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The Study of Roadway Sustainability in Texas: A Case Study with the Use of the Greenroads^{TM} Rating System

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The Study of Roadway Sustainability in Texas: A Case Study with the Use of the Greenroads^{TM} Rating System

by

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Abstract

The Study of Roadway Sustainability in Texas: A Case Study with the Use of the Greenroads™ Rating System

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In the state of Texas, the roadway network consists of approximately 313,228 miles of roads (Federal Highway Administration, 2013), accounting for 7.61% of the public roads in the United States. To put it in perspective, this is equal to 12.6 times the circumference of Earth. In order to manage this network, the state and local transportation agencies use millions of tons of natural resources to construct and maintain these facilities. If these resources are not being properly used, Texas might end up wasting them, producing more pollutants, and imposing threats to its natural environment. Moreover, there is no way to quantify and record the efforts made by the Texas transportation community in becoming sustainable. Thus, there is a need to promote and keep track of ongoing sustainability efforts. In this study, we explore the trend of roadway sustainability in Texas, and propose a Texas version of sustainability rating system that is based on Greenroads. The Greenroads sustainability rating system is a third-party rating system developed by the University of Washington and aimed at recognizing sustainable practices in roadway projects. First, two of its projects in Texas are selected as the case study for the purpose of understanding the system. Second, 1,594 pavement projects are extracted from Texas highway construction database called Site Manager that is maintained by the Texas Department of Transportation (TxDOT) to understand

the state of practice. Third, some material data that comes from TxDOT division engineers is included as well. Together with them, a Greenroads-based sustainability rating system, especially adapted in terms of material selection and pavement technology, is proposed. As a result, the implementation of this system is expected to spark more pursuits of roadway sustainability in Texas.

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CHAPTER 1: INTRODUCTION

Federal Highway Administration (FHWA) reported in 2013 that the number of public road mileage in the state of Texas, including those maintained by the state highway agency, the federal agency, local agencies and other jurisdictions, is approximately 313,228, accounting for 7.61% of the public road mileage in the United States (FHWA, 2013). This network represents about 12.6 times the circumference of Earth. For the past few decades, Texas has been ranked first in the total state road mileage among all of the states in the U.S. In managing this network, Texas public agencies, including Texas Department of Transportation (TxDOT) and many other local transportation authorities, have put countless effort and used millions of tons of natural resources to construct and maintain this vast highway network, indicating a great potential of being sustainable in using these resources.

In terms of vertical construction projects, i.e. buildings, many rating systems have been widely used to evaluate their sustainability performance. For example, Leadership in Energy and Environmental Design (LEED) is a set of sustainability rating systems developed by the U.S. Green Building Council (USGBC) in 1998. It is intended to recognize sustainable design, construction and operation practices for building, interior design and neighborhood development. While LEED has been developed for almost 30 years, it is not until recently that the sustainability of horizontal construction projects was being noticed. In 2007, the University of Washington initiated a research project to develop a rating system especially for roadway projects, called Greenroads (University of Washington and CH2M HILL, Inc., 2011). Since then, several versions of Greenroads have been developed, and the system is now operated by the Greenroads Foundation.

The state of Texas can greatly benefit from the adoption of such a sustainability rating system or, more broadly speaking, the concept of sustainability behind the system. Many sustainable practices recognized in Greenroads, such as the recycling of pavement materials, and the use of warm mix asphalt (Estakhri et al., 2010) and the design of long-life pavements, etc., could be easily achieved in Texas, promoting more sustainable construction or maintenance practices, consuming less energy and producing less greenhouse gas. However, it can be imagined that some sustainable practices might be difficult or even unsuitable for the state of Texas. Therefore, on the one hand, for those sustainable practices that can be easily achieved in Texas, their criteria must be set higher. On the other hand, for those practices that are difficult to implement in Texas, some adjustment must be done. Based these two principles, a sustainability rating system can therefore be built, and further benefit the entire transportation community.

This thesis' objective is to provide a glimpse into the Texas transportation community's potential of being sustainable, and more importantly, to propose a Greenroads-based sustainability rating system that is more suitable to Texas. The Greenroads rating system was chosen to measure this potential, because it (1) encourages the innovation of sustainable practices, (2) has been developed since 2007, and (3) is the rating system that has been applied inside and outside the U.S. In the next chapter, the definition of sustainability, the description of Greenroads with the sustainable practices targeted, and the introduction of a project construction database maintained by TxDOT are provided as the background of the study. Chapter 3 introduces a case study including two of the Greenroads projects located in Texas as well as their performances in terms of the targeted sustainable practices. Changes are then proposed to the material selection and pavement technology parts of Greenroads in Chapter 4, which are based on the result of the case study, the construction projects extracted from the database, and the information provided by TxDOT division engineers. Chapter 5 concludes this thesis with a discussion on the trend of roadway sustainability in Texas, the implementation of the proposed changes as well as some potential studies.

CHAPTER 2: BACKGROUND

2.1. SUSTAINABILITY

The word sustainability is derived from the Latin *sustinere*, which means the ability to be held up. Thus, *Sustain* can mean “maintain”, “support” or “endure” (Onions, 1964). Nowadays, the most widely quoted definition of sustainability stems from the concept of sustainable development: *“sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”* (Brundtland Commission, 1987).

Furthermore, the World Summit on Social Development (2005) identified the three pillars of sustainable development, i.e. economic development, social development, and environmental protection. These three pillars can be perfectly explained by the concept of Profit, People and Planet, a.k.a. the “triple bottom lines” (TBL) coined by John Elkington at SustainAbility, a British consultancy that he founded, in 1994 (Elkington, 1997). He argued that companies should be preparing three different bottom lines, including Profit, People and Planet. First, the Profit is the conventional measure of corporate profit, which is analogous to the world economic development. Second, the People is the measure of how socially responsible an organization has been throughout its operations, which is similar to the world social development. Third, the Planet is the measure of how environmentally responsible an organization has been, which is equivalent to the last pillar of sustainable development, the environmental protection (Tim, 2008).

2.2. THE GREENROADS RATING SYSTEM

Anderson (2012) stated that while the definitions of sustainability offered by many of the authors and organizations address the three pillars, most of them are not directly applicable for a roadway construction project, of little utility and, difficult to implement since the meaning of sustainability cannot be tracked or measured. Therefore, there is surely a need to develop a measuring tool that can help people to quantify the sustainability of a project, to establish the performance criteria and to compare the results of these projects. The motivation above gave birth to the Greenroads™ Rating System, the focus of this study.

Greenroads features three key ideas: (1) physical constraints or natural laws, (2) satisfaction of basic human needs or human values, and (3) the idea that roadway projects are best perceived as systems (University of Washington and CH2M HILL, Inc., 2011). These keys can be viewed as the concept and implementation of sustainability. The first two keys are consistent with the three pillars of sustainable development, i.e. economic development (human values), social development (human values) and environmental protection (natural laws). As for the last key, Anderson (2008) explained that a system-based approach, i.e. evaluating project sustainability via a rating system, including only natural laws and human needs is incomplete. The implementation of this approach must include well-defined boundaries within which the sustainability is measured, the performance criteria, what has been learned from the implementation, and the requests of ongoing education and public awareness.

The Greenroads™ Rating System Rating (Greenroads) consists of eleven mandatory Project Requirements (PR) followed by thirty-seven Voluntary Credits (VC), totaling 108 points and divided into Environment and Water (EW), Access and Equity (AE), Construction Activities (CA), Materials and Resources (MR), and Pavement Technologies (PT) categories. It is a sustainability rating system that aims at the design and construction phases of a project. In order to have the project certified by Greenroads, a project team needs to submit specific documentation in support of all the project requirements and certain voluntary credits that the team is pursuing. After the team completes the project, the certification will be awarded (or denied) according to the total points achieved by the team. These points come from thirty-seven VCs, in which each credit has one to five points available. Achieving any of the PRs will not result in any additional points, since Greenroads defines them as the basic requirements for a project to be considered sustainable (University of Washington and CH2M HILL, Inc., 2011).

In this study, with a focus on Greenroads Verstion 1.5, twelve VCs were selected and studied, including six credits in MR and six credits in PT, because they are more relevant to the material selection and pavement construction parts of a project than the rest of the sustainable practices. Table 1 provides a summary of the targeted sustainable practices. While all of the PRs are obligatory with no points available, twenty-three points are available for MRs and twenty points are available for PTs. As for the definitions of these targeted sustainable practices, they are described as follows.

Table 1: Descriptions of Targeted Project Requirements, Materials and Resources and Pavement Technologies

Sustainability Practice	Points	Goal
MR-1, Lifecycle Assessment	2	Create new lifecycle assessment information for roads
MR-2, Pavement Reuse	1 – 5	Reuse existing pavement and structural materials
MR-3, Earthwork Balance	1	Reduce need for transport of earthen materials by balancing cut and fill quantities
MR-4, Recycled Materials	1 – 5	Reduce lifecycle impacts from extraction and production of virgin materials
MR-5, Regional Materials	1 – 5	Promote use of locally sourced materials to reduce impacts from transportation emissions, reduce fuel costs, and support local economies
MR-6, Energy Efficiency	1 – 5	Reduce lifetime energy consumption of lighting systems for roadways

Table 1 (Cont.): Descriptions of Targeted Project Requirements, Materials and Resources and Pavement Technologies

Sustainability Practice	Points	Goal
PT-1, Long-Life Pavement	5	Minimize life cycle costs by promoting design of long-lasting structures
PT-2, Permeable Pavement	3	Improve flow control and quality of stormwater runoff through use of permeable pavement technologies
PT-3, Warm Mix Asphalt	3	Reduce fossil fuel use at the hot mix asphalt plan, decrease emissions at the plant, and decrease worker exposure to emissions during placement
PT-4, Cool Pavement	5	Reduce contribution to localized increased air temperatures due to pavement reflectance and minimize stormwater runoff temperatures
PT-5, Quiet Pavement	2 – 3	Improve human health by reducing tire-pavement noise
PT-6, Pavement Performance Tracking	1	Allow for more thorough performance tracking by integrating construction quality and pavement performance data

2.2.1. MR-1 Lifecycle Assessment

The goal of the first credit in the MR category is to create new lifecycle assessment (LCA) information for roads (University of Washington and CH2M HILL, Inc., 2011). Originally, this credit had two points that can be earned by conducting a detailed process-based lifecycle assessment (ISO-LCA) or hybrid economic input-output lifecycle assessment (Hybrid-EIO) for the final roadway design alternative. However, later in 2013, it was modified to one or two points available, where one point will be awarded for projects that complete an extended lifecycle inventory (LCI) representing the entire project, and one additional point for projects that complete a lifecycle impact analysis (LCIA) using the extended LCI data. Moreover, LCA Certified Professional (LCACP) must be involved in the project (Greenroads Foundation, 2013).

A lifecycle is defined as "consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal or end-of life" (International Standards Organization, 2006). Generally, a LCA has four steps, including (1) goal definition and scoping, (2) life cycle inventory, (3) life cycle impact assessment, and (4) life cycle interpretation. Among these four steps, LCI is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity (Scientific Applications International Corporation, 2006). Its result contains a list of the quantities of pollutants released to the environment, and the amount of energy and material consumed. As for LCIA, as the third step of an LCA, it consists of the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI (SAIC, 2006). LCIA provides a more meaningful basis to make comparisons, and its results show the relative differences in potential environmental impacts for each option. For example, it helps to answer the question such as "with 9,000 tons of carbon dioxide and 5,000 tons of methane released from a construction project, which of them could have a greater potential impact?" There are eight impact categories in LCIA, including global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, aquatic toxicity, human health, resource depletion, land use and water use (SAIC, 2006). According to University of Washington and CH2M HILL, Inc. (2011), the applicant is required to show a minimum of three impact categories.

2.2.2. MR-2 Pavement Reuse

As the second VC in the MR category, this credit has one to five points available. Its goal is to reuse existing pavement and structural materials. According to University of Washington and CH2M HILL, Inc. (2011), the material considered in volume calculations can include but are not limited to hot mix asphalt (HMA), Portland cement concrete (PCC), bridge decking, unbound granular base material, stabilized base material, structural foundation, etc. As can be seen in Table 2, at least 50% of the existing materials should be reused with one-point earning for every 10% increment.

Table 2: Point Scale for MR-2 Pavement Reuse

MR-2 Points	**1**	**2**	**3**	**4**	**5**
% Reuse of Existing Pavement Materials or Structural Elements	50	60	70	80	90

"*Reuse*" is defined as a continued use or repurposing of existing materials within the project limits (University of Washington and CH2M HILL, Inc., 2011). Thus, in this category, reused materials are the existing materials that do not leave the project boundary and are reused in the project with either the same or different purpose. Some of the common pavement reuse methods that meet the Greenroads "*Reuse*" definition include surface treatments, overlay, hot in-place recycling (HIR), cold in-place recycling (CIR), full-depth reclamation (FDR), crack-and-seat of PCC pavements, and rubblization of PCC pavements (University of Washington and CH2M HILL, Inc., 2011). Among these methods, typical FDR depths are six to nine inches. It involves pulverizing the full existing pavement structure and a portion of the underlying subgrade and combining the resultant material with water or a stabilizing agent to form a uniform stabilized base course (ARRA, n.d.).

2.2.3. MR-3 Earthwork Balance

The goal of this credit is to reduce need for transport of earthen materials by balancing cut and fill quantities. One point can be earned by minimizing earthwork cut (excavation) and fill (embankment) volumes such that the percent difference between cut and fill is less than or equal to 10% of the average total volume of material moved (University of Washington and CH2M HILL, Inc., 2011). The calculation of the percent difference between cut and fill is shown below.

$$\frac{(A+C)-(B+D)}{\frac{1}{2}(A+B+C+D)}\times 100\% \leq 10\% \qquad (1)$$

Where

A is the volume of cross section cut.

B is the volume of cross section fill.

C is the volume of miscellaneous cut.

D is the volume of miscellaneous fill.

Miscellaneous cut and fill include channel change, outlet ditch, unstable material, salvage material, entrances, intersecting roads, muck excavation and so on (South Dakota Department of Transportation, n.d.) "Soil banking", a practice that unused cut or imported fill materials that serve no purpose on one project may be used in other projects at some time later, often on different nearby sites, helps to avoid import of new materials and therefore qualifies for one point (University of Washington and CH2M HILL, Inc., 2011).

Ideally, a balanced earthwork project is one that matches cut and fill volumes and therefore does not require cut export or fill import (University of Washington and CH2M HILL, Inc., 2011). For rural projects, earthwork balancing can be accomplished by choosing the appropriate roadway profile so that cut volumes are roughly equal to fill volumes. For urban projects, it may be difficult since these projects are often constrained by right-of-way or required to match existing elevations. Besides, one of the most common difficulties to balanced earthwork is that in-situ materials are unsuitable to be used as fill or foundation for structures or pavements. Instead of removing and replacing them with suitable fill, which will result in unbalanced earthwork, these unsuitable materials may be treated with the soil stabilization technique. According to the Department of the Army, the Navy, and the Air Force (1994), three soil-stabilization additives, including Portland cement, lime and asphalt emulsions, can be mixed with the unsuitable materials.

2.2.4. MR-4 Recycled Materials

The goal of this credit is to reduce lifecycle impacts from extraction and production of virgin materials. According to Greenroads Foundation (2015), four options are provided to calculate the fraction of recycled materials being used: (1) consider only the binder materials, and structural and steel reinforcing materials, (2) consider only the HMA and PCC pavement materials, and steel materials, (3) consider all materials including granular base layers, structural fill, and soil improvements, and (4) consider all project materials. As can be seen in Table 3 below, points are awarded based on the option selected and the average recycled content (ARC) (University of Washington and CH2M HILL, Inc., 2011).

Table 3: Point Scale for MR-4 Recycled Materials

MR-4 Points	**1**	**2**	**3**	**4**	**5**
ARC for Option 1 and 2	10	20	30	40	50
ARC for Option 3 and 4	20	30	40	50	60

$$ARC(\%) = \frac{\sum r_n}{\sum W_n} \times 100\% \qquad (2)$$

Where

r_n is the total weight of recycled materials for that individual material or assembly.

W_n is the total weight of each individual material or assembly.

n represents the number of materials used in the pavement section.

Recycling, according to University of Washington and CH2M HILL, Inc. (2011), is a method to reduce the required raw materials by recovering, processing, and repurposing waste materials as a substitute for raw materials. Different from the reused materials, the recycled materials are the materials being transported outside the boundary of the project, treated with recycling agents or chemical admixtures, and then reused in the construction process. This kind of material can be used in granular base, in HMA as asphalt binder and aggregate, and in PCC as cementitious material and aggregate. Typical recycled materials include coal fly ash, ground granulated blast furnace slag (GGBFS), reclaimed asphalt pavement (RAP), silica fume and so on. Of those, coal fly ash is a finely-divided residue generated in coal-fired power plants. It has the similar particle size distribution as Portland cement, and provides good workability, reduced permeability, increased long-term strength, and many other benefits. Thus, coal fly ash is often used to as a partial replacement for Portland cement in concrete production. The optimum amount of fly ash varies with the application, composition and proportions of all the materials, and so forth (Thomas, 2007). In pavement use, typically fly ash replacement is limited to 15-25% of the cementitious material by specification (FHWA, n.d.).

2.2.5. MR-5 Regional Materials

In this credit, Greenroads encourages the use of locally sourced materials to reduce impacts from transportation emissions, reduce fuel costs, and support local economies (University of Washington and CH2M HILL, Inc., 2011). In Table 4, two options are provided with one to five points available for this credit. First, the project team has to choose local materials and product suppliers. If this option is selected, the percentage of the total cost that has been paid to material suppliers, processors, distributors, and producers within a fifty-mile radius of the geographic center of the project has to be at least 60%, followed by 75, 84, 90, and 95%.

Table 4: Point Scale for MR-5 Regional Materials

MR-5 Points	1	2	3	4	5
Option 1: % of Total Cost	60	75	84	90	95
Option 2: Maximum Fronthaul Distance (miles)	500	337.5	225	150	100

Second, according to University of Washington and CH2M HILL, Inc. (2011), the project team can also break each material, component or product into the basic materials, and calculate the cumulative fronthaul distance for each basic material from the point of origin to the location of the project and then show that 95% of these basic materials have traveled less than the cumulative distance specified in Table 4 above.

"*Fronthaul*" described by University of Washington and CH2M HILL, Inc. (2011) is the traveling from the origin of the basic material and any of the places it has traveled on its way to the final destination in the project. By contract, "*Backfaul*" is the process that materials are taken away from the site, or sometimes an empty truck returns to its point of origin for another load (University of Washington and CH2M HILL, Inc., 2011). The latter does not need to be considered for purposes of this credit. As for the basic material, its definition described by University of Washington and CH2M HILL, Inc. (2011) is that it cannot be taken apart without changing the chemical composition of the material component itself, including binders, aggregate, base and subbase materials, metal, finished plastic and wood or whole components assembled with these materials (University of Washington and CH2M HILL, Inc., 2011).

2.2.6. MR-6 Energy Efficiency

The goal of the last credit in the MR category is to reduce lifetime energy consumption of lighting systems for roadways. In order to earn points from this credit, the applicant needs to install lighting systems with luminaries that meet or exceed the 2009 Energy Star standard for roadway lighting (ENERGY STAR[1], 2009). Points are

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[1] ENERGY STAR is a U.S. EPA voluntary program that helps businesses and individuals save money and protect the climate through superior energy efficiency (EPA, n.d.).

awarded based on the fraction of total luminaries installed on the project with energy efficient fixtures that are 2009 ENERGY STAR compliant, as can be seen in Table 5.

Table 5: Point Scale for MR-6 Energy Efficiency

MR-6 Points	**1**	**2**	**3**	**4**	**5**
% of 2009 ENERGY STAR compliant luminaries	20	40	60	80	100

After construction is completed, the direct electricity consumption of all roadways can be primarily attributed to roadway lighting systems (University of Washington and CH2M HILL, Inc., 2011). Much progress has been made in lighting technologies to provide feasible alternatives to traditional methods that can provide comparable performance with significantly reduced energy use. Solid-state lighting, which uses light emitting diodes (LED), can replace typical sodium, such as high pressure sodium (HPS), or mercury luminaries to meet lighting needs. The benefits of LED include energy savings, longer service life, which reduces the need for replacement and maintenance, and thus decreases material waste and pollution. While the most significant barrier to the use of LED roadway lighting is the increased initial capital costs of such systems (University of Washington and CH2M HILL, Inc., 2011), it will be paid back in 1.2 to 6.3 years (Wu et al., 2009) since the costs associated with energy consumption and maintenance frequencies are decreased.

