Stabilized Soil			6" Compacted Aggregate Base No. 53	11.43
			14" Stabilized Subgrade	0.00
No Curb	0.00		No Curb	0.00
Total (Max.)	34.58		Total (Max.)	90.44
Total (Min.)	23.15		Total (Min.)	71.65

Adding a stabilized base adds multiple variables to the equation. As indicated above there are three basic options for chemically stabilizing soil base, by adding flyash, lime, or CKD. Some methods use a mix of two chemicals, but that will be outside the focus of this research. For simplicity only one chemical additive is evaluated at a time, based on the application rates given above. Comparing both OKC and Fishers, there are three different depth of soil stabilization; 6", 8", 10" and 14". The carbon footprint per 1" of depth of soil stabilization was determined and is provided in Table 2.

TABLE 2 Soil Stabilization Carbon Footprint per inch of depth

	% Modification	kg/SF/in	% Soil	kg/SF/in	Combined kg/SF/in
Fly-Ash	14%	0.044	86%	0.87	0.913
CKD	5%	5.976	95%	0.96	6.937
CKD*	5%	--	--	--	0.386
Lime	5%	0.247	95%	0.96	1.208

By a summary glance, it could be assumed that CKD has the highest carbon footprint. It is true that the process to manufacture CKD has a high energy use associated with it. CKD is a by-product of the cement manufacturing process and by recycling it into other products, like as a soil stabilization technique, is preferable to the material entering the waste stream. The purpose of CKD is different from flyash and lime as CKD is typically used for sandy soils. CKD* is calculated with soil by Hammond and Jones and will be used as an appropriate value (2011).

There are many options for reducing the carbon footprint of a roadway. Chevotis and Galehouse (2010) have tabulated a variety of carbon footprints associated with roadway maintenance. Although the concrete, asphalt and base materials are considered additive in this paper, utilizing alternative methods like warm mix asphalt can be considered a potential reduction.

Trees and soil may be considered for carbon sequestration in an urban environment (Melson et al. 2011). Calculations for carbon sequestration frequently consider trees as a group making it difficult to apply a carbon offset for a singular tree. However, some research has focused on individual trees and more particularly street trees as a carbon offset (Akbari 2002 and Tang et al. 2016). From research in the Twin Cities, values on a per tree basis were determined (Akbari 2002) and is provided in Table 3 adapted from that research. The adapted table uses a street tree lifespan of 50-60 years as provided by Strohbach at al. (2012). A standard tree spacing must also be identified.

TABLE 3 Carbon Sequestration of Trees (Chen and Zhao 2016)

Tree Type	Carbon in kg	Tree Type	Carbon in kg
Norway maple	160	Robusta and Siouxland hybrid	745
Sugar maple	145	Kentucky coffee tree	105
Hackberry	135	Red maple	140
American and little-leaved linden	265	White pine	210
Black walnut	150	Blackhills (white) spruce	165
Green ash	180	Blue spruce	335
		Average	**230**

Spacing may be determined by the designer or engineer for a roadway project. Akbari's study focuses on a crown of 50 m2 or 538 sq.ft., or approximately 26 foot diameter (2002). Using a slight overlap, trees will be assumed to be spaced at 20' on center. Using the average carbon sequestration and a 50 year life cycle, a carbon offset per tree can be estimated at 230 kg over the life of the tree. Based on a 20' spacing the average carbon offset per linear foot would be 11.5 kg/lf.

Similarly, adding turf grass can be used to offset carbon. More specifically instead of turf grass alone, consider the use of a vegetative drainage channel or ditch instead of a concrete channel or underground storm sewer for carbon sequestration. Like any other system, there is a carbon footprint to the installation of the turf system itself.

When using a vegetative "filter strip" or ditch, a value of 36 kgC/sq.ft. may be used, calculated for a variety of locations in North Carolina. These values may be increased when using a wetland area or area which is continually wet (Bouchard et al. 2013). Although these results may not be considered complete and for extrapolation to all locations, it is important to note that data could be compiled at other locations to obtain a locally appropriate carbon offset.