2.2.7. PT-1 Long-Life Pavement

The first pavement sustainable practice in Greenroads has the goal of minimizing lifecycle costs by promoting the design of long-lasting structures (Greenroads Foundation, 2013). Five points can be earned from this credit by meeting two requirements. First, at least 75% of the total new or reconstructed pavement surface area for regularly trafficked lanes needs to be designed for long life, i.e. 40-year initial design life (University of Washington and CH2M HILL, Inc., 2011). Second, the requirements of long-life pavement can be achieved by either using the Long-Life Pavement Design Graph (Figure 1) specified by University of Washington and CH2M HILL, Inc. (2011), or being in accordance with a design procedure that is formally recognized, adopted and documented by the project owner.

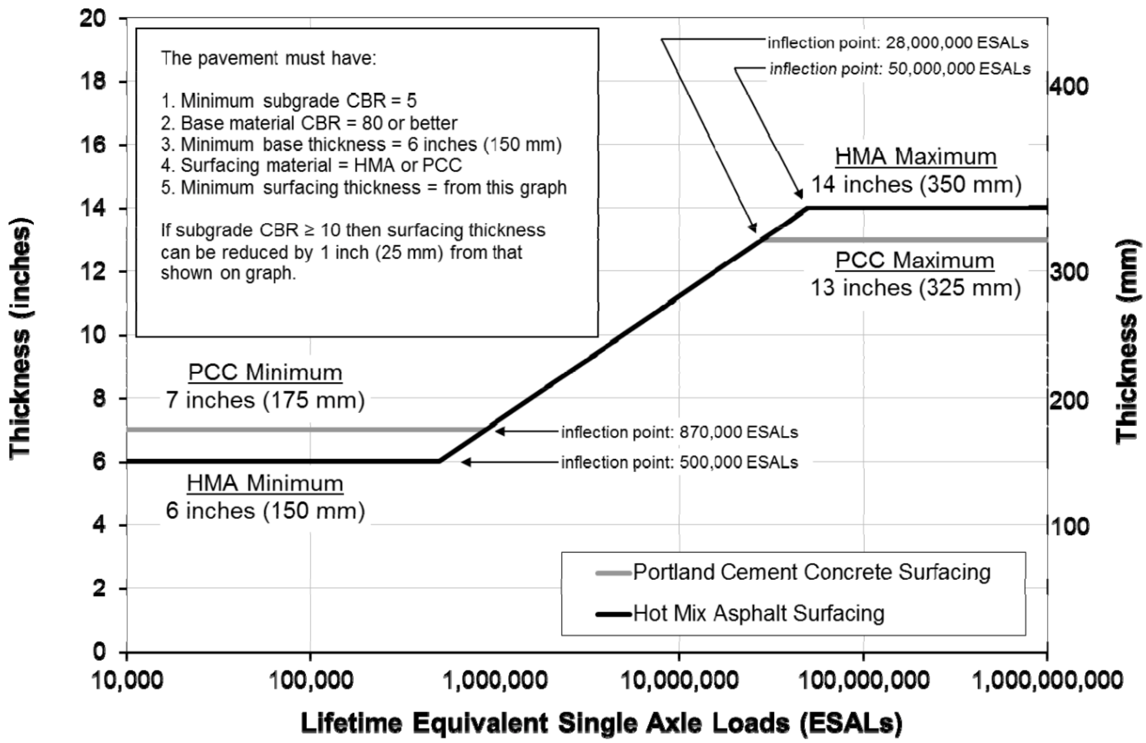


Figure 1: Long-Life Pavement Design Graph

In Figure 1, the x-axis is the lifetime equivalent single axle loads (ESALs), and the y-axis is the minimum surface thickness for a pavement to be considered as long-life. Two lines are used to indicate the minimum surface thickness given the lifetime ESALs, where the grey line is for PCC pavement, and the black line is for HMA pavement. In order to use this figure, the type of surface material, lifetime ESALs, design thickness, base, and subgrade California Bearing Ratio (CBR) need to be prepared. For example, given the lifetime ESALs equal to 100,000 and subgrade CBR equal to 5, the minimum surface thickness for HMA pavement is 6 inches, and that for PCC pavement is 7 inches. Furthermore, if the subgrade CBR is greater than or equal to 10, the minimum surface thickness can be reduced by 1 inch. In the case above, the final minimum thickness for HMA pavement is 5 inches, and that for PCC pavement is 6 inches.

As for the design procedure adopted by the project owner, some of the common methods are recommended by University of Washington and CH2M HILL, Inc. (2011). They include but are not limited to (1) 1993 AASHTO Method, (2) Asphalt Institute Method, and (3) Mechanistic-Empirical Pavement Design Guide (MEPDG). The first method can be found in the 1993 version of the AASHTO Guide for Design of Pavement Structures (1993). The second method can be referred to Asphalt Institute (1981). At last, the third method is described in AASHTO (2008).

2.2.8. PT-2 Permeable Pavement

For this credit, its goal is to reduce the developed footprint due to hardscape areas and promote infiltration where possible (Greenroads Foundation, 2013). If this credit is targeted, the project team needs to compute the total amount of impervious area with Curve Number (CN) of 98 or greater on the project before construction (CN_1) and after construction (CN_2), respectively. CNs are determined according to the ground cover and soil type, and are used to approximate the varying infiltration, interception and storage capacities of different land covers (USDA, 1986). A high CN (such as 98 for impervious pavement) indicates low infiltration and high runoff. Points are awarded for increments of reduced impervious area, or developed footprint reduction (DFR), in increments of 5%. As can be seen in Table 6, DFR is equal to the difference between CN_1 and CN_2 divided by CN_1, and is expressed as the percentage of the preconstruction conditions (Greenroads Foundation, 2013).

Table 6: Point Scale for PT-2 Permeable Pavement

PT-2 Points	**1**	**2**	**3**
DFR	5	10	15

$$DFR(\%) = \frac{CN_1 - CN_2}{CN_1} \times 100\% \quad (3)$$

Where

CN_1 is the total amount of impervious area with CN of 98 or greater on the project before construction.

CN_2 is the total amount of impervious area with CN of 98 or greater on the project after construction.

According to University of Washington and CH2M HILL, Inc. (2011), typical types of permeable pavements include (1) porous asphalt, (2) porous concrete, (3) block pavers, (4) open-graded aggregate, (5) artificial turf, and (6) turf reinforcement. Permeable pavements allow stormwater to either infiltrate into an underground storage basin or exfiltrate to the soil, ultimately recharging the groundwater, and potentially removing pollutants (Brattebo and Booth, 2003). Greenroads not only requests the applicant to reduce the impervious surface area by constructing permeable pavement, but also to maintain its permeability. The maintenance works must be performed in order to promote maximum performance of permeable pavement, such as vacuum the pavement twice per year, maintain planted areas adjacent to pavement, monitor the permeable pavement in the winter, apply organic deicers as necessary, and so on (Pennsylvania Department of Environmental Protection, 2006).

2.2.9. PT-3 Warm Mix Asphalt

With three points available, the goal of this credit is to reduce fossil-fuel use at the hot mix asphalt plant, decrease emissions at the plant, and decrease worker exposure to emissions during placement (University of Washington and CH2M HILL, Inc., 2011). In order to achieve this credit, the project team is required to reduce the mixing temperature of asphalt mixture by at least 50°F and use this reduced temperature mix, or warm mix asphalt (WMA), in at least 50% of the paving area. To be more specific, the mixing temperature should be measured as the temperature of the mixture as it exits the mixing drum or pugmill. In fact, there are many benefits of constructing WMA. Based on a master thesis written by Kristjansdottir (2006), the primary advantages of WMA are reduced energy consumption, reduced emissions and reduced viscosity at working temperatures. The first two aspects are directly related to the sustainability of a pavement structure, while the last one makes the mixture more workable, resulting in better construction quality and indirect sustainable benefits.

Greenroads Foundation (2013) updated this credit by adding two additional requirements that may be met for projects that are non-HMA projects. First, the applicants now can choose to select an ENERGY STAR certified cement production plant for cementitious materials. To be ENERGY STAR certified, the plant must score in the top 25% based on the Environmental Protection Agency (EPA) National Energy Performance Energy Rating System (Greenroads Foundation, 2013). Second, the applicants can also burn recycled oil, waste materials, or other fuel saving technologies in HMA plant or cement production plant to reduce conventional fuel usage by a minimum of 25% (Greenroads Foundation, 2013).

2.2.10. PT-4 Cool Pavement

For this credit, its goal is to reduce contribution to localized increased air temperatures due to pavement reflectance and minimize stormwater runoff temperatures (University of Washington and CH2M HILL, Inc., 2011). Two options are provided with five points available. First, the project team can use a pavement surface with a minimum albedo of 0.3 (light-colored surface area, LSA) for a minimum of 50% of the total project pavement surfacing by area. Albedo is a measure of the reflectivity of a surface and can be expressed as a simple number or percentage figure. The higher the number of the material is, the more energy is reflected back to the source. The second option is to use a porous pavement or pavers (permeable surface area, PSA) for a minimum of 50% of the pavement surfacing by area (University of Washington and CH2M HILL, Inc., 2011).

$$CP(\%) = \frac{LSA + PSA}{A} \times 100\% \qquad (4)$$

Where

CP represents the percent of cool pavement surface area.

LSA is the total light-colored or high albedo surface area.

PSA is the total permeable or porous surface area.

A is the total pavement surface area on the project.

The urban heat island (UHI) effect is "*…a measurable increase in ambient urban air temperatures resulting primarily from the replacement of vegetation with buildings, roads, and other heat-absorbing infrastructure*" (EPA, 2009). Rose et al. (2003) found that pavements make up to 29 to 45% of the total land coverage, and about half the total UHI contributing surface coverage. Pavements are a significant contributor to the UHI temperature increase. Thus, University of Washington and CH2M HILL, Inc. (2011) encourages the use of cool pavements to reduce the absorption of the sun's energy and consequently radiate less heat to the surrounding environment. There are two main types of cool pavement technologies. The first way is to reduce solar reflectance, and the implementation of it includes the use of a more reflective material such as PCC for the pavement surface, a light-colored aggregate (e.g. HMA with limestone), and the change of pavement's surface color (University of Washington and CH2M HILL, Inc., 2011). The other way is to improve pavement cooling. For this method, the implementation includes the construction of porous pavement, and permeable wearing courses (University of Washington and CH2M HILL, Inc., 2011).

2.2.11. PT-5 Quiet Pavement

The goal of this credit is to improve human health by reducing tire-pavement noise (University of Washington and CH2M HILL, Inc., 2011). The implementation of it requires the construction of 75% of the total pavement surface area for regularly trafficked lanes where the speed limit is at least 30 miles per hour with a surface course that produces tire-pavement noise levels at or below a certain level (University of Washington and CH2M HILL, Inc., 2011). The noise measuring method should be the on-board sound intensity (OBSI) method. This test method provides an objective measure of the acoustic power per unit area at points near the tire/pavement interface (AASHTO, 2012). One OBSI measurement should be done for each roadway section, which is pavement surface at least 500 feet long, having the same speed limit, and the surface material over its entire length.

For the facility with the speed limit between 30 and 54 miles per hour, two points are awarded for the OBSI noise level of 91 dBA or lower, and three points are awarded for 88 dBA or lower. For the facility with the speed limit of 55 miles per hour or higher, two points are awarded for the OBSI noise level of 99 dBA or lower, and three points are awarded for 95 dBA or lower. The point scale of PT-5 is summarized in Table 7 below.

Table 7: Point Scale for PT-5 Quiet Pavement

Facility Posted Speed Limit	Test Speed	2 points	3 points
55 mph or more	**60 mph**	99 dBA	95 dBA
30 to 54 mph	**35 mph**	91 dBA	88 dBA
Less than 30 mph	Does not qualify for credit		

University of Washington and CH2M HILL, Inc. (2011) recommends several options for reducing the tire-pavement noise. The first option, which is also the most recognized one, is the use of open-graded mixture of HMA or textured PCC for a pavement surface course. Open-graded refers to a general lack of fine aggregate material in the mixture resulting in interconnected air voids (University of Washington and CH2M HILL, Inc., 2011). Sandberg and Ejsmont (2002) find that these interconnected air voids tend to reduce noise by (1) reducing the generation of noise, and (2) absorbing generated noise in the air void structure of the mixture. For PCC, surface texturing is a technique that makes pavement generate less noise. Four typical types of surface texturing include transverse tining, longitudinal tining, carpet drag, and diamond grinding. Moreover, Rasmussen et al. (2008) indicate that construction technique and details can also influence texturing effects on noise.

2.2.12. PT-6 Pavement Performance Tracking

With one point available, the credit has the goal to allow for more thorough performance tracking by integrating construction quality and pavement performance data

(University of Washington and CH2M HILL, Inc., 2011). This credit can be separated into two parts. The first part of the credit specifies that construction quality measurements must be located within 25 feet of the actual location where the material or process that was measured is located. University of Washington and CH2M HILL, Inc. (2011) indicates that a permanent location system is needed to store and maintain these construction quality records. To be more specific, construction quality measurements include but are not limited to the data from (1) density tests, (2) water/air content tests, (3) slump tests, (4) compressive strength tests, (5) asphalt content tests, and (6) gradation tests (University of Washington and CH2M HILL, Inc., 2011). Namely, the information on material characteristic used in each project must be recorded in electronic form, geotagged at the construction site, and linked to a pavement performance database, which is the second part of this credit.

The second part requires the pavement performance measurements to be stored in the same system. A system that stores pavement performance measurements is usually referred to the pavement management system (PMS). A PMS is a system used to determine the timing of pavement M&R, and to aid in maintenance decision making at a network level. For applicants targeting at this credit, a PMS has to be linked to the construction quality data to meet the requirement. As Greenroads Foundation pointed out in its errata (2013), this credit is often confused with the utilization of PMS. In fact, it requires the use of PMS as well as the tracking of construction quality measurements. Namely, not only the tracking of pavement performance, the project team is also required to conduct a thorough tracking on material character quality.

The completion of this credit would improve pavement performance through a better understanding of how construction quality influences long-term pavement performance and allow existing data to be better used to evaluate the performance of new materials, concepts, and design methods (University of Washington and CH2M HILL, Inc., 2011).

2.3. TxDOT Site Manager Database and Pavement Projects

In this study, a construction item database maintained by TxDOT was explored for the purpose of understanding the state of the practice in pavement industries in Texas. The database is called Site Manager (SM), which contains project locations, completion years, project items, their descriptions and quantities. It also includes asphalt mixture properties such as air voids, binder content, gradation and other material information (Buddhavarapu et al., 2014). 1,594 pavement construction and maintenance projects were extracted from the SM database to study Texas roadway sustainability and to propose a Texas version of sustainability rating system. In the following section, a brief description of SM is provided along with an overall summary of the extracted projects.

2.3.1. Site Manager

The Site Manager (SM) database consists of several tables serving different purposes. Three tables were explored in the study, including ITM, DT, and DISTRICT. Table 8 below provides a description of the extracted fields in these tables.

The ITM table stores the construction item information of all of the TxDOT projects. Each project is separated into several items, depending on the plan and budget of the project. Namely, each row in the SM database indicates one specific item, which is encoded with an eight-digit number (ITM_CD) where the first four digits correspond to the TxDOT Standard Specification for Construction and Maintenance of Highways, Streets and Bridges (2014). ITM_DESC provides a brief description of the item. Each project has its unique combination of control section job number (CONT_ID) and project number (PRJ_NBR). CONT_ID is given to an individual contract whereas PRJ_NBR indicates the corresponding project (Buddhavarapu et al., 2014). Therefore, a unique CONT_ID may be associated with several PRJ_NBR (one contract consists of several different projects).

TxDOT uses the SM database to keep track of all change orders of its projects. LN_ITM_NBR is the field that stores the sequence of the items in an increasing order. For example, if one project has two items with identical names but different quantities, then the one with larger LN_ITM_NBR is added to the database later and thus is actually being placed or constructed in the project. The quantity of the item is stored in three fields, including BID_QTY, PRJ_QTY and FNL_QTY. As their names imply, BID_QTY stands for the bidding quantity of the item whereas PRJ_QTY is the planning quantity of the item and FNL_QTY reports the final quantity of the item that is actually placed. In this study, FNL_QTY is used to check the usage of the item and its actual quantity. As for the unit and the price of the item, they are recorded in the UNT_T and BID_PRICE fields. At last, DIST_NUM is represented by an integer between 1 and 25, indicating the district where project is located.

Second, in the DT table, each row records the project status change and its date. An individual contract (CONT_ID) might include several rows, indicating the history of the status changes. CRIT_DT_T stores twenty-one types of status of a project, where ACPT is used to indicate the acceptance of a project. At last, LAST_MODFD_DT indicates the date of the status change. Thus, in the study, the ITM table and the DT table are linked via the CONT_ID field, and the ACPT date of the contract is used to indicate the completion date of the projects in the ITM table.

Third, the DISTRICT table, similar to the DT table, contains the district number and the corresponding district name. As can be seen in Table 9 below, DIST_NUM stores an integer between 1 and 25, and DIST_NAME indicates the corresponding district name. For example, the district number of Austin is 14, and Houston is 12.

Table 8: Site Manager database

Table	Field name	Format	Description
ITM	**CONT_ID**	TEXT	Control section job number
	PRJ_NBR	TEXT	Project number
	ITM_CD	INT	Item code in TxDOT specification
	LN_ITM_NBR	INT	Line item number
	ITM_DESC	TEXT	Item description
	BID_QTY	FLOAT	Bidding quantity
	PRJ_QTY	FLOAT	Project planning quantity
	FNL_QTY	FLOAT	Final quantity
	UNT_T	TEXT	Quantity unit
	BID_PRICE	FLOAT	Bidding price
	DIST_NUM	INT	District number
DT	**CONT_ID**	TEXT	Control section job number
	CRIT_DT_T	TEXT	Project status change
	LAST_MODFD_DT	TEXT	Status change date
DISTRICT	**DIST_NUM**	INT	District number
	DIST_NAME	TEXT	District name

Table 9: Site Manager – DT table

DIST_NUM	DIST_NAME	DIST_NUM	DIST_NAME
1	Paris	**14**	Austin
2	Fort Worth	**15**	San Antonio
3	Wichita Falls	**16**	Corpus Christi
4	Amarillo	**17**	Bryan
5	Lubbock	**18**	Dallas
6	Odessa	**19**	Atlanta
7	San Angelo	**20**	Beaumont
8	Abilene	**21**	Pharr
9	Waco	**22**	Laredo
10	Tyler	**23**	Brownwood
11	Lufkin	**24**	El Paso
12	Houston	**25**	Childress
13	Yoakum		

2.3.2. Pavement Projects in Site Manager

In this study, 1,594 pavement construction and maintenance projects were extracted from the SM database. The type of the project is determined based on the items included in it. Based on the TxDOT Standard Specification for Construction and Maintenance of Highways, Streets and Bridges (2014), Table 10 below shows the item codes that were used to classify the projects. As can be seen, the projects are classified into four classes, including flexible pavement project, rigid pavement project, earthwork project and roadway luminary project. Among them, earthwork project and roadway luminary project are actually further separated on the basis of flexible/rigid pavement classification. Namely, all of these 1,594 projects involve pavement construction work; if a project further includes earthwork or roadway luminary item, it will be extracted for other analyses. As for Special Specifications, TxDOT uses them to provide regulations and instructions on new materials or technologies that have not been updated to the standard specification, such as LED projects. Therefore, some items belonging to the special specifications were also extracted from the SM database.

Table 10: Project Classification

Item code	Item description	Classification
0340	Dense-graded hot mix asphalt (small quantity)	Flexible pavement
0341	Dense-graded hot mix asphalt	
0342	Permeable friction course	
0344	Superpave mixtures	
0346	Stone-matrix asphalt	
0347	Thin overlay mixtures	
0348	Thin bonded friction courses	
0350	Microsurfacing	
0360	Concrete pavement	Rigid pavement
0110	Excavation	Earthwork
0132	Embankment	
0610	Roadway illumination assembly	Roadway luminary
0614	High mass illumination assembly	
Special Specification	TxDOT uses the special specification to regulate new materials or technologies that have not been included in the standard specification.	According to the item description

Among the 1,594 projects, 1,292 are flexible pavement projects, and 517 are rigid pavement projects. There is a small overlap, since some projects might involve flexible pavement items and rigid pavement items. Figure 2 shows that the number of flexible pavement projects has a significant increase between 2005 and 2009, while the number of rigid pavement projects shows a relatively steady trend.

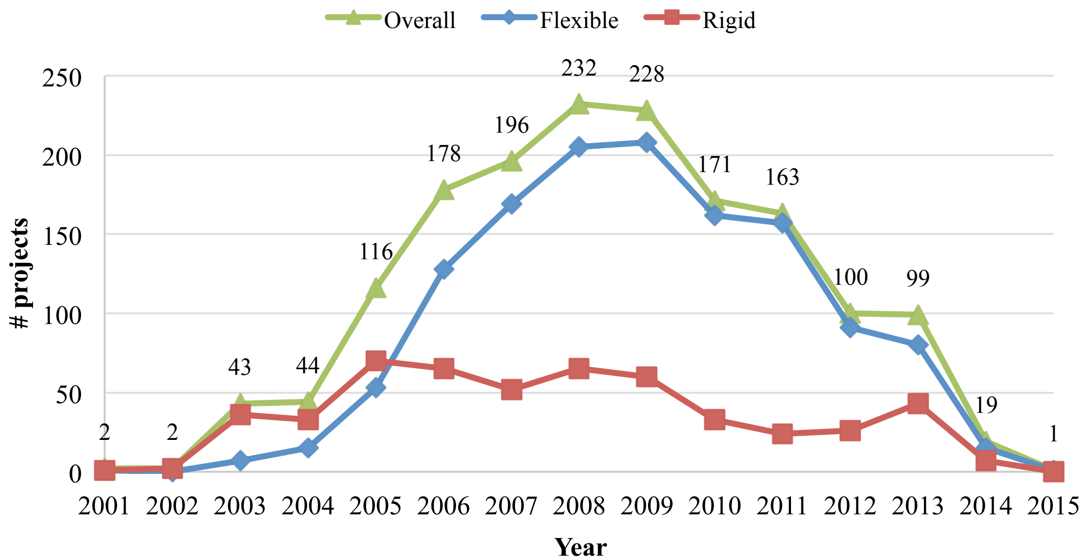


Figure 2: TxDOT pavement projects between 2001 and 2015

Figure 3 below shows the distribution of these projects per district. The twenty-five districts in Texas are divided into four regions, according to Figure 4 (TxDOT, n.d.). In general, most of the projects are located in the central and east Texas, where Austin has the most projects, followed by Fort Worth, Beaumont, and Tyler.

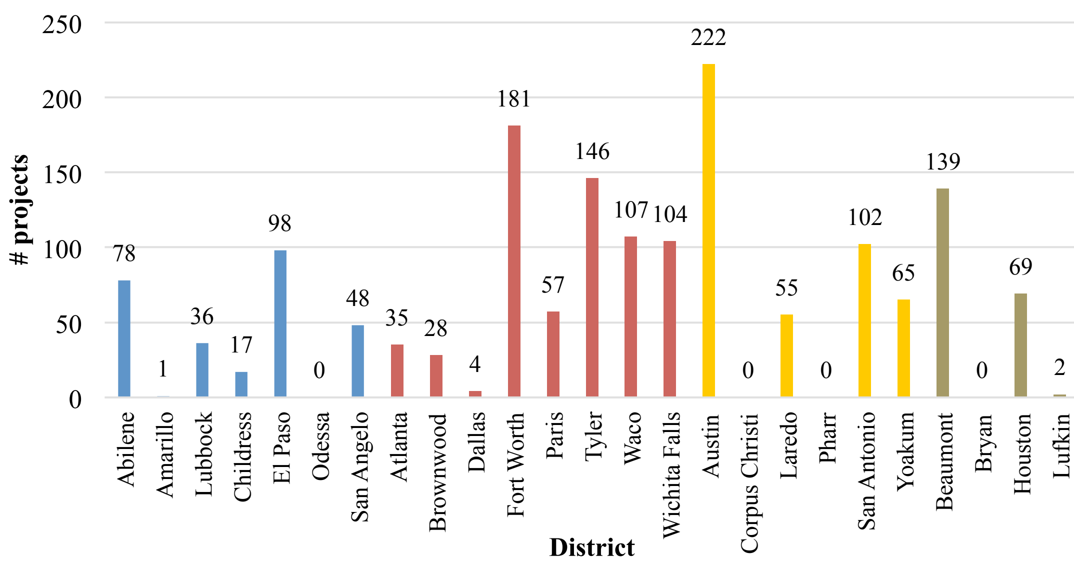


Figure 3: TxDOT pavement projects in different districts

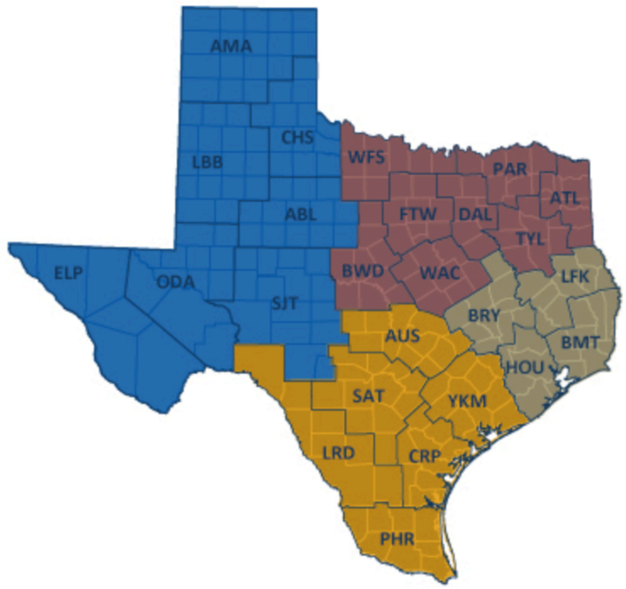


Figure 4: TxDOT district map

Figure 5 shows the distribution of these projects based on the TxDOT highway system. Among 1,594 projects, 1,014 of them are located on interstate highways, state highways and US highways.

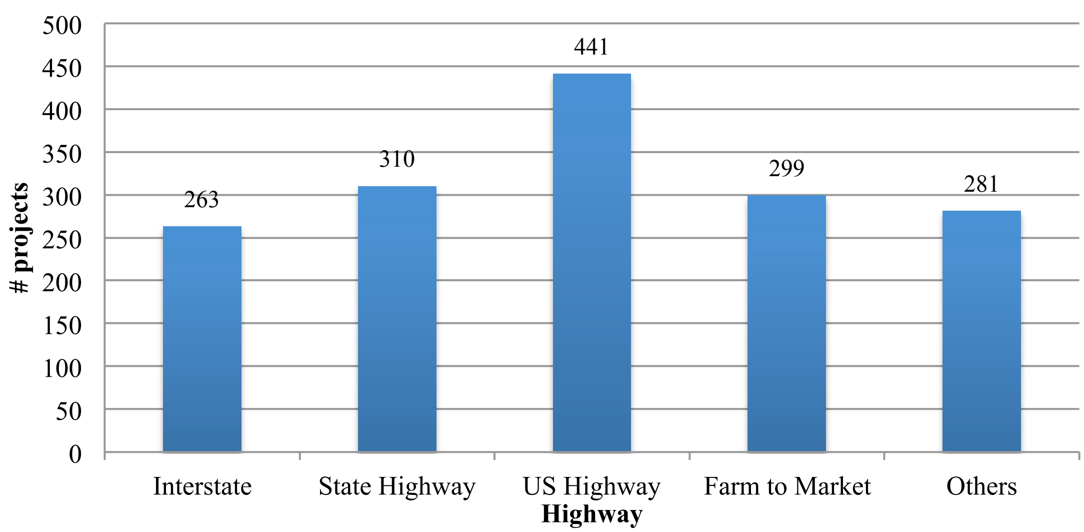


Figure 5: TxDOT pavement projects on different highways

CHAPTER 3: CASE STUDY

Two Greenroads projects were selected as case studies to explore the state-of-practise of roadway sustainability in Texas. The first one is the Bagby Street Reconstruction project located in Houston. This project was awarded the Greenroads Silver certification, being the project earning the most points among all of the projects certified by Greenroads at the time of the study. Moreover, as the first Greenroads certified project in Texas, the Bagby Street Reconstruction project is featured by its emphasis on people-focused development, the improvement in pedestrian/bicycle accessibility, the use of fly ash concrete as well as the decrease in surface temperature (Walter P. Moore, 2013).

The second one is the Todd Lane Improvements project located in Austin. The project is part of the Imagine Austin, an initiative that engages the Austin community to emphasize sustainability, livability and interconnectivity in one of the fastest growing cities in the United States. Together with seven other priority programs, the Green Infrastructure program seeks to manage Austin's urban and ecosystems in a sustainable and coordinated manner, commencing the Todd Lane Improvements Project as well as the pursuit of Greenroads certification (City of Austin, 2012).

3.1. PROJECT DESCRIPTION

3.1.1. Bagby Street Reconstruction Project

As can be seen in Figure 6, Bagby Street is a one-way major collector located in downtown Houston with the existing asphalt surface in poor condition before the project began. The project is about 0.62 miles long, and its purpose was to replace the existing structure with jointed concrete pavement and to accommodate the growing needs of pedestrian and bicycle. The sustainable practices featured by the project include the installation of rain gardens, the emphasis on people-focused development, the improvement in pedestrian and bicycle accessibility, the use of fly ash concrete as well as the decrease in surface temperature.

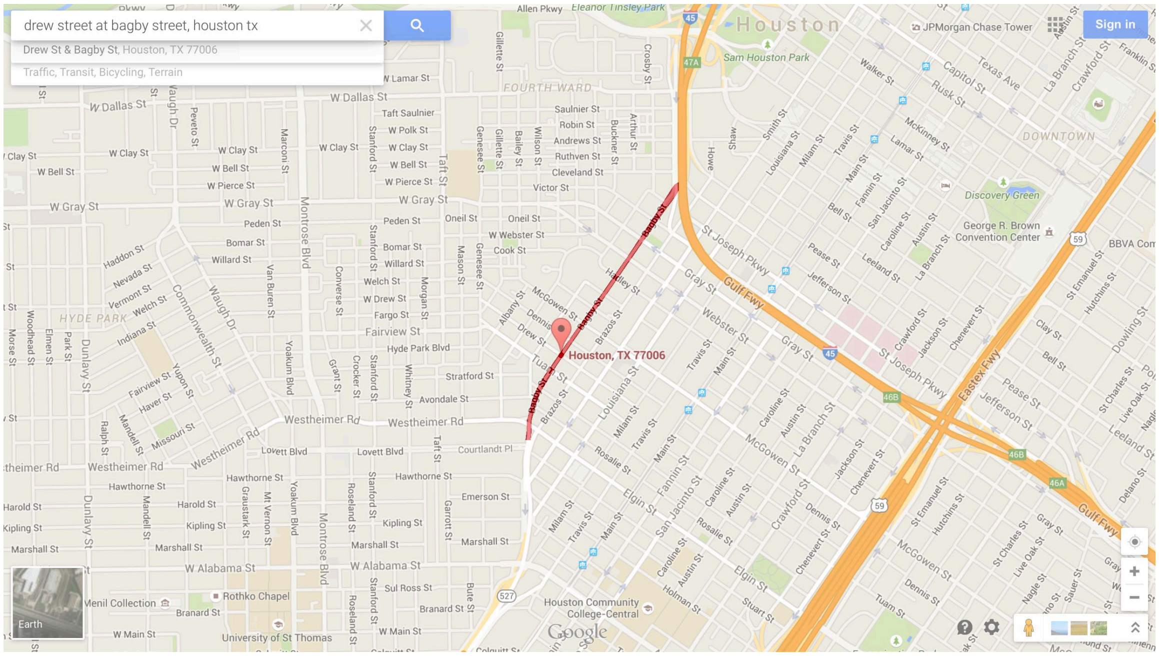


Figure 6: Map of Bagby Street in Houston, Texas

The project started in July 2011 and was completed in June 2013. The project team earned eleven PRs and forty-five points distributed in five different voluntary credits. Table 11 shows the results of MR and PT categories. It can be seen that out of 23 points available in the MR category, 10 points are achieved and distributed in the following credits: MR-3, MR-4, MR-5, and MR-6. The second part of Table 11 shows that in the PT category, 10 points were earned with a total of 20 points available. These points are distributed in 2 credits: PT-1, and PT-4. During the time of the study, the author visited the design consultant of the project, Walter P Moore, and had a conversation with three of their engineers. The summary below is based the information provided by Walter P Moore as well as the author's interpretation.

Table 11: Bagby Street Reconstruction Project – MR and PT categories

Materials and Resources	Points Available	Result
MR-1, Lifecycle Assessment	2	0
MR-2, Pavement Reuse	1 – 5	0
MR-3, Earthwork Balance	1	1
MR-4, Recycled Materials	1 – 5	2
MR-5, Regional Materials	1 – 5	4
MR-6, Energy Efficiency	1 – 5	3
Subtotal	23	10
Pavement Technologies	**Points Available**	**Result**
PT-1, Long-Life Pavement	5	5
PT-2, Permeable Pavement	3	0
PT-3, Warm Mix Asphalt	3	0
PT-4, Cool Pavement	5	5
PT-5, Quiet Pavement	2 – 3	0
PT-6, Pavement Performance Tracking	1	0
Subtotal	20	10

3.1.2. Todd Lane Improvements Project

Originally, Todd Lane was a two-lane undivided arterial located in South Austin. Figure 7 shows the location of Todd Lane in Google Map. According to the geotechnical report included in the Project Manual (Zhang, 2013), the existing pavement thickness differs in each lane of travel. In the northbound lanes, the asphalt thickness ranges from 6.5 inches to 7.5 inches, and the underlying base thickness ranges from 6 to 16 inches. In the southbound lanes, the asphalt thickness ranges from 14.5 to 17.0 inches, and the base course with a thickness ranging from 0 to 2.5 inches is found. Below the base layer is the fill material with depths of 2.3 feet to 2.8 feet followed by the fat clay with depths of 4 to

6 feet. The fat clay encountered under Todd Lane is a highly expansive material with liquid limits ranging from 59% to 80% and plastic indexes (P.I.) ranging from 39 to 56.

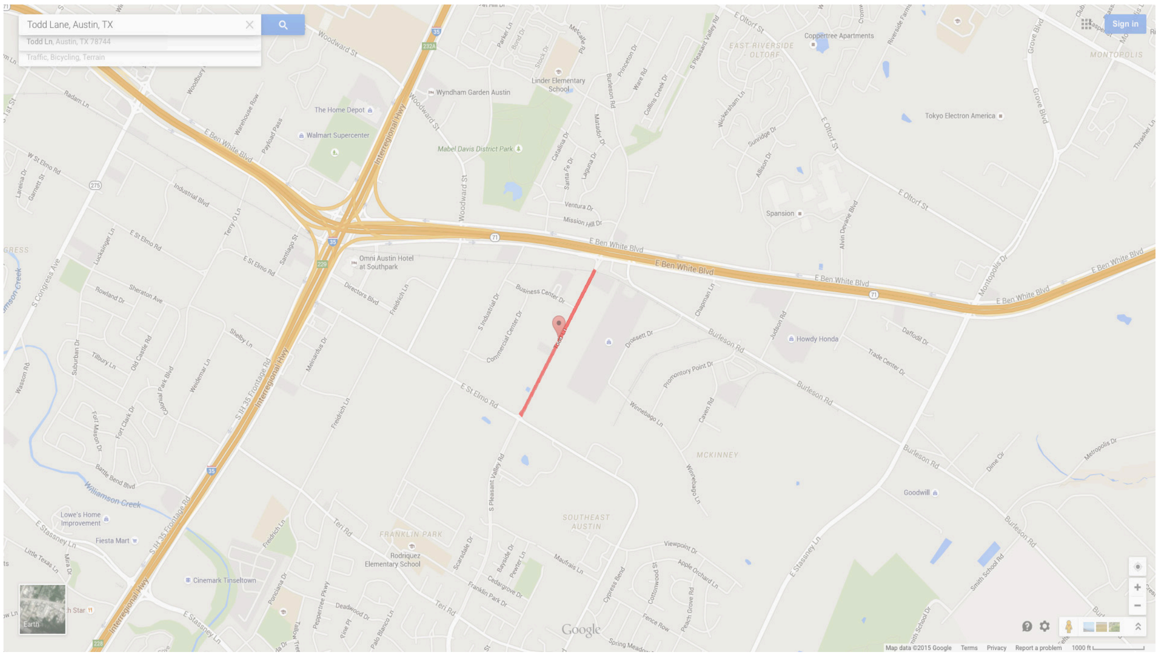


Figure 7: Map of Todd Lane in Austin, Texas

The project began in April 2014 with the expected completion time of October 2015. It includes the reconstruction and widening of the existing roadway. Based on that, the proposed geometric design is a three-lane undivided hot mix asphalt concrete (HMAC) pavement with a turning lane in the middle of the roadway, two bike lanes, and two sidewalks along the road. The main purpose is to increase multimodal capacity due to the growth of its neighboring communities, and a newly planned corridor connecting Todd Lane with the southern area.

According to the 2014 Pilot Project Assessment of Todd Lane Improvements (Greenroads Foundation, 2014), the project team demonstrated the intent to meet six of eleven PRs and thirteen VCs, totaling thirty-two points. The estimated result is a potential Bronze certification. As can be seen in Table 12, the project team has the potential to earn fourteen points in MR, including MR-2, MR-4, MR-5, and MR-6. In terms of PT, eight points can be earned, including PT-1, and PT-3.

Table 12: Todd Lane Improvements Project – MR and PT categories

Materials and Resources	Points Available	Possible Result
MR-1, Lifecycle Assessment	2	0
MR-2, Pavement Reuse	1 – 5	2
MR-3, Earthwork Balance	1	0
MR-4, Recycled Materials	1 – 5	2
MR-5, Regional Materials	1 – 5	5
MR-6, Energy Efficiency	1 – 5	5
Subtotal	23	14
Pavement Technologies	**Points Available**	**Possible Result**
PT-1, Long-Life Pavement	5	5
PT-2, Permeable Pavement	5	0
PT-3, Warm Mix Asphalt	3	3
PT-4, Cool Pavement	5	0
PT-5, Quiet Pavement	2 – 3	0
PT-6, Pavement Performance Tracking	1	0
Subtotal	20	8

In order to be familiar with the Greenroads application process and to have a deep understanding about the project, the author started the study by working with the project team in the City of Austin. The results regarding MR and PT categories are presented in the following section with a summary of the trend of roadway sustainability in Texas.

3.2. PROJECT EVALUATION RESULT

3.2.1. Lifecycle Assessment

Bagby Street Reconstruction: according to the conversation between the author and the engineers in Walter P Moore, the application of Greenroads certification was not initiated in the beginning of the project, causing some of the credits missed due to the limitations of budget and time. MR-1 was one of these credits that were not achieved by the project team. Moreover, based on Greenroads' feedback on the project, this credit would be critical and hard to achieve for a project under $10 million, since it requires an outside consultant, including LCACPs, to complete the task (University of Washington and CH2M HILL, Inc., 2014). Thus, because of the budget constraint as well as the timing of the application, MR-1 was not attempted in this project.

Todd Lane Improvements: the project cost estimated by the project team in the City of Austin (Zhang, 2013) is about $7.8 million, which is also under $10 million. Besides, according to the Pilot Project report prepared by the Greenroads Foundation (2014), the similar feedback was provided stating that MR-1 would be unusual for projects under $10 million, since it requires outside consultants to complete the analysis and to access to specific project data. Due to the budget limit, the project team tends not to pursue this credit. Thus, no points are expected from MR-1.

3.2.2. MR-2 Pavement Reuse

Bagby Street Reconstruction: for this credit, according to the engineers in Walter P Moore, since the concrete pavement was used to replace the existing asphalt surface, it would be unusual to reuse the asphalt material in the new design. However, there is a chance for RAP to be reused as the base material with some appropriate treatments, if planned beforehand (refer to Section 3.3 for further discussion).

Todd Lane Improvements: according to the project design plan (Appendix A.1) as well as the calculation sheet provided by the City of Austin (Figure 8), the existing pavement structure is planned to be removed up to a depth of 36 inches, treated with lime and cement, and constructed as the new base course. From Figure 8, the total volume of existing pavement is about 17,024 cubic yard, and 14,626 cubic yard of it will be reused in the base layer, resulting in a reuse percentage of 86%. Thus, based on the requirement specified in MR-2, 4 points are expected from this credit.

City of Austin
PUBLIC WORKS DEPARTMENT
Project Management Division & Engineering Services Division
505 Barton Springs Road, Suite 900, Austin, TX 78704

Memorandum

To: Jaralee Anderson Ph.D, P.E, LEED-AP–Executive Director Greenroads Foundation Inc.

From: Clay Harris, PMP – City of Austin Project Manager

Date: April 10, 2015

Project: Todd Lane Improvements from Ben White to St. Elmo (6755.002)

Subject: Greenroads application (14USTX001) – Pavement Reuse (MR-2)

Please be advised that the project is estimated to reuse a minimum of 86% of existing pavement materials by estimated volume or weight.

The calculations are as follows;

Total volume of existing pavement:

48 ft (width) x 3 ft (avg depth) x 3192 ft (length) => 459,648 cf x 1 cy / 27 cf => 17,024 cy

Reused volume of existing pavement:

55 ft (width) x 2.79 ft (avg depth) x 3192 ft (length) => 394,902 cf x 1 cy / 27 cf => 14, 626 cy

Percentage of existing pavement reused;

14,626 cy / 17,024 cy = 0.859 => 86% reuse

If you need additional information please contact me at (512)-974-7895.

Best Regards,

Clay Harris, PMP
Project Manager – Public Works Department

The City of Austin is committed to compliance with the Americans with Disabilities Act.
Reasonable modifications and equal access to communications will be provided upon request.

Figure 8: Volume of Reused Pavement in the Todd Lane Improvements Project

3.2.3. MR-3 Earthwork Balance

Bagby Street Reconstruction: as for MR-3, no information or data were available. However, according to the Final Review Results (Greenroads Foundation, 2013), the percent difference between cut and fill is less than 10%. Therefore, one point was earned from this credit.

Todd Lane Improvements: according to the discussion with the project team, MR-3 was not targeted. Since it was not planned at the beginning of the project, pursuing this credit would induce additional significant expense. Besides, the bid table in the Project Manual shows that some materials will be imported via three hauling companies (Zhang, 2013). The table also indicates that the percent difference between cut and fill is unlikely smaller than 10%. Thus, no points are expected from MR-3.

3.2.4. MR-4 Recycled Materials

Bagby Street Reconstruction: based on the document provided by Walter P. Moore, 25% of the cement by weight was replaced with fly ash. As can be seen in Figure 9, the total approximate volume of the pavement structure was 5,594 cubic yard, including a 5,197 cubic yard of 10-inch concrete pavement used for the traffic lanes and a 397 cubic yard of 7-inch pavement for the parking area. Additionally, the amount of cement used in a standard design is 517 pounds per cubic yard of pavement structure, resulting in a total of 1,446 tons of cement. For the mix design with fly ash replacement, the amount of cement proposed by Walter P Moore is 386 pounds and that of the fly ash is 131 pounds per cubic yard of pavement structure, resulting in 1,085 tons of cement and 362 tons of fly ash, respectively. Namely, 362 tons of cement were replaced by fly ash, which is equivalent to 25% of reduction in cement. Therefore, the first option "consider only the binder materials, and structural and steel reinforcing materials" was met, resulting in two points.

Calculations by: J. Camilo Daza, PE 14-Mar-12

WALTER P MOORE

From the American Scientific Website "Cement, which is mostly commonly composed of calcium silicates, requires heating limestone and other ingredients to 2,640 degrees F (1,450 degrees C) by burning fossil fuels and is the third largest source of greenhouse gas pollution in the U.S., according to the U.S. Environmental Protection Agency. Making one ton of cement results in the emission of roughly one ton of CO2—and in some cases much more."

Reducing the amount of cement in concrete reduces the amount of CO2 produced.

Quantity of 10" Pavement	18709	SY	=	5197	CY
Quantity of 7" Pavement	2041	SY	=	397	CY

Pre the contractor's submittal 25% of the cement is replaced with fly ash

Weight per yard

Weight of cement in a standard mix =	517	lbs
Weight of cement in Bagby mix =	386	lbs
Weight of fly ash in Bagby mix =	131	lbs
Total weight of 1 CY of concrete =	3931	lbs

Total weight of cement for project w/o fly ash replacement =	1446	Tons
Total weight of cement in project w/ fly ash replacement =	1085	Tons
Reduction in cement by fly ash replacement =	362	Tons

Since the production of 1 ton of cement results in the production of 1 ton of CO2, the project results in the reduction of approximately 363 Tons of CO2.

From the US EPA website, the average passenger car emits 691 lbs (0.35 tons) of CO2 per month

The replacement of 25% of the cement with fly ash is the equivalent of removing 1034 passenger cars off the road for one month!

Figure 9: Calculations of Recycled Materials Used in the Bagby Street Reconstruction Project

Todd Lane Improvements: the City of Austin Project Manual Volume I (2013) specifies that the use of RAP will not be permitted in the surface course. For the base course, RAP is allowed but the amount should not be more than 20%. Therefore, when targeting the third option “consider all materials including granular base layers, structural fill, and soil improvements” in MR-4, the project team has the potential to earn one point from this credit. However, the project team indicated that the use of RAP is not considered in the design phase. Thus, no point can be earned from this credit.

3.2.5. MR-5 Regional Materials

Bagby Street Reconstruction: Walter P Moore provided the map of material suppliers, as shown in Figure 10. In the figure, 22 material suppliers, indicated by the red markers, were within the 50-mile radius of the geographic center of the project, indicated by the green arrow. The engineers in Walter P Moore indicated that they targeted on the first option "choose local materials and product suppliers". While the detailed calculation is not available, the map provides the only evidence showing that most of the suppliers are within the radius. Thus, four points were awarded to the project.

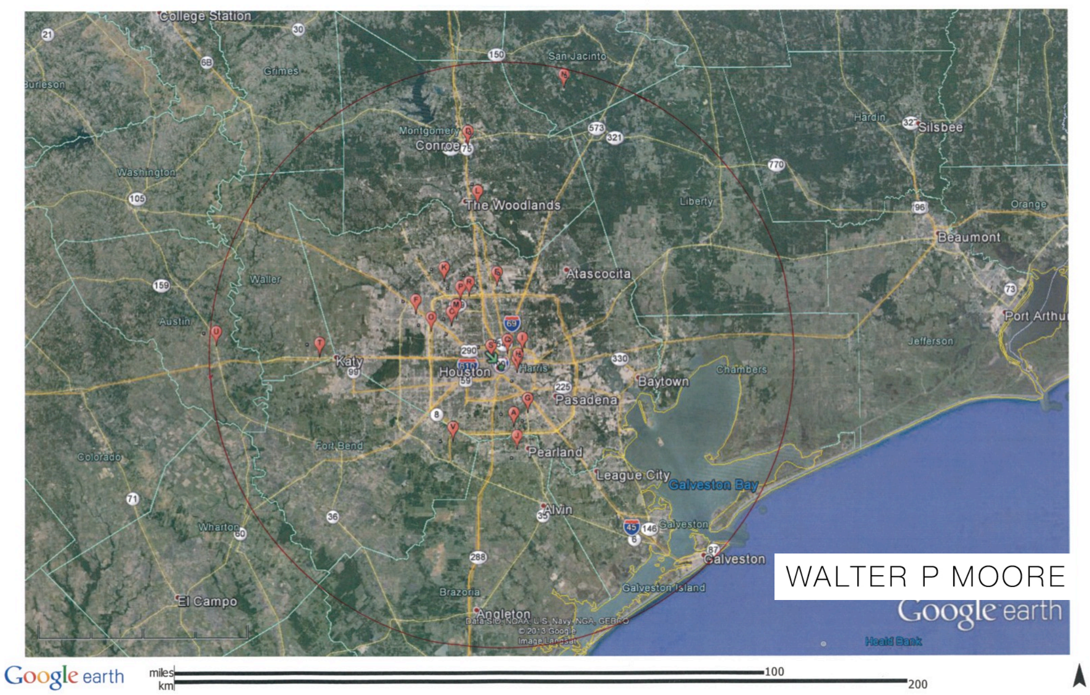


Figure 10: Map of Material Suppliers in the Bagby Street Reconstruction Project

Todd Lane Improvements: Based on the information provided by the City of Austin, the first option was selected. Table 13 shows the list of the material suppliers with a distribution map presented in Figure 11. Among these suppliers, only three of them are not within the 50-mile radius. As a result, most of the suppliers can be defined as the local suppliers with 97.9% of the material cost spent on them. Thus, five points are expected from this credit.

Table 13: Calculation of the Percentage of Local Material Suppliers

Supplier	Material	Cost	Percentage	Distance to Project
Chasco	Pond, Asphalt Concrete, Inlet, etc.	$799,266	15.89%	23.71
Avery Lee Williamson	Landscape	$203,900	4.05%	25.4
Panther Creek Transportation, Inc.	Hauling	$62,500	1.24%	39.76
Texas Trucking Company, Inc.	Hauling	$62,500	1.24%	35.62
PEK, Inc. – Serviceline Transport	Hauling	$52,000	1.03%	33.22
Woolrey Custom Fences	Fence, Gate	$13,420	0.27%	21.96
Austin White Lime Company	Lime	$231,200	4.60%	17.0
Ferguson Waterworks	Pipe, Valve, etc.	$490,395	9.75%	18.2
Hanson Pipe	Junction Box, Inlet, Concrete Box Culvert, etc.	$981,130	19.50%	6.3
Hanson Pressure Pipe	Pressure Tap	$18,500	0.37%	181.71
Larwell Industries	Pedestrian Rail	$64,206	1.28%	185

Table 13 (Cont.): Calculation of the Percentage of Local Material Suppliers

Supplier	Material	Cost	Percentage	Distance to Project
Lauren Concrete, and Texas Metal Technologies	Cement, PCC, Reinforcing Steel, Fast Set CLSM	$1,199,124	23.84%	20.6
Mickie Service Company	Valve	$23,000	0.46%	154
TXI Operations, LP	Cement	$199,840	3.97%	49.89
APAC/Wheeler	Asphalt Concrete	$489,751	9.73%	23.18
DIJ	Pavement Marking	$31,965	0.64%	43.2
N-LINE	Construction Sign	$103,950	2.07%	6.07
COLORADO	Base Material	$4,200	0.08%	26.1
Total (only for those within 50 miles)		$4,925,141	97.90%	

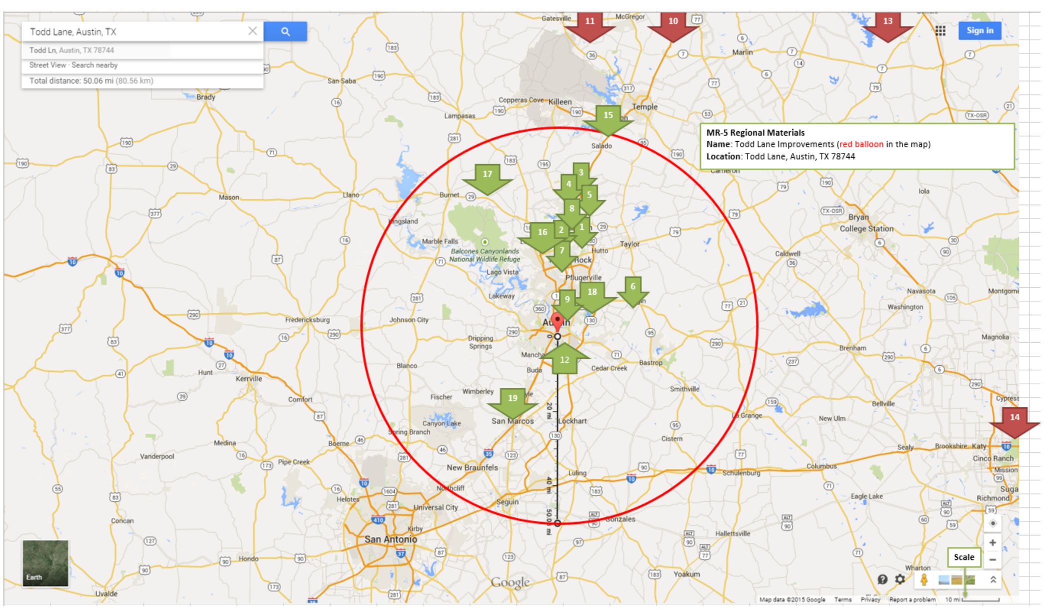


Figure 11: Map of Material Suppliers in the Todd Lane Improvements Project

3.2.6. MR-6 Energy Efficiency

Bagby Street Reconstruction: based on the discussion between the author and Walter P Moore, 71% of the installed roadway luminaries use LED to reduce energy consumption. The streetlight design requirements in the City of Houston's Infrastructure Design Manual (Rudick and Lincoln, 2014) specify that currently 100-Watt and 250-Watt HPS light fixtures are included. Namely, the use of LED has not been required by the city, although the installed roadway luminaries are mostly composed of LED on the project. Subsequently, three points were awarded to this project.

Todd Lane Improvements: based on the bid table in the Project Manual (Zhang, 2013), no item indicating the installation of LED was found. However, according to the Pilot Project report (Greenroads Foundation, 2014), the intent of installing LED for all of the roadway luminaries is confirmed by the team manager and presented to the Greenroads Foundation. With the assumption that 100% of the installed roadway luminaries use LED, five points are expected from MR-6.

3.2.7. PT-1 Long-Life Pavement

Bagby Street Reconstruction: according to the Infrastructure Design Manual developed by the City of Houston (Rudick and Lincoln, 2014), the minimum concrete slab thickness for pavement width less than or equal to 27 feet is 6 inches, for pavement width greater than 27 feet is 7 inches, and for major thoroughfare is 8 inches. In the case of Bagby Street, the minimum thickness of 7 inches was considered. As indicated in Figure 12, the newly designed pavement is a 10-inch jointed reinforced concrete pavement (JRCP) on the top of an 8-inch subgrade stabilized with 7% lime (for the project design plan, please refer to Appendix A). The California Bearing Ratio (CBR) value for the subgrade is 13. The design equivalent single axle load (ESAL) is 5,481,000. Next, these two values are used in the Long-Life Pavement Design Graph specified by Greenroads. The result is presented in Figure 13. As can been seen, the minimum thickness required to obtain credit is about 9 inches, which is less than the design thickness. Therefore, five points were earned from this credit.

Bagby Street Reconstruction
Greenroads PT-1 Credit computations
By: Thusitha Silva
Date: 10/4/13

WALTER P MOORE

According to PT1.1, Long Life pavement design graph, the Pavement must have:

1. Minimum subgrade CBR=5
2. Base material CBR = 80 or better
3. Minimum base thickness= 6inches (150 mm)
4. Surface material = MHA or PCC
5. Minimum surface thickness=9" from graph

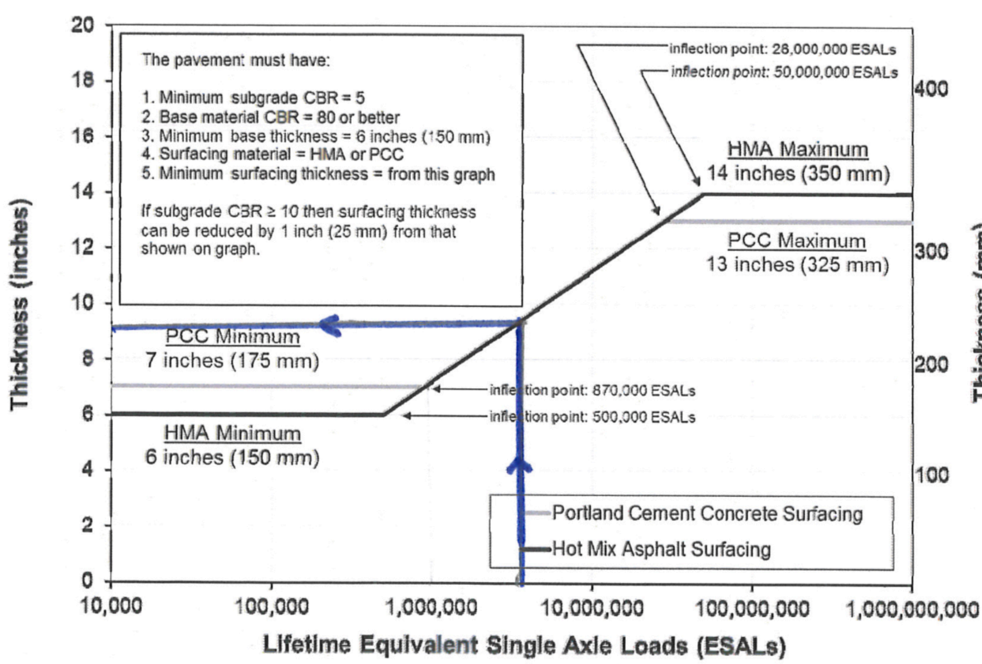
Design Values for Bagby Street:

1. CBR value for stabilized subgrade = 13 (Provided by Aviles Engineering Corp.)
2. Base material CBR is not applicable for this project as described below in Design Guidelines
3. Stabilized subgrade thickness = 8 inches
4. Surface material= Reinforced PCC
5. Pavement thickness = 10 inches
6. ESAL(over design Life)= 5,481,100
7. Total Area of 10 inch Reinforced Concrete Pavement= 18,709 sy (100% of the trafficked lanes)

Design Guidelines

City of Houston Design Manual. The roadway typical section for the City with reinforced concrete pavement is that the pavement slab is on stabilized subgrade. Please see attached City of Houston detail. The subgrade for Bagby is eight inch (8") lime stabilized subgrade with 7% lime.

Figure 12: Long-Life Pavement in the Bagby Street Reconstruction Project



WALTER P MOORE Figure PT-1.1: Long-life pavement design graph.

Figure 13: Minimum Thickness for the Bagby Street Reconstruction Project

Todd Lane Improvements: As indicated in the project design plan (Appendix A), the proposed pavement structure is a 9.5-inch HMAC surface on the top of a 24-inch lime-cement treated base. In order to examine the expected life of this pavement structure, the method for designing flexible pavement in the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO, 1993) was used with the traffic data provided by the project team (Appendix A, Figures A3 to A7). Table 15 shows the parameters needed in the AASHTO design method, including the traffic data, reliability, and serviceability. As indicated in Table 14, the design thickness of the HMAC surface is 3.5 inches, and that of the base layer is 12 inches. These two numbers are both smaller than the thicknesses in the project design plan, in which the HMAC surface is 9.5 inches and the lime-cement treated base is 24 inches.

Supporting the design ESAL in the 40-year period is only one of the reasons for proposing such a strong pavement structure. According to the pavement engineer in the City of Austin, the main concern in the project is the property of the existing soil. As can be seen in Figure 14, the existing subgrade underneath Todd Lane consists of three types of soil: Houston Black clay (HnA), Houston Black soil (HsD), and Lewisville silty clay (LcB) (U.S. Department of Agriculture, 2015). Thus, clay accounts for about 40% of the existing soil. As indicated by the geotechnical report in the Project Manual (Zhang, 2013), this type of clay is highly expansive. Therefore, the soil stabilization technique as well as the proposed pavement with thick surface and base layers have been adopted to prevent the shrink-swell of the clay from damaging the structure.

Since the proposed pavement structure will be constructed to replace the existing pavement, which meets the requirement of 75% of the project area is designed for long-life. Thus, 5 points are expected from this credit.

Table 14: Results of AASHTO Design Method with 40-Year Design Period

Traffic Data, Reliability, and Serviceability			
Initial AADT	**% Growth**	**% Truck**	**Truck Factor**
13,300	4%	15.8%	0.62
Directional Distribution Factor	**Lane Distribution Factor**	**1-year ESAL**	**Design ESAL**
0.5	1	237,936	22,610,017
Reliability	**Standard Error**	**Initial Serviceability**	**Terminal Serviceability**
95%	0.5	4.5	2.5
Required Structural Number[2]			
6.45			
HMAC Surface			
Required Thickness		**Layer Coefficient**	
3.5 inches		0.42	
Lime-Cement Treated Base			
Required Thickness	**Layer Coefficient**	**Drainage Coefficient**	**Resilient Modulus**
12 inches	0.43	1	446,000 psi
Subgrade			
Resilient Modulus			
5000 psi			

[2] The required SN means given the subgrade resilient modulus, 5000 psi in this case, the total SN needed to support the design ESAL.

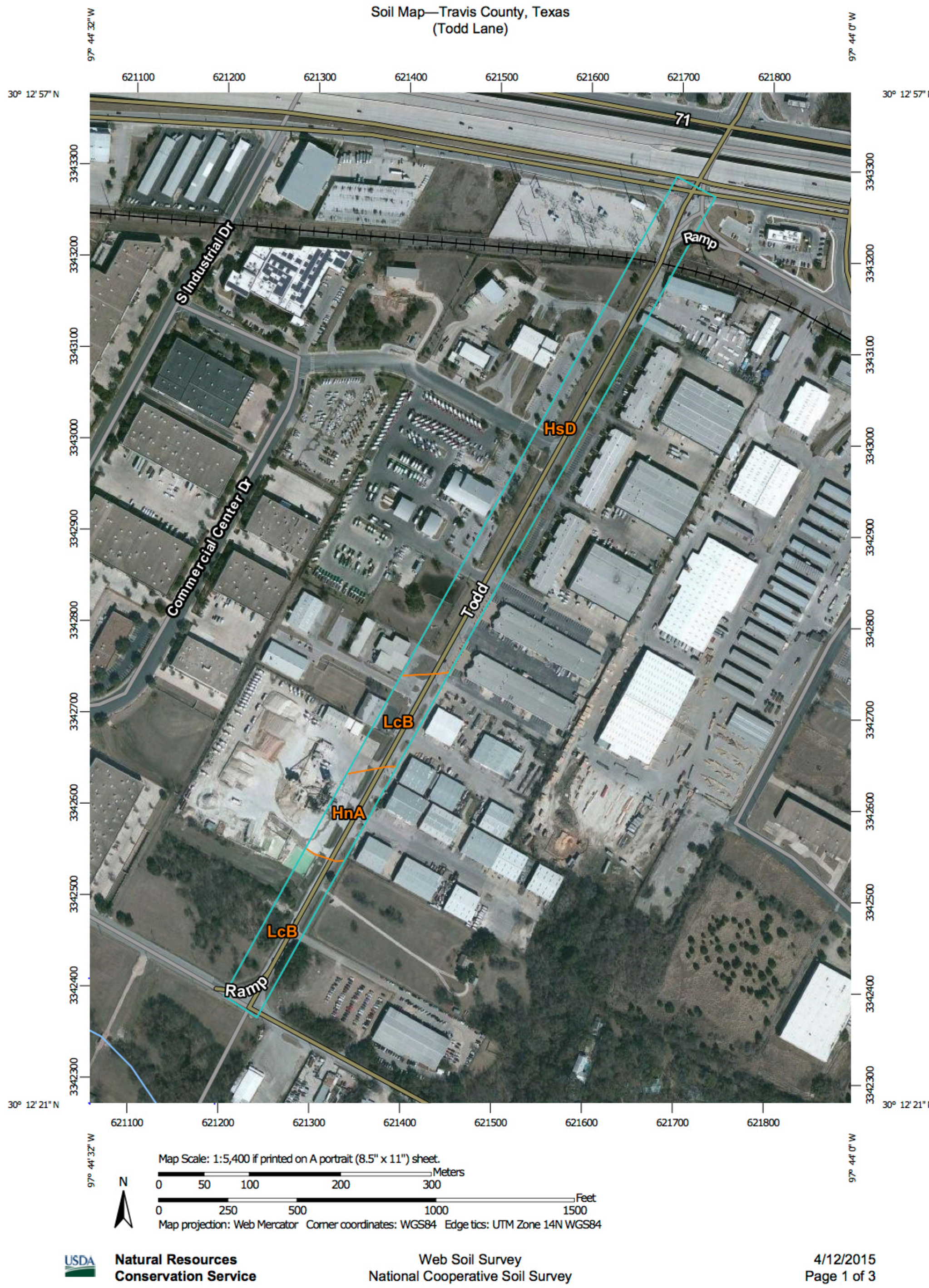


Figure 14: Soil Map on Todd Lane, Travis County, Texas

3.2.8. PT-2 Permeable Pavement

Bagby Street Reconstruction: originally, the project team attempted to achieve this credit, but was denied by the Greenroads Foundation. Figure 15 provides the calculation of the proposed impervious area of the project. One can find that, except for driveways and brick pavers, the proposed impervious areas of the pavement, and sidewalks both increase. Although the overall impervious area decreased by 2%, the attempt to obtain this credit failed because a minimum of 5% reduction is required. Therefore, no points were awarded to the project.

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BAGBY STREET
Greenroads PT-2 Computation

	Existing Impervious Area (SF)	Proposed Impervious Area (SF)
Pavement	147,401	157,287
Brick Pavers	11,392	4,770
Sidewalk	24,651	35,873
Driveways	22,018	3,502
Totals	**205,462**	**201,432**
Net Reduction		4030 SF
Percent Impervious Reduction		2%

Figure 15: Proposed Impervious Area for the Bagby Street Reconstruction Project

Todd Lane Improvements: according to the Pilot Project report (Greenroads Foundation, 2014), this credit can be achieved by using permeable pavement in bike lanes and sidewalks or reducing the impervious area from existing conditions. However, the project team did not target this credit at the beginning of the project, making it difficult to achieve at the construction phase. Thus, no points are expected from PT-2.

3.2.9. PT-3 Warm Mix Asphalt

Bagby Street Reconstruction: since the construction of WMA was beyond the scope of the project, in which the project team decided to use jointed concrete pavement, this credit was not attempted. Based on that, no points were earned from this credit.

Todd Lane Improvements: according to Rand and Lee (2012), TxDOT has placed over 2,250,000 tons of WMA by 2011, indicating that WMA has been widely adopted in Texas. However, similar to the construction of permeable pavement, the project team did not take WMA into consideration at the design phase, making this credit not applicable. Therefore, no points are expected from PT-3.

3.2.10. PT-4 Cool Pavement

Bagby Street Reconstruction: Figure 16 shows the calculation of albedo across Bagby Street after the project was finished. It can be seen that all of the sections have albedo greater than 0.3. The reason is mainly due to the color of concrete material, as opposed to the color of asphalt concrete, which usually has low albedo. Based on that, the percentage of the pavement surface with an albedo greater than 0.3 is about 100%. Therefore, five points were earned from this credit.

STREET	AMBIENT	REFLECTIVE	ALBEDO
2+00	22134	9577	0.4326828
4+00	32758	19386	0.5917944
6+00	32642	15744	0.4823234
8+00	16952	8941	0.5274304
10+00	13648	6401	0.4690064
12+00	14486	5644	0.3896176
14+00	30807	16135	0.5237446
16+00	17664	14992	0.8487319
18+00	20780	15672	0.7541867
20+00	16377	14047	0.8577273
22+00	15830	11831	0.7473784
24+00	21066	8349	0.3963258
26+00	14243	11162	0.7836832
28+00	20394	9922	0.4865156
30+00	24702	10242	0.4146223
32+00	14329	8985	0.62705

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Bagby Lux Readings

Tuesday, October 01, 2013

Figure 16: After-construction Albedo Calculations on Bagby Street

Todd Lane Improvements: in this project, permeable pavement is not used. Moreover, the proposed pavement is a 9.5-inch HMAC, which has albedo between 0.05 and 0.15 (Li et al., 2015). Neither of them is qualified for the requirement of this credit. Thus, no points are expected from PT-4.

3.2.11. PT-5 Quiet Pavement

Bagby Street Reconstruction: according to the credit requirement, it is only applicable for the project with the speed limit of trafficked lanes greater than or equal to 30 miles per hour. Since Bagby Street is a heavily-walker pedestrian corridor and located in the heart of Houston, its speed limit is restricted to 30 mph. Moreover, based on the discussion between the author and engineers in Walter P Moore, this credit would not benefit the neighboring area significantly because of the low speed limit. Due to the nature of the project, no points were earned from this credit.

Todd Lane Improvements: similar to PT-2 and PT-4, this credit was not targeted at the beginning. Also, the noise control specified in the Project Manual (Zhang, 2013) only includes the construction-related noise, whereas the activities regarding pavement-tire noise testing were not found. Based on that, it is difficult for the project team to meet the credit requirement and to earn points from it. Thus, no points are expected from PT-5.

3.2.12. PT-6 Pavement Performance Tracking

Bagby Street Reconstruction: in the Greenroads errata (2013), this credit has never been achieved by any Greenroads-certified project due to the lack of existing technologies. Therefore, no points were awarded to the project.

Todd Lane Improvements: according to the project team, the City of Austin had a computerized system that keeps track of the network maintenance history, but it is currently not being used. Moreover, data stored in this system are not the construction quality measurements, as specified by Greenroads. The second part requires the pavement performance measurements to be stored in the same system. The City of Austin is expecting to reinstate their PMS by purchasing a new computerized system in the end of 2015. Moreover, the pavement management engineers in the City of Austin indicate that they have been able to collect pavement condition data, including IRI and four major types of cracking, in 9 of the past 14 years, and that the newly constructed Todd Lane will be covered in the city's data collection effort. Thus, the second part of the credit is met, but the first part is not. As a result, no point is expected for this credit.

3.3. CHAPTER CONCLUSIONS

This chapter summarizes the results of two Greenroads projects, including the Bagby Street Reconstruction project in Houston and the Todd Lane Improvements project in Austin. Both are reconstruction projects due to the changes in the environmental and social conditions. However, the former is constructed with a new concrete surface, and the later sticks to the same type, which is an asphalt surface. Greenroads provides a framework for two roadway projects different in their natures and surroundings to be compared in terms of sustainability. For instance, although these two projects are located in two different cities, the result of MR-5 Regional Material shows that the Todd Lane Improvements project with five points outperforms the Bagby Street Reconstruction project with four points. It means that in terms of using local materials to reduce emissions and promote local economies, the Todd Lane Improvements project does a better job.

Moreover, in PT-1 Long-Life Pavement, while both projects get five points, the Bagby Street Reconstruction project uses the Long-Life Pavement Design Graph specified by Greenroads, and the Todd Lane Improvements project uses the 1993 AASHTO Guide for Design of Pavement Structures to demonstrate their work. It should be pointed out that Greenroads allows different methods to be employed for the purpose of becoming sustainable. Moreover, one certified project could serve as an example of sustainability to other applying projects, suggesting them a way to achieve their goal. However, not all of the Greenroads credits are achieved or achievable for a project. This may be attributed to some reasons, which are summarized as follows:

1) Timing: some sustainable practices cannot be achieved because they are not planned beforehand. Namely, extra cost or time prohibits the sustainable practice to be implemented. MR-2 in the Bagby Street Reconstruction project and PT-2, PT-3, and PT-4 in the Todd Lane Improvements project are all good examples.
2) Specification: some sustainable practices are not achieved due to the specification. Very often, the project team relies on the project specification to complete the project. If the team has no reference (and intent), it is sometimes difficult to implement a sustainable practice. Conversely, there are some practices that are achieved due to the similar requirement in the specification. The project team can therefore meet the requirement in the specification and achieve the sustainable practice at the same time. PT-5 in the Todd Lane Improvements project is an example in the first case, and PT-1 in the Bagby Street Reconstruction project is another in the second case.

The observations above indicate that: first, the project team has to take Greenroads into consideration as early as possible, since Greenroads is a system that aims at affecting projects in the design and construction phases; second, the requirements in Greenroads (or any other rating system) must correspond to the current specification, or go beyond the specification, in order to effectively promote the sustainability in the roadway project.

CHAPTER 4: PROPOSED RATING SYSTEM

For the state of Texas, Greenroads or, more broadly speaking, a sustainability rating system for highway pavements is relatively new. As presented previously, Greenroads helped two of the roadway projects in Texas in many aspects, such as noise, air and water quality and energy, to become more sustainable. With no doubt, this kind of rating system will benefit the entire Texas transportation community. However, there are many differences between Texas and Washington, where Greenroads was developed – i.e. size, climate conditions, distributions of natural resources, pavement technologies in practice, and so on. Therefore, it will be beneficial if Texas can have a sustainability rating system that is built or calibrated based on its local conditions.

Based on the results above, major changes are proposed for the Material Resources and Pavement Technologies categories in order to accommodate the circumstances in Texas. The following section provides a comprehensive description of the proposed changes in these sustainable practices.

4.1. MATERIALS AND RESOURCES

4.1.1. MR-1 Lifecycle Assessment

Proposed credit point: 0 point

Proposed credit requirement: complete an extended lifecycle inventory (LCI) representing the entire project, and use the extended LCI data to complete a lifecycle impact analysis (LCIA).

Based on the Greenroads' feedback for two of the projects in the case study, first, this credit is difficult and unusual for projects under $10 million to achieve, and second, the Greenroads Foundation has never awarded points to any of its certified projects in terms of this credit. Besides, there are no projects or records in the SM database or the TxDOT specification addressing LCA. Based on these reasons, the points of this credit will be moved to other credit, temporarily making this credit ineffective. Although the point of this credit is moved, it is expected that when the time that LCA is more accessible to the public comes near, the proposed rating system for Texas will incorporate and encourage pavement LCA.

Nowadays, although the process is complicated and requires tons of input, pavement LCA is a methodology that is becoming more popular in aiding the decision making phase of roadway projects. Santero et al. (2010) provided a review of existing literature and modeling tools related to pavement LCA. They pointed out that pavement LCA is an expanding but still limited research topic research topic, mainly impeded by inconsistent functional units, improper system boundaries, imbalanced data for asphalt and cement, use of limited inventory and impact assessment categories, and poor overall utility. FHWA (2014) in its TechBrief introduces the whole process of pavement LCA, including its principles, purpose, and phases. It also states that full LCA requires access to relevant datasets and software, which are currently limited and generic.

4.1.2. MR-2 Pavement Reuse

Proposed credit point: 1 to 5 points

Proposed credit requirement: reuse a minimum percentage of existing pavement materials or structural elements by estimated volume or weight as shown in Table 15 below. The material can include but are not limited to hot mix asphalt (HMA), Portland cement concrete (PCC), bridge decking, unbound granular base material, stabilized base material, structural foundation, etc.

Table 15: Proposed Point Scale for MR-2 Pavement Reuse

MR-2 Points	1	2	3	4	5
% Reuse of Existing Pavement Materials or Structural Elements	50	70	85	95	100

Based on the data extraction from the SM database, there is no information regarding the volume or weight of existing materials that have been used in TxDOT projects. Since no data or information can be used to estimate the percentage of reused materials in Texas, no change is proposed to the credit requirement. However, in order to encourage applicants to more existing materials, the difference between each point level decreases as the use of higher percent of existing materials is targeted.

4.1.3. MR-3 Earthwork Balance

Proposed credit point: 1 point

Proposed credit requirement: minimize earthwork cut and fill volumes such that the percent difference between cut and fill is less than or equal to 40% of the average total volume of material moved.

$$\frac{(A + C) - (B + D)}{\frac{1}{2}(A + B + C + D)} \times 100\% \leq 40\% \qquad (5)$$

Where

A is the volume of cross section cut.

B is the volume of cross section fill.

C is the volume of miscellaneous cut.

D is the volume of miscellaneous fill.

The original percent difference between cut and fill is required to be less than or equal to 10% of the average total volume of material moved. The proposed percent difference is raised up to 40%, according to the pavement projects that involve earthwork in the SM database.

Among 1,594 projects, 745 of them contain item 0110 (excavation) or 0132 (embankment), and are classified as projects that involve earthwork. The quantity of these two items indicates the volume of the material that is exported or imported to the project. The percent difference between cut and fill of each project is then calculated based on the quantities of item 0110 and 0132. The mean percent difference of the 745 projects is 111.16%, indicating that on average, the volume of imported materials is higher than the volume of exported materials. Figure 17 shows the cumulative percentage plot of the percent difference, and Table 16 provides the percent differences and their corresponding percentiles. As presented below, if the current Greenroads requirement is applied to TxDOT projects, only 8.18% of them (about 61 projects out of 745) can earn one point from this credit. It means that the current percent difference is too difficult for TxDOT projects to achieve earthwork balance. Therefore, a new, slightly higher percent difference, 40%, is proposed to replace the current one. According to the table, 19.62% of the projects (about 146 projects out of 745), which is more than double the number of projects under current requirement, can meet the proposed requirement.

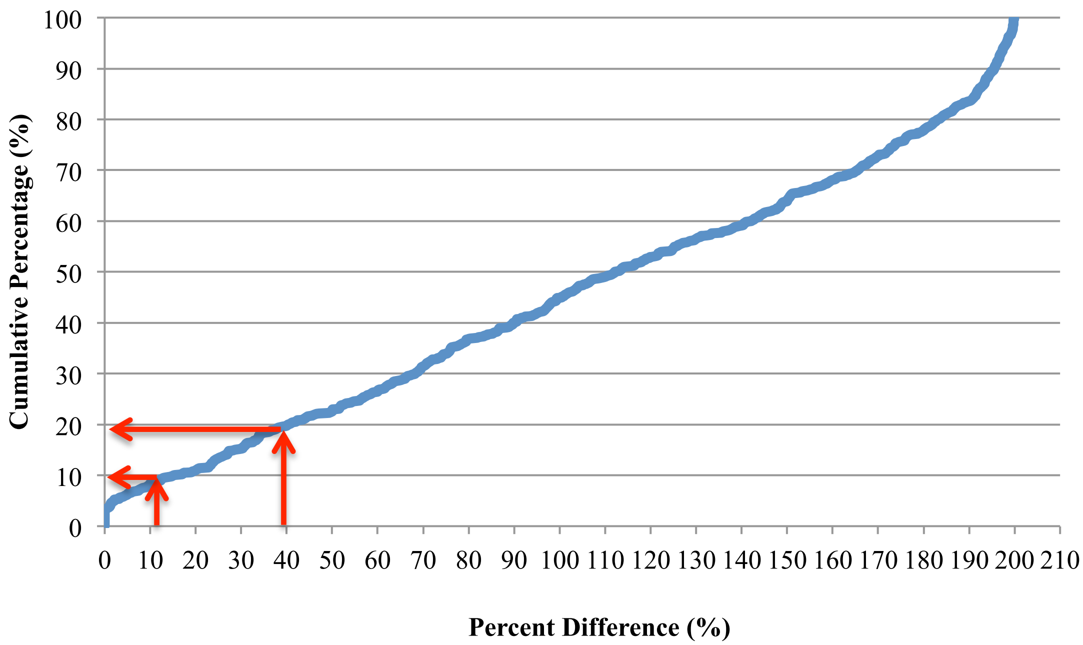


Figure 17: Cumulative Percentage of Percent Difference for Site Manager Projects

Table 16: Percent Difference and its Percentile

Percent Difference	Percentile	Note
10	8.18	Current Requirement
40	19.62	Proposed Requirement

4.1.4. MR-4 Recycled Materials

Proposed credit point: 1 to 5 points

Proposed credit requirement: use recycled materials as a substitute for virgin materials. The fraction of recycled materials used can be calculated using one of four options below:

1) Consider only the binder materials, and structural and reinforcing steel materials
2) Consider only the hot mix asphalt or Portland cement concrete pavement materials and steel materials
3) Consider all materials including granular base layers, structural fill and soil improvements
4) Consider all project materials

Table 17: Proposed Point Scale for MR-4 Recycled Materials

MR-4 Points	**1**	**2**	**3**	**4**	**5**
ARC for Option 1 and 2	6	11	15	18	20
ARC for Option 3 and 4	16	21	25	28	30

$$ARC(\%) = \frac{\sum r_n}{\sum W_n} \times 100\% \quad (6)$$

Where

ARC is the average recycled content.

r_n is the total weight of recycled materials for that individual material or assembly.

W_n is the total weight of each individual material or assembly.

n represents the number of materials used in the pavement section.

For MR-4, no change is proposed to the credit requirement except for its point scale, as can be seen in Table 17 above. Originally, the maximum ARC for the first and second options was 50%, and that for the third and fourth options was 60%. According to the TxDOT Standard Specifications for Construction and Maintenance of Highways, Streets and Bridges (TxDOT, 2014), the maximum allowable percentage of RAP and recycled asphalt shingles (RAS) depends on the mix type and the layer in which they are used. Generally speaking, the maximum allowable percentage of RAP is 40% in the base layer, 30% in the intermediate layer, and 20% in the surface layer. The 20% maximum for the surface layer is used as the new maximum for the ARC in the first and second options.

As for the projects in the SM database, there is currently no information regarding the amount of RAP (or any other recycled materials) used in the project. However, thanks to the engineers in TxDOT, a table containing the average percentage of RAP used in twenty-five Texas districts in 2014 is provided to the author (Appendix A, Figure A7). The data in the table provided by TxDOT is not a direct comparison to the calculation specified by Greenroads, as it is the average percentage of each district, not each project. However, due to the limited availability of the data, the table is used as an approximation to the real situation, and thus the comparison is considered reasonable.

Figure 18 below shows the cumulative percentage curve of the average percentage of RAP over twenty-five districts, and Table 18 shows the average percentages of RAP and their corresponding percentiles. In the table, the first row can be interpreted as follows: 20% of the districts use 5.8% of RAP or less over the total amount of pavement materials. Therefore, the proposed ARC for the first and second options is based on the average percentage of RAP that corresponds to the percentile together with a maximum of 20%. Also, it is important to note that in order to encourage the applicants to use higher percentage of RAP in their projects, the difference between each point decreases as the higher ARC percentage is targeted.

It can be noticed that in the original credit requirement, the required ARC between two options has a ten percent difference, regardless of the point level. The same strategy is applied in the proposed point scale, resulting in a maximum ARC of 30% for the third and fourth options. It is worth noticing that this maximum does not violate the requirement specified in the TxDOT specification.

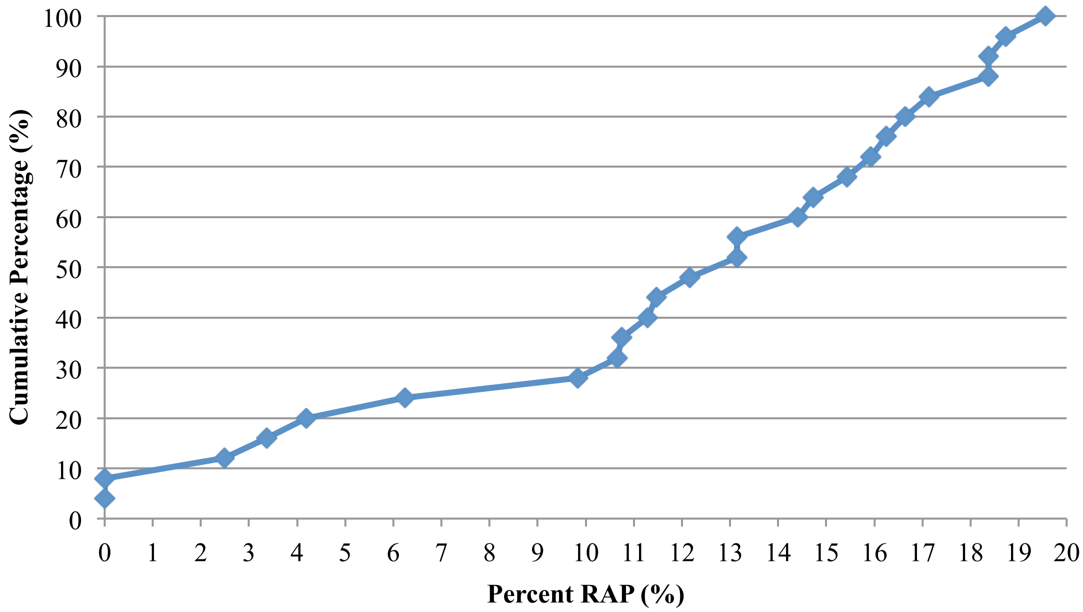


Figure 18: Cumulative Percentage of Average Percentage of RAP

Table 18: Average Percentage of RAP and Percentile

Percentile	Average Percentage of RAP (%)	Proposed ARC (%)
20	5.8	6
40	11.4	11
60	14.5	15
80	16.7	18

4.1.5. MR-5 Regional Materials

Proposed credit point: 1 to 5 points

Proposed credit requirement: choose one of the two options provided in Table 19 below. For the first option, calculate the percentage of the total cost that has been paid to material suppliers, processors, distributors, and producers within a fifty-mile radius of the geographic center of the project. For the second option, break each material, component or product into the basic materials, and calculate the cumulative fronthaul distance for each basic material from the point of origin to the location of the project. Show that 95% of these basic materials have traveled less than the cumulative distance specified in Table 19.

Table 19: Proposed Point Scale for MR-5 Regional Materials

MR-5 Points	1	2	3	4	5
Option 1: % of Total Cost	60	72	81	88	95
Option 2: Maximum Fronthaul Distance (miles)	500	370	263	175	100

For this credit, no change is proposed to the credit point and requirement except for the point scale. Although the information regarding all of the items in the project is stored in the SM database, the item suppliers, their points of origin, transport distances are not included. It makes the computation of the percent of the total cost spent on local suppliers or the cumulative fronthaul distance of all basic materials difficult and nearly impossible to achieve. However, a minor modification is proposed based on the two reasons below. First, the same design philosophy as the point scale of MR-4 is applied here. In order to encourage the applicants to use more local materials, the difference between each point level decreases as the higher percent of total cost or lower maximum fronthaul distance is targeted.

Second, since such a rating system is proposed for the first time, the overall difficult of this credit is designed to be slightly lower than the original credit. By doing so, it is expected that the entire community will first be more familiar with the system, and then the whole system will be updated as the industry gains knowledge. As can be seen in Figure 19 and 20 below, three lines are drawn for each of the options. In these two figures, the blue line represents the current requirement, and the red line is simply a straight line between the minimum and maximum point level. The proposed requirement is the average of the current requirement and the straight line at each point level. Moreover, each number is rounded to the nearest whole number.

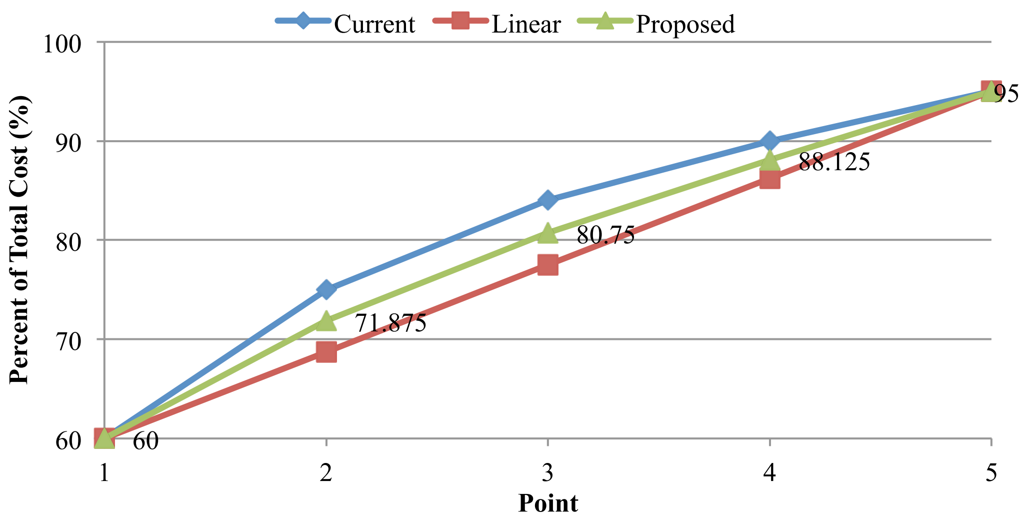


Figure 19: Point Scale Adjustment for the First Option

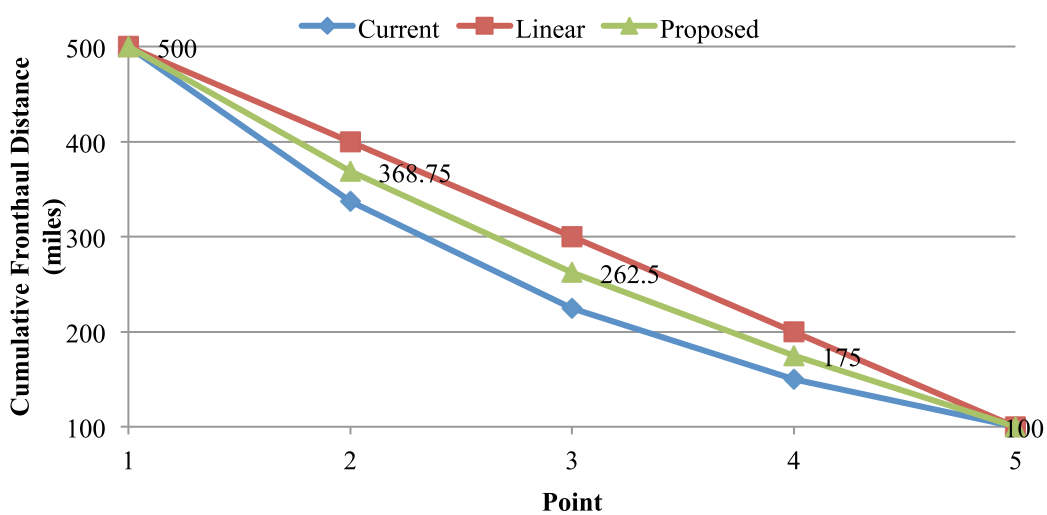


Figure 20: Point Scale Adjustment for the Second Option

4.1.6. MR-6 Energy Efficiency

Proposed credit point: 1 to 5 points

Proposed credit requirement: install lighting systems with luminaries that meet or exceed the 2009 Energy Star standard for roadway lighting. Points are awarded based on the fraction of total luminaries installed on the project with energy efficient fixtures that are 2009 ENERGY STAR compliant, as specified in Table 20.

Table 20: Proposed Point Scale for MR-6 Energy Efficiency

MR-6 Points	1	2	3	4	5
% of 2009 ENERGY STAR compliant luminaries	20	60	80	90	95

In the SM database, item 0610 and 0614 represent roadway illumination assemblies and high mass illumination assemblies. Among them, according to the engineer in TxDOT, high pressure sodium is a very common type of roadway luminary. As for this credit, a good example of achieving this credit is the installation of LED. This type of roadway luminary is currently not included in the standard specification (TxDOT, 2014). Instead, TxDOT uses the special specification to specify the use of LED in its projects. In the SM database, 1,000 projects that involve the installation of any roadway luminaries are extracted and shown in Figure 21. As can be seen, 967 of the projects still use HPS as its illumination devices. As for the LED projects, the item quantity of these projects is extracted for further analysis.

As mentioned earlier, for each item in the SM database, there are three fields storing quantity, including FNL_QTY, PRJ_QTY and BID_QTY. In all of the thirty-three LED projects, the FNL_QTY fields that store the final quantities of HPS and LED are all cero, indicating that these items might be cancelled and not installed for some reasons. Instead, the bidding quantity (BID_QTY) of the item is used to present the fraction of total luminaries that meets the credit requirement. Based on that, the cumulative percentage of percent of LED is plotted in Figure 22. As can be seen, most of the projects plan to use at least 70% of LED in their roadway luminaries. It means that if

LED is included in the project plan, its percent of usage is usually high for TxDOT projects. However, these projects only account for a small portion of the roadway luminary projects. It means that the installation of LED to light the road is still not commonly adopted. Therefore, a new point scale is proposed. In order to encourage more installation of roadway luminaries that meet or exceed the 2009 Energy Star standard, the difference between each point level decreases as higher fraction of energy-efficient luminaries is targeted.

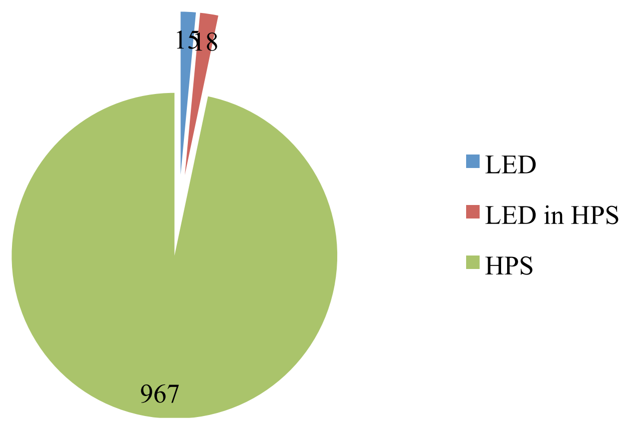


Figure 21: Pie Chart of Roadway Luminary Projects

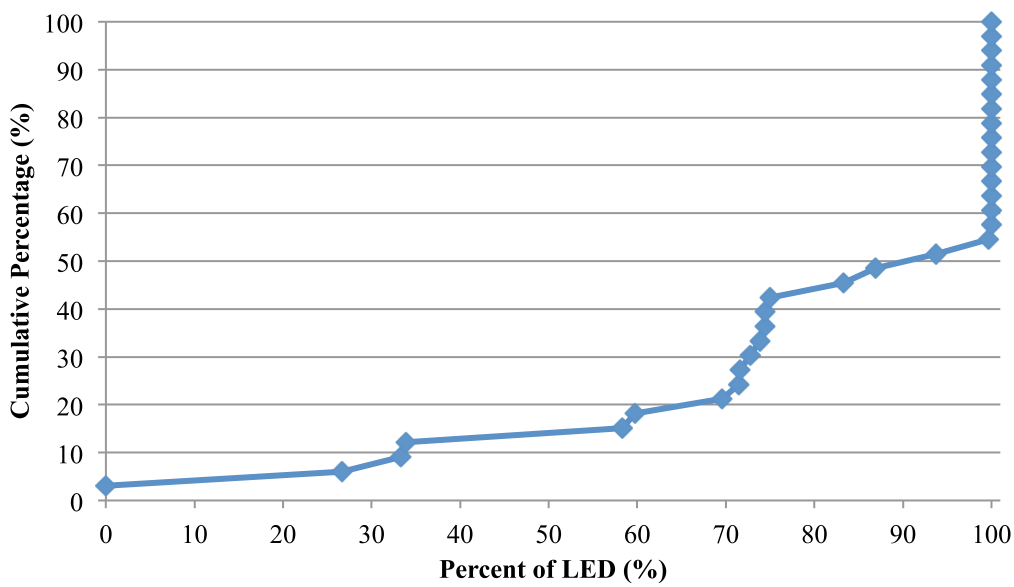


Figure 22: Cumulative Percentage of Percent of LED

4.2. PAVEMENT TECHNOLOGIES

4.2.1. PT-1 Long-Life Pavement

Proposed credit point: 2 to 5 points

Proposed credit requirement: design at least 75% of the total new or reconstructed pavement surface area for regularly trafficked lanes to meet the pavement design life specified in Table 21. The design needs to be in accordance with a design procedure that is formally recognized, adopted and documented by the project owner.

Table 21: Proposed Point Scale for PT-1 Long-Life Pavement

PT-1 Points	2	3	4	5
Pavement design life	25	30	35	40

The original credit only awards five points to the design of a pavement structure with 40-year life. In the SM database, the pavement design life used in each project is not recorded. Although there is another TxDOT database called Pavement Management Information System (PMIS) storing the pavement performance measurements at the network level, it is difficult to use any pavement performance prediction models to re-estimate the initial design life of each project. The reasons are: (1) TxDOT regularly maintains the pavement to prevent it from failure, making the estimation of design life difficult, and (2) since the design life required is based on project level, there is no way to obtain the construction project limits in PMIS.

According to TxDOT Pavement Design Guide (2011), the traffic data required for the design procedure is only twenty years long. It means that the pavement design life specified by TxDOT is twenty years. Therefore, in order to make this credit more reachable, a new point scale is proposed. The minimum required design life is twenty-five years. Moreover, since the pavement design life is usually a multiple of five, this has been taken into consideration. Therefore, the encouragement for applicants as included in the previous credit is not applied here.

4.2.2. PT-2 Permeable Pavement

Proposed credit point: 1 to 3 points

Proposed credit requirement: compute the total amount of impervious area with Curve Number (CN) of 98 or greater on the project before construction (CN_1) and after construction (CN_2), respectively. Points are awarded for increments of reduced impervious area, or developed footprint reduction (DFR), in increments of 5%. As can be seen in Table 22, DFR is equal to the difference between CN_1 and CN_2 divided by CN_1, and is expressed as the percentage of the preconstruction conditions.

Table 22: Point Scale for PT-2 Permeable Pavement

PT-2 Points	**1**	**2**	**3**
DFR	5	10	15

$$DFR(\%) = \frac{CN_1 - CN_2}{CN_1} \times 100\% \quad (7)$$

Where

CN_1 is the total amount of impervious area with CN of 98 or greater on the project before construction.

CN_2 is the total amount of impervious area with CN of 98 or greater on the project after construction.

No change is proposed to the credit point and requirement of this credit. Although there are 125 PFC projects found in the SM database, the item unit is recorded in tonnage and no information regarding the construction area is available. Therefore, no direct comparison can be made to propose any changes. However, as shown in Figure 23 and 24, PFC has been used on Texas highway network for the past decade.

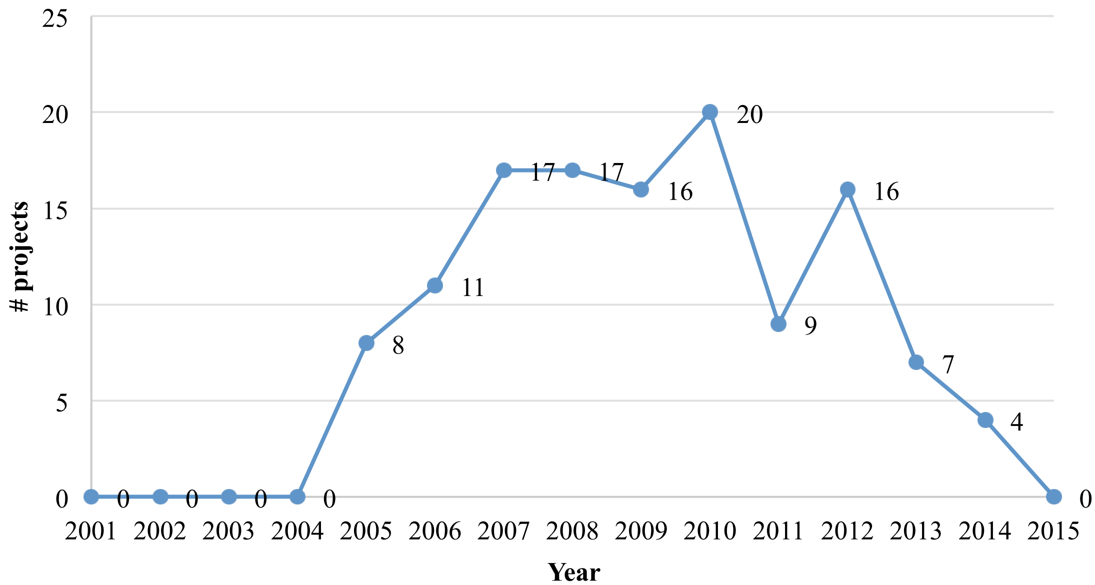


Figure 23: Distribution of PFC Projects from 2001 to 2015

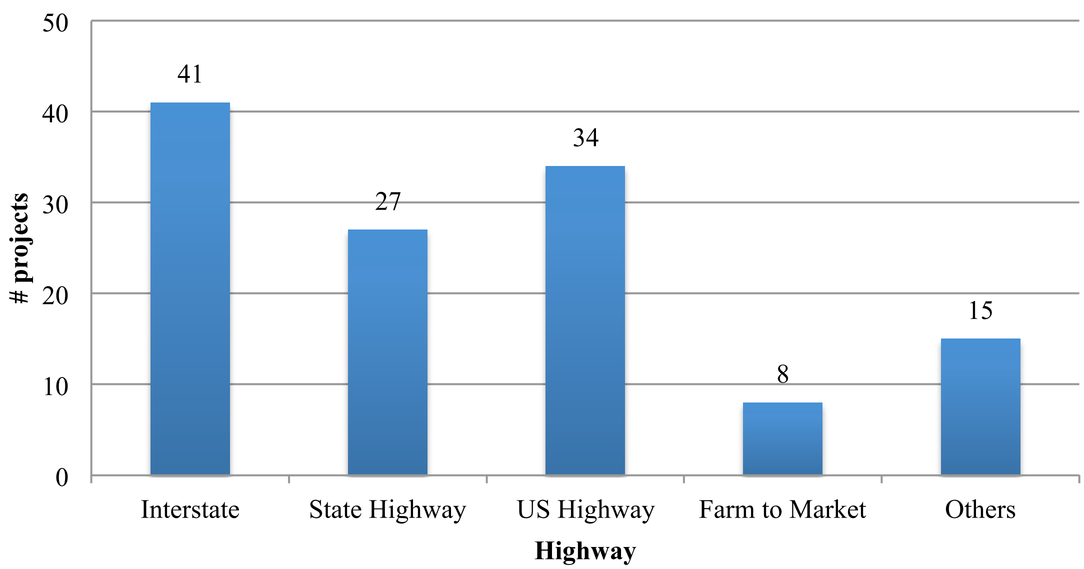


Figure 24: Distribution of PFC Projects on Different Highways

As mentioned earlier, Greenroads provides a list of alternatives that can be used to achieve this credit, including (1) porous asphalt, (2) porous concrete, (3) block pavers, (4) open graded aggregate, (5) artificial turf, and (6) turf reinforcement. Among them, an overlay that is often referred to as Permeable Friction Courses (PFC) or Open Graded Friction Courses (OGFC) is included in the TxDOT specification item 0342. It is a layer of porous asphalt up to about 50 mm thick placed as an overlay on top of an existing conventional concrete or asphalt surface (Barrett, 2008). Rain that fails on the PFC is conveyed along the boundary with the underlying original impervious road surface to the edge of the roadway. PFC has many environmental benefits such as the runoff generated from the PFC surface is of better quality than that from the conventional asphalt surface (Barett, 2008), the drivability in wet weather is improved since the skid resistance is increased with the rainfall drainage of PFC (Luce et al., 2007), and the noise derived from the tire/pavement interaction is significantly reduced with the use of PFC (Trevino and Dossey, 2006).

4.2.3. PT-3 Warm Mix Asphalt

Proposed credit point: 3 points

Proposed credit requirement: reduce the mixing temperature of asphalt mixture to the range of 215°F to 275°F with the use of WMA additives approved by TxDOT and use this reduced temperature mix in at least 25% of the paving area.

While the credit point remains unchanged, the credit requirement is proposed to meet the requirement specified in the TxDOT specification, Section 341.2.6.2 (2014). In the specification, TxDOT allows WMA to be used with higher amount of recycled binders as compared to the use of HMA. Table 23 shows a portion of Table 5 – Allowable Substitute PG Binders and Maximum Recycled Binder Ratios under Item 0341 in the TxDOT specification (2014). As can be seen in the table, when the original binder is replaced with the substitute binder, the use of recycled binder is allowable but needs to meet the maximum ratio as specified. Moreover, the maximum ratio of recycled binder to total binder for WMA is higher than that for HMA. It can be interpreted that

TxDOT encourages the use of WMA, since the extra cost induced by the WMA additives can be made up by using lower levels of asphalt binders.

Table 23: Example of Allowable Substitute PG Binders and Maximum Recycled Binder Ratios in the TxDOT Specification

Original Specified PG Binder	Allowable Substitute PG Binder	Maximum Ratio of Recycled Binder to Total Binder (%)		
		Surface	Intermediate	Base
HMA				
76-22	70-22 or 64-22	20	20	20
WMA				
76-22	70-22 or 64-22	30	35	40

As for the projects in the SM database, there is currently no information regarding the amount of WMA used in the project. However, besides RAP, the engineers in TxDOT also provide a table containing the average percentage of WMA used in twenty-five Texas districts in 2014 (Appendix A, Figure A8). Figure 25 below shows the cumulative percentage curve of the average percentage of WMA over twenty-five districts, and Table 24 shows the average percentages of WMA and their corresponding percentiles.

The table shows that 84% of the districts use 50% of WMA or less over the total amount of pavement materials. Namely, only 16% of the districts can meet the current requirement. In order to make this credit more achievable to more projects in Texas, 25% of WMA over the total amount of pavement materials is proposed to replace 50%. Under current circumstances, 69% of the districts use 25% of WMA or less; on the other hand, 31% of them use 25% or more. Therefore, the propose percentage of WMA is still challenging, but more achievable to the roadway projects in Texas.

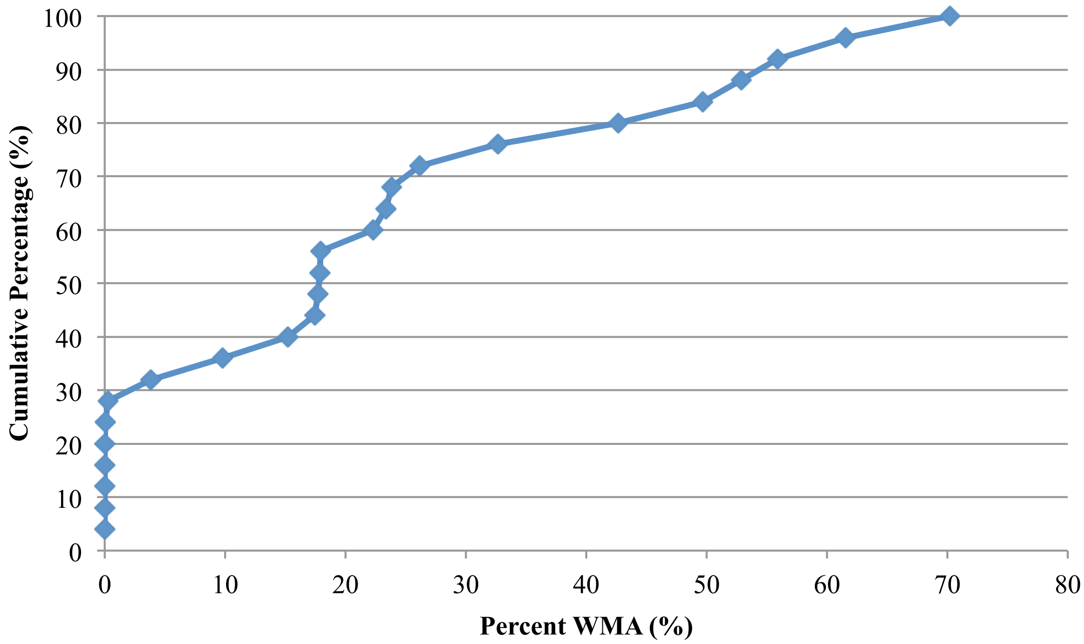


Figure 25: Cumulative Percentage of Average Percentage of WMA

Table 24: Average Percentage of WMA and Percentile

Percentile	Average Percentage of WMA (%)	Note
84	50	Current Requirement
69	25	Proposed Requirement

4.2.4. PT-4 Cool Pavement

Proposed credit point: 5 points

Proposed credit requirement: use a pavement surface with a minimum albedo of 0.3 (light-colored surface area, LSA) or a porous pavement or pavers (permeable surface area, PSA) for a minimum of 50% of the total project pavement surfacing by area.

$$CP(\%) = \frac{LSA + PSA}{A} \times 100\% \quad (8)$$

Where

CP represents the percent of cool pavement surface area.

LSA is the total light-colored or high albedo surface area.

PSA is the total permeable or porous surface area.

A is the total pavement surface area on the project.

According to Li et al. (2015), the albedo of different pavement treatment materials is summarized in Table 25 below. As shown in the table, generally speaking, the albedo of asphalt pavements is about 0.1, which is lower that of concrete pavements. Even with reflective coating, the average albedo of asphalt pavement is 0.2, which is close to the albedo of grass, but still lower than that of concrete pavement.

Table 25: Albedo of Different Pavement Treatment Materials

Material Type	Albedo	
	Range	Average
Asphalt Concrete	0.05 – 0.15	0.1
Asphalt Concrete with Reflective Coating	0.2 – 0.3	0.2
Portland Cement Concrete	0.15 – 0.35	0.25
Conventional Interlocking Concrete Pavement	0.25 – 0.3	0.26
Permeable Asphalt Pavement	0.08 – 0.12	0.1
Permeable Concrete Pavement	0.18 – 0.28	0.25
Grass	0.18 – 0.20	0.19

In the SM database, item 0342 and 0360 represent PFC and concrete pavement, respectively. As mentioned earlier, 125 PFC projects are extracted with the item unit in tonnage. As for concrete pavement, 517 projects are found with the item unit also in tonnage. Figure 26 and 27 show the distributions of PFC and concrete pavement projects from 2001 to 2015 on different highways. It can be observed that TxDOT is constantly using PFC and concrete pavement on the Texas highway network. However, since there is no information regarding the construction area, no change is proposed to this credit.

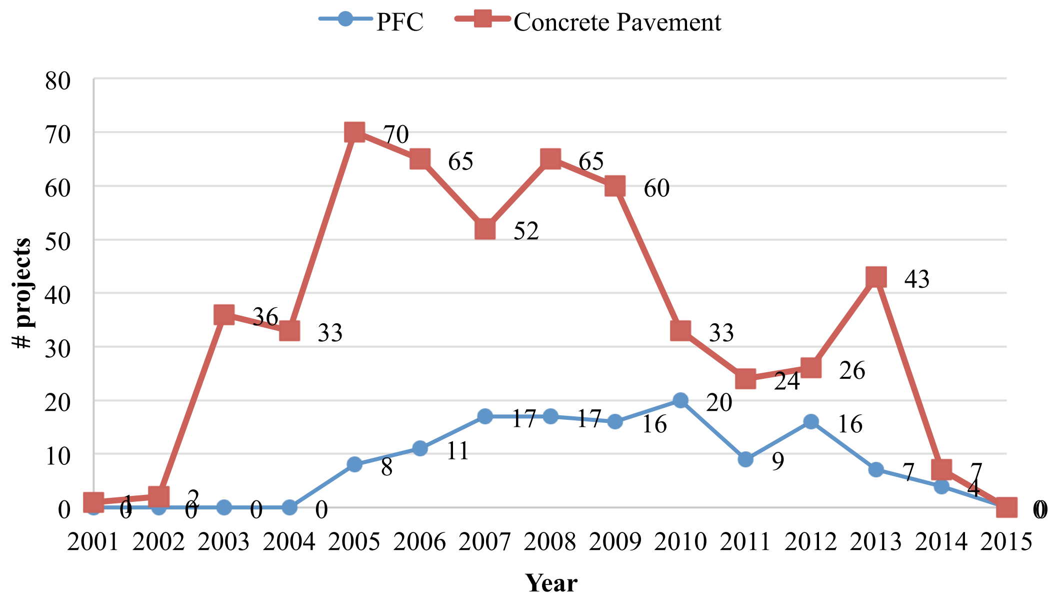


Figure 26: Distribution of PFC and Concrete Pavement Projects from 2001 to 2015

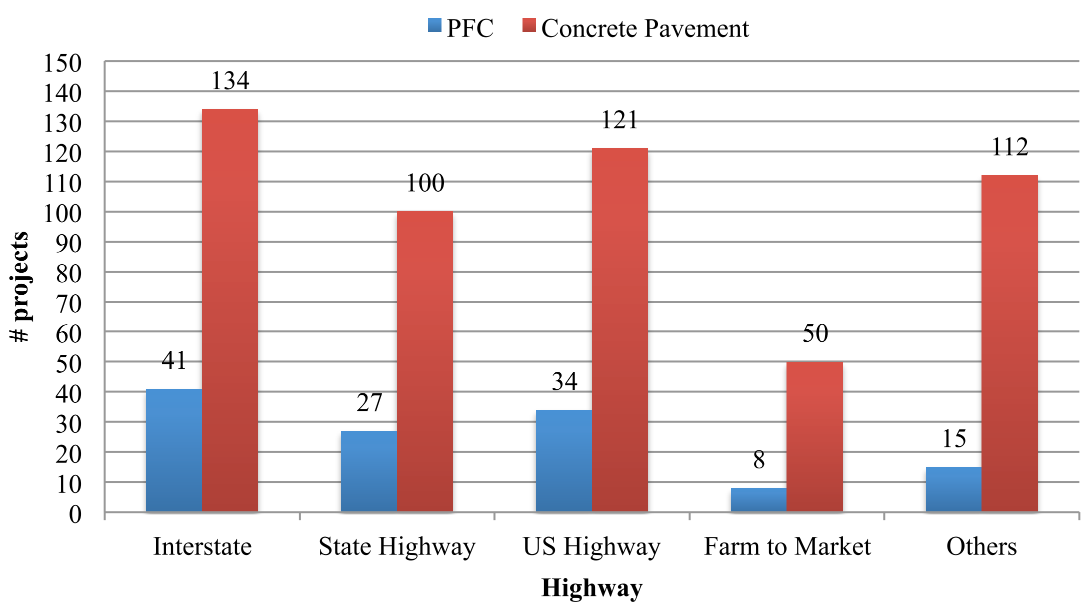


Figure 27: Distribution of PFC and Concrete Pavement Projects on Different Highways

4.2.5. PT-5 Quiet Pavement

Proposed credit point: 2 to 3 points

Proposed credit requirement: construct 75% of the total pavement surface area for regularly trafficked lanes where the speed limit is at least 55 miles per hour with a surface course that produces tire-pavement noise lower than the noise level specified in Table 26. The noise measuring method should be the on board sound intensity (OBSI) method. Two points are awarded for the OBSI noise level of 102 dBA or lower, and three points are awarded for 100 dBA or lower.

Table 26: Proposed Point Scale for PT-5 Quiet Pavement

Facility Posted Speed Limit	Test Speed	2 points	3 points
55 mph or more	**60 mph**	102 dBA	100 dBA
Less than 54 mph	Does not qualify for credit		

While the credit point remains unchanged, a new credit requirement is proposed with a focus on high-speed facilities and new noise levels. Based on the tire/pavement noise measured by the engineers in TxDOT (Appendix A, Figure A9), thirteen types of pavement surface with their noise levels are presented in Table 27 and Figure 28.

Table 27: Average Noise Level in Texas

Pavement Type	Average Noise Level
Overall	102.5
Flexible	102.3
Rigid	103.1

Table 27 shows the average noise level of all types of surface, that of flexible surface and that of rigid surface. In Figure 28, it can be observed that several surface types have a wide range of tire/pavement noise level, such as PFC, asphalt rubber PFC (AR-PFC), continuously reinforced concrete pavement (CRCP) and microsurfacing. For some types of surface, including coarse matrix high binder (CMHB-C) and crack attenuating mixture, there are few sections available for testing, and therefore, the measurements are limited. The propose point scale is based on the overall noise level of all these types of pavement surface. Moreover, since these measurements are obtained from the OBSI Method with the standard test speed of 60 miles per hour, the second alternative with the test speed of 35 miles per hour in the original requirement is deleted.

Two lines indicating the proposed noise level are also plotted in Figure 28. Based on the current measurements, only PFC, AR-PFC, thin overly mixture (TOM), CAM, microsurfacing and stone matrix asphalt (SMA) might meet the two-point requirement, although some of their measurements have a wide range. Therefore, although the proposed noise level is higher than the original one, it is challenging yet achievable for the roadway projects in the state of Texas.

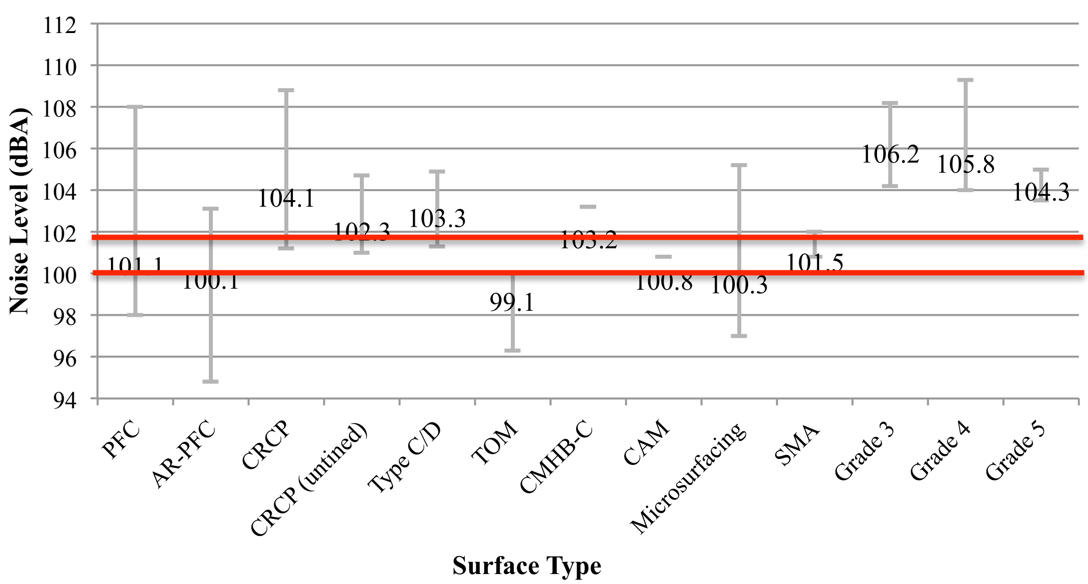


Figure 28: Tire/Pavement Noise Level on Different Surface Types

4.2.6. PT-6 Pavement Performance Tracking

Proposed credit point: 3 points

Proposed credit requirement: provide project construction quality measurements. These construction quality measurements must be submitted in electric format and include, but are not limited to, the data from (1) density tests, (2) water/air content tests, (3) slump tests, (4) compressive strength tests, (5) asphalt content tests, and (6) gradation tests.

For this credit, changes are proposed to both its point and requirement. Two points from MR-1 Lifecycle Assessment are moved to this credit, increasing the total available point to be three. The first reason of doing so is to re-emphasize the importance of this credit. As mentioned earlier, the integration of these construction quality and pavement performance measurements would improve pavement performance through a better understanding of how construction quality influences long-term pavement performance (University of Washington and CH2M HILL, Inc., 2011). The second reason is to expedite the integration of construction quality and pavement performance measurements. PMIS, as described in Section 4.2.1, has been annually updated by TxDOT to keep track of the highway condition over the entire network. Pavement performance measurements in it can be treated as the fulfillment of second part of the original credit. With the construction quality measurements required by the proposed credit, the integration of these two parts of data will be more feasible in Texas.

However, based on the previous observation of this study, the information stored in the SM database is not complete enough for integration and other uses. For example, in the study of PT-2 Permeable Pavement, the amount of PFC is stored by its weight but not by its construction area, making the computation of impervious area unfeasible. Moreover, in the study of PT-3 Warm Mix Asphalt, no information regarding the construction quantity, and the mixing temperature is available. Therefore, it is expected that the proposed credit and the whole system will help to collect project construction information, and to improve the integrity of the current database.

4.3. CHAPTER CONCLUSIONS

In the study, two voluntary credits that are associated with material selection and pavement construction in Greenroads are adjusted to adapt the environmental conditions and the current state of practice in Texas. Table 28 below summarizes the proposed Materials and Resources and Pavement Technologies categories. All of the credits and their available points in these two categories are subject to some adjustment, except for PT-2 Permeable Pavement and PT-4 Cool Pavement. Besides, an achievement encouragement is applied to all of the point scales. Namely, it becomes easier to earn more points with decreasing extra efforts required. By doing so, the proposed rating system will attract the applicants to be more sustainable in their projects.

Table 28: Summary of Proposed MR and PT Categories

Credit	Requirement	Point	Note
MR-1	Deleted	0	Temporarily deleted
MR-2	Reuse a minimum percentage of existing materials by volume or weight as specified	1 – 5	Point scale adjusted
MR-3	Minimize earthwork cut and fill volumes such that the percent difference between cut and fill is less than or equal to 40%	1	Percent difference between cut and fill adjusted
MR-4	Use recycled materials as a substitute for virgin materials	1 – 5	Point scale adjusted
MR-5	(1) Calculate the percentage of the total cost that has been paid to local suppliers within a fifty-mile radius, or (2) Calculate the cumulative hauling distance for each basic material	1 – 5	Point scale adjusted
MR-6	Install lighting systems with luminaries that meet or exceed the 2009 Energy Star standard for roadway lighting	1 – 5	Point scale adjusted

Table 28 (Cont.): Summary of Proposed MR and PT Categories

Credit	Requirement	Point	Note
PT-1	Design at least 75% of the pavement surface area for regularly trafficked lanes to meet the pavement design life as specified	2 – 5	New pavement design life added
PT-2	Compute the total amount of impervious area before and after construction	1 – 3	N/A
PT-3	Reduce the mixing temperature of asphalt mixture to the range of 215°F to 275°F and use it in at least 25% of the paving area	3	Mixing temperature range added; Percent requirement adjusted
PT-4	(1) Use a pavement surface with a minimum albedo of 0.3 or (2) a porous pavement or pavers for a minimum of 50% of the paving area	5	N/A
PT-5	Construct 75% of the paving area with a surface course that produces tire-pavement noise lower than the noise level as specified	2 – 3	Point scale adjusted
PT-6	Provide project construction quality measurements in electric form	3	Points increased; PMS requirement deleted

CHAPTER 5: CONCLUSION

This study proposes changes and adjustments to the Materials and Resources and Pavement Technologies categories of the Greenroads sustainability rating system after analyzing two Greenroads projects in Texas, 1,594 pavement projects from the Site Manager database, and three datasets regarding RAP, WMA and tire/pavement noise from Texas. Based on the analyses conducted as part of this thesis, these changes are proposed to adjust Greenroads in order to make it more achievable yet challenging to the Texas transportation community.

Among thirty-seven voluntary credits in Greenroads, twelve of them from Materials and Resources and Pavement Technologies are selected and studied, because they are more relevant to the material selection and pavement construction parts of a project than to the rest of the voluntary credits. Moreover, with the goal of encouraging the project to be more sustainable when targeting on these twelve credits, a principle of adjustment is applied to almost all of the point scales. In other words, the difference/difficulty between each point level decreases, as higher points are targeted. This principle is expected to familiarize the roadway projects in Texas with this sustainability rating system, and to encourage them to achieve more when implementing these voluntary credits.

Different scales of adjustment are applied to these twelve voluntary credits, depending the differences between each credit requirement and the relevant state of practice in Texas. For MR-1 Lifecycle Assessment, its credit point is temporarily moved to other credits, since performing pavement LCA requires access to many datasets and inputs, which is currently infeasible for roadway projects in Texas. For MR-2 Pavement Reuse, the credit requirement remains unchanged due to the lack of data in the Site Manager database to support any changes. However, with the minimum percent reuse of existing materials fixed, the principle of adjustment is applied to its point scale to encourage using more existing materials. For MR-3 Earthwork Balance, the percent difference between cut and fill in its credit requirement is raised to 40% from 10%, since the data in Site Manager suggests that the adjustment will increase the amount of the qualified projects from 8.18% to 19.62%. For MR-4 Recycled Materials, the credit requirement remains unchanged. Confined by the maximum allowable recycled material specified in the TxDOT specification, the point scale is subject to some adjustment based on the principle of adjustment and the average percentage of RAP used in all of the Texas districts in 2014. For MR-5 Regional Materials, the original credit requirement is kept. Although no relevant information can be found in Site Manager, the principle of adjustment is applied to the calculation of the total cost of local suppliers, and to that of the cumulative hauling distance of all project materials, making them both slightly easier. For MR-6 Energy Efficiency, the data from Site Manager indicates that although LEDs are used in only 33 projects in the past three years, but they account for most of the roadway luminaries in these projects. Therefore, the proposed point scale is adjusted to reflect this observation.

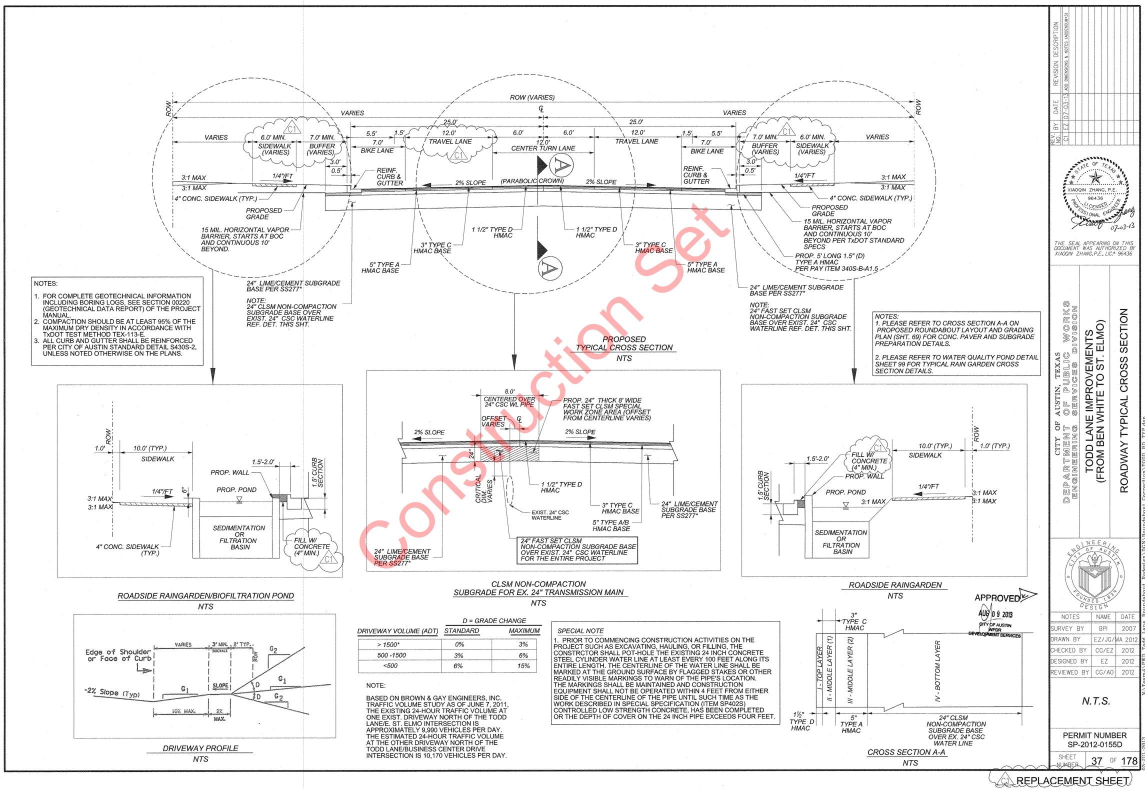
For PT-1 Long-Life Pavement, since the TxDOT specification requires at least a 20-year design life for its pavement projects, the options of long-life pavement design is increased from a 40-year design to 25-, 30-, 35-, and 40-year designs. By providing these choices, the projects in Texas are expected to go beyond the standard specification. For PT-2 Permeable Pavement, neither its credit point nor credit requirement are proposed to be changed, due to the lack of data in Site Manager. However, the construction of permeable friction course and its benefits are introduced as one of the alternatives in the credit. For PT-3 Warm Mix Asphalt, the credit requirement is adjusted to meet TxDOT specification by replacing "reduce the mixing temperature of hot mix asphalt by a minimum of 50°F" with "reduce the mixing temperature of asphalt mixture to the range of 215°F to 275°F". Also, the minimum paving area of WMA is reduced from 50% to 25% based on the dataset provided by the division engineer. For PT-4 Cool Pavement, no change is proposed to its credit point or credit requirement. The units of permeable pavement and concrete pavement are both recorded in tonnage but not in terms of paving area, and therefore, this cannot be used to adjust the original requirement. For PT-5 Quiet Pavement, the required noise level is increased by 3 to 5 dBA according to the tire/pavement noise data available in Texas. Besides, the requirement of test speed at 35 miles per hour is deleted since no data in Texas is provided based on this test speed. For PT-6 Pavement Performance Tracking, the credit point of MR-1 is added to this credit, increasing the total point from 1 to 3. Moreover, only the part of the credit that requires the construction quality measurements is kept, since the second part of the original credit that requires the pavement performance measurements is annually performed in TxDOT.

The proposal of these credit changes is primarily based on the state of practice in Texas roadway projects, including two Greenroads projects, 1,594 TxDOT projects and three datasets from the TxDOT. However, when looking into the future, we expect that the project data analyzed as part of this thesis will help to improve the Site Manager database (or any other TxDOT databases), and to interact with it beneficially. More importantly, the adjustment to the rest of the Greenroads rating system needs to be done so that a more thorough system will be developed to improve the roadway sustainability in Texas effectively. In general, the awareness of sustainability has just been raised in the past few decades. For this effort to be successful, not only the involvement of academia is required, but also the input from industry. It not only affects the lives of our generation, but also those in the coming future. As stated in a quote attributed to Moss Cass, the Australian Minister for the Environment and Conservation in 1974, "*We do not inherit the earth from our ancestors; we borrow it from our children*."

APPENDIX A

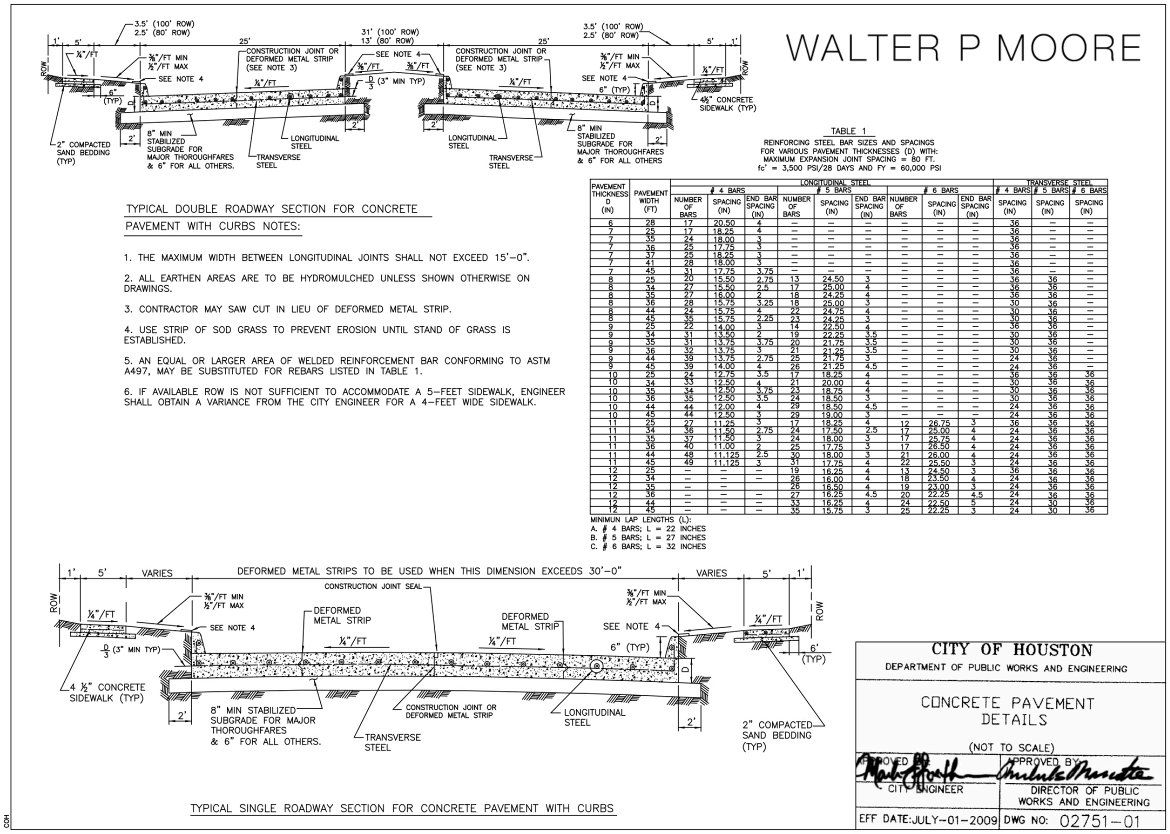
A1: Project Design Plan of the Todd Lane Improvements

Source: City of Austin



A2: Project Design Plan of the Bagby Street Reconstruction

Source: Walter P Moore



TYPICAL DOUBLE ROADWAY SECTION FOR CONCRETE PAVEMENT WITH CURBS NOTES:

1. THE MAXIMUM WIDTH BETWEEN LONGITUDINAL JOINTS SHALL NOT EXCEED 15'–0".
2. ALL EARTHEN AREAS ARE TO BE HYDROMULCHED UNLESS SHOWN OTHERWISE ON DRAWINGS.
3. CONTRACTOR MAY SAW CUT IN LIEU OF DEFORMED METAL STRIP.
4. USE STRIP OF SOD GRASS TO PREVENT EROSION UNTIL STAND OF GRASS IS ESTABLISHED.
5. AN EQUAL OR LARGER AREA OF WELDED REINFORCEMENT BAR CONFORMING TO ASTM A497, MAY BE SUBSTITUTED FOR REBARS LISTED IN TABLE 1.
6. IF AVAILABLE ROW IS NOT SUFFICIENT TO ACCOMMODATE A 5–FEET SIDEWALK, ENGINEER SHALL OBTAIN A VARIANCE FROM THE CITY ENGINEER FOR A 4–FEET WIDE SIDEWALK.

TABLE 1

REINFORCING STEEL BAR SIZES AND SPACINGS FOR VARIOUS PAVEMENT THICKNESSES (D) WITH: MAXIMUM EXPANSION JOINT SPACING = 80 FT. fc' = 3,500 PSI/28 DAYS AND FY = 60,000 PSI

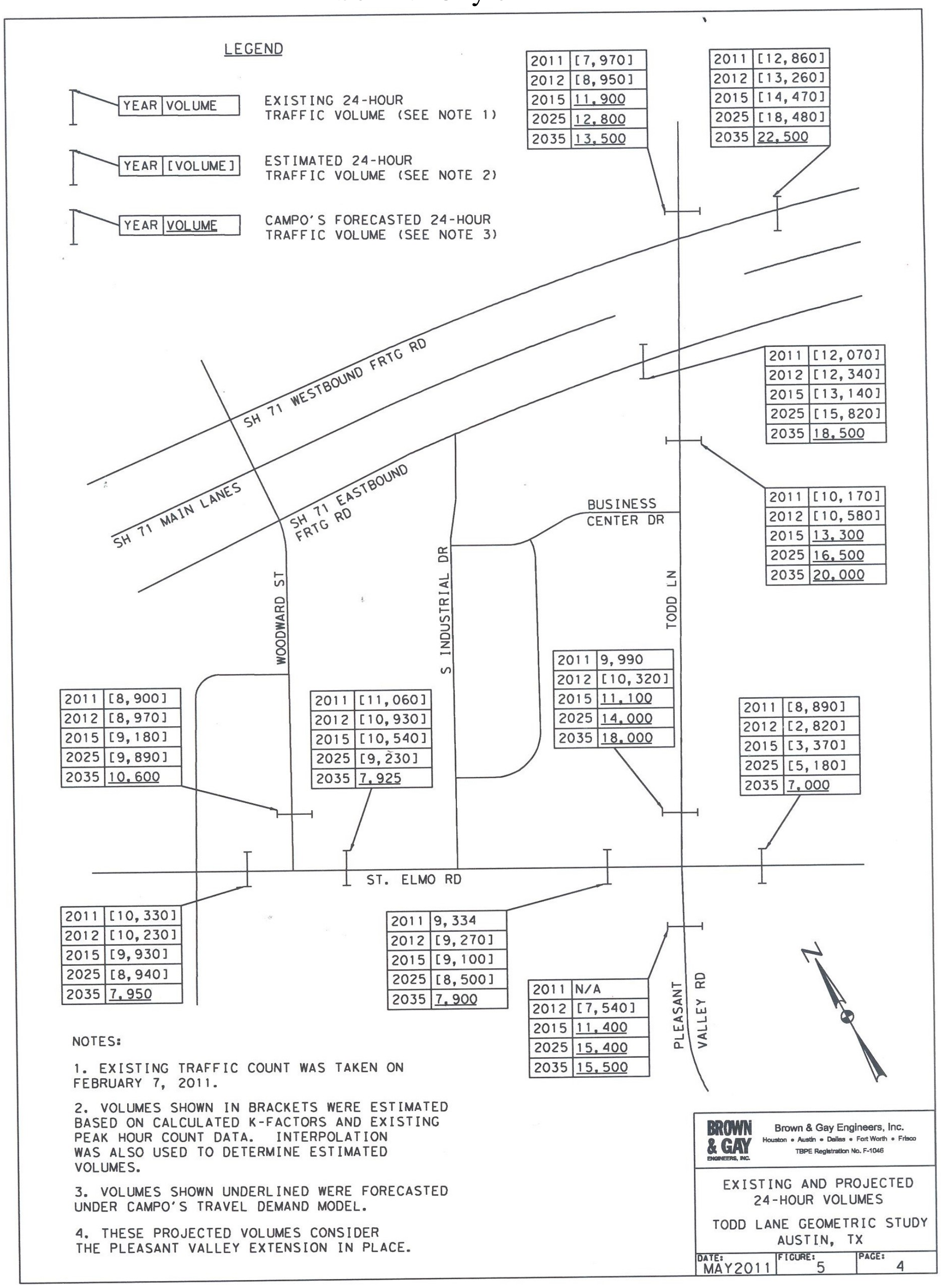
PAVEMENT THICKNESS D (IN)	PAVEMENT WIDTH (FT)	LONGITUDINAL STEEL									TRANSVERSE STEEL		
		# 4 BARS			# 5 BARS			# 6 BARS			# 4 BARS	# 5 BARS	# 6 BARS
		NUMBER OF BARS	SPACING (IN)	END BAR SPACING (IN)	NUMBER OF BARS	SPACING (IN)	END BAR SPACING (IN)	NUMBER OF BARS	SPACING (IN)	END BAR SPACING (IN)	SPACING (IN)	SPACING (IN)	SPACING (IN)
6	28	17	20.50	4	–	–	–	–	–	–	36	–	–
7	25	17	18.25	4	–	–	–	–	–	–	36	–	–
7	35	24	18.00	3	–	–	–	–	–	–	36	–	–
7	36	25	17.75	3	–	–	–	–	–	–	36	–	–
7	37	25	18.25	3	–	–	–	–	–	–	36	–	–
7	41	28	18.00	3	–	–	–	–	–	–	36	–	–
7	45	31	17.75	3.75	–	–	–	–	–	–	36	–	–
8	25	20	15.50	2.75	13	24.50	3	–	–	–	36	36	–
8	34	27	15.50	2.5	17	25.00	4	–	–	–	36	36	–
8	35	27	16.00	2	18	24.25	4	–	–	–	36	36	–
8	36	28	15.75	3.25	18	25.00	3	–	–	–	30	36	–
8	44	24	15.75	4	22	24.75	4	–	–	–	30	36	–
8	45	35	15.75	2.25	23	24.25	3	–	–	–	30	36	–
9	25	22	14.00	3	14	22.50	4	–	–	–	36	36	–
9	34	31	13.50	2	19	22.25	3.5	–	–	–	30	36	–
9	35	31	13.75	3.75	20	21.75	3.5	–	–	–	30	36	–
9	36	32	13.75	3	21	21.25	3.5	–	–	–	30	36	–
9	44	39	13.75	2.75	25	21.75	3	–	–	–	24	36	–
9	45	39	14.00	4	26	21.25	4.5	–	–	–	24	36	–
10	25	24	12.75	3.5	17	18.25	4	–	–	–	36	36	36
10	34	33	12.50	4	21	20.00	4	–	–	–	30	36	36
10	35	34	12.50	3.75	23	18.75	4	–	–	–	30	36	36
10	36	35	12.50	3.5	24	18.50	3	–	–	–	30	36	36
10	44	44	12.00	4	29	18.50	4.5	–	–	–	24	36	36
10	45	44	12.50	3	29	19.00	3	–	–	–	24	36	36
11	25	27	11.25	3	17	18.25	4	12	26.75	3	36	36	36
11	34	36	11.50	2.75	24	17.50	2.5	17	25.00	4	24	36	36
11	35	37	11.50	3	24	18.00	3	17	25.75	4	24	36	36
11	36	40	11.00	2	25	17.75	3	17	26.50	4	24	36	36
11	44	48	11.125	2.5	30	18.00	3	21	26.00	4	24	36	36
11	45	49	11.125	3	31	17.75	4	22	25.50	3	24	36	36
12	25	–	–	–	19	16.25	4	13	24.50	3	36	36	36
12	34	–	–	–	26	16.00	4	18	23.50	4	24	36	36
12	35	–	–		26	16.50	4	19	23.00	3	24	36	36
12	36	–	–	–	27	16.25	4.5	20	22.25	4.5	24	36	36
12	44	–	–	–	33	16.25	4	24	22.50	5	24	30	36
12	45	–	–	–	35	15.75	3	25	22.25	3	24	30	36

MINIMUN LAP LENGTHS (L):
A. # 4 BARS; L = 22 INCHES
B. # 5 BARS; L = 27 INCHES
C. # 6 BARS; L = 32 INCHES

CITY OF HOUSTON
DEPARTMENT OF PUBLIC WORKS AND ENGINEERING
CONCRETE PAVEMENT DETAILS
(NOT TO SCALE)
APPROVED BY: CITY ENGINEER
APPROVED BY: DIRECTOR OF PUBLIC WORKS AND ENGINEERING
EFF DATE:JULY–01–2009 DWG NO: 02751–01

A3: Todd Lane Alternative Geometric Design Study

Source: City of Austin



A4: Traffic Classification Report of Todd Lane

Source: City of Austin

CITY OF AUSTIN
TRAFFIC DATA REPORT
CLASSIFICATION STUDY

Description 1: 4108 TODD LANE
Description 2: 298' South of Business Center Drive
Description 3: NORTHBOUND/SOUTHBOUND

Site: G26JDC
Date: 2/7/2011
Monday

24 Hour Vehicle Classification
Channel: NB

Time	Total	Bike	Cars & Trailer	2 Axle Long	Buses	2 Axle 6 Tire	3 Axle Single	4 Axle Single	<5 Axl Double	5 Axle Double	>6 Axl Double	<6 Axl Multi	6 Axle Multi	>6 Axl Multi
1:00 PM	308	3	166	78	17	25	0	0	11	7	0	0	0	1
2:00 PM	309	1	179	77	12	20	4	0	13	2	0	0	0	1
3:00 PM	387	3	251	80	10	27	0	0	12	1	0	3	0	0
4:00 PM	428	3	259	104	19	31	1	0	8	1	0	2	0	0
5:00 PM	445	2	314	86	11	20	1	0	6	2	0	2	0	1
6:00 PM	337	1	228	64	14	18	1	0	6	0	0	2	0	3
7:00 PM	198	0	135	42	7	14	0	0	0	0	0	0	0	0
8:00 PM	138	0	107	23	0	6	0	0	2	0	0	0	0	0
9:00 PM	99	1	77	17	0	4	0	0	0	0	0	0	0	0
10:00 PM	76	0	58	15	0	3	0	0	0	0	0	0	0	0
11:00 PM	47	0	33	10	1	2	0	0	1	0	0	0	0	0
2/8/2011														
12:00 AM	20	0	17	3	0	0	0	0	0	0	0	0	0	0
1:00 AM	25	0	21	3	0	0	0	0	0	1	0	0	0	0
2:00 AM	26	0	15	9	0	2	0	0	0	0	0	0	0	0
3:00 AM	27	0	17	7	0	3	0	0	0	0	0	0	0	0
4:00 AM	43	0	30	9	0	1	2	0	1	0	0	0	0	0
5:00 AM	96	1	55	30	1	3	1	0	2	2	0	1	0	0
6:00 AM	257	1	137	51	8	22	25	0	6	5	0	2	0	0
7:00 AM	480	3	262	112	29	33	7	1	25	6	0	2	0	0
8:00 AM	429	5	226	104	16	43	9	0	18	7	0	1	0	0
9:00 AM	307	1	168	75	13	29	8	0	4	7	0	2	0	0
10:00 AM	292	2	161	73	7	31	7	0	3	8	0	0	0	0
11:00 AM	264	1	160	59	6	18	7	0	6	7	0	0	0	0
12:00 PM	326	5	193	76	18	19	1	0	7	4	0	1	0	2
Total	5364	33	3269	1207	189	374	74	1	131	60	0	18	0	8
%		0.6	60.9	22.5	3.5	7.0	1.4	0.0	2.4	1.1	0.0	0.3	0.0	0.1

A5: Summary of Minimum Paving Thickness

Source: City of Austin

Table 3-11 Summary of Minimum Paving Thickness

(modified 10/21/02 to include Truck %, Terminal Serviceability, Truck Factor, and Lane Distribution Factor)

Street Classification	Austin Transportation Study (ATS) Designation	ROW Width (Ft.)	Paving Width E-E (Ft.)	Median Width F-F (Ft.)	Initial ADT (VPD)	Percent Growth (%)	Total Equivalent 18 Kip Single Axle Load Applications (20 Year Flexible Design)	Minimum Percent Truck