Another option is to reduce the carbon footprint of the associated utilities. Based on the Hammond and Jones inventory (2011), the carbon footprint for a variety of pipes can be determined. Using a 12" diameter pipe and weight per linear foot, the carbon footprint of clay, iron, HDPE, PVC, steel, RCC are 13.02, 43.92, 8.30, 11.62, 55.39 and 10.39 respectively. However, an in-depth analysis of the carbon footprint of utilities is not provided herein.

Discussion / Results

A roadway section greenhouse gases emission is determined, using the pavement section, soil stabilization options, and utility pipes. Trees is considered in the roadway section as offsets of greenhouse gases emission and will reduce the overall carbon footprint. Entering all of the options into a table, a maximum and minimum carbon footprint can be determined.

Some notes should be made about Table 4. The original pavement sections included options for base material. The soil stabilization methods are optional and may not be used in all locations. CKD is typically used in Indiana but may not be used in Oklahoma, however it was used in the calculation for minimum for both roadway sections. A subtotal was provided based on the roadway options only. To calculation the maximum including trees and utilities, only the maximum and minimum carbon footprint for pipe were considered, specifically steel and HDPE. Trees were only added to the minimum carbon footprint. The assumption is the worst-case for carbon footprint would be without street trees as an offset.

TABLE 4 Total Carbon Footprint for a 24' HMA Roadway section

OKC	**CO2 (kg/lf)**		**Fishers**	**CO2 (kg/lf)**
Typ HMA Section 102 - 24'			Main St/Secondary St	
3" Type "B" Asphalt	21.67		1.5" Type A HMA Surface	10.83
6" Compacted Subgrade	1.48		2. 5" Type A HMA Intermediate	15.43
			2. 5" Type A HMA Base	15.43
*10" Stabilized Soil			14" Stabilized Subgrade	
Fly-Ash (14%)	9.13		Fly-Ash (14%)	12.79
CKD (5%)	3.86		CKD (5%)	5.40
Lime (5%)	12.08		Lime (5%)	16.91
			*3" Type A HMA Base	18.52
Or			Or	
**6" Stabilized Aggregate Base	11.43		**6" Compacted Aggregate Base No. 53	11.43
No Curb	0		No Curb	0
Subtotal (Max.)	35.23		Subtotal (Max.)	77.12
Subtotal (Min.)	27.01		Subtotal (Min.)	58.53
Street Trees @ 20' o.c.	-11.5		Street Trees @ 20' o.c.	-11.5
Pipe (HDPE Min.)	8.3		Pipe (HDPE Min.)	8.3
Pipe (Steel Max.)	55.39		Pipe (Steel Max.)	55.39
Total (Max.)	**90.62**		**Total (Max.)**	**132.5**
Total (Min.)	**23.81**		**Total (Min.)**	**55.33**

Conclusions

A large quantity of research is now available to quantify the carbon footprint using a variety of construction materials of roadway section. Although Chevotis and Galehouse provided one application (2010) and Mosier et al. has provided another (2014), very little has been published in the area of application of the collected carbon footprint values in infrastructure construction. This research attempts to further the application of the carbon footprint in infrastructure construction, by applying known carbon footprint values to actual roadway sections in order to calculate a carbon footprint. More specifically, this framework is applicable to the Envision rating system for determining the carbon footprint of an infrastructure project/

In reviewing Table 4, the carbon footprint for two types of roadways in two different areas of the country were calculated. It is obvious that the two municipalities vary in their minimum roadway section and this also causes a dramatic difference in carbon footprint. The maintenance of the two different sections would be at different which would affect the life-cycle carbon footprint which is not considered here. That would be an obvious next step for research. From the larger perspective, there has been enough information collected and calculated to start producing a carbon footprint for any infrastructure construction project.

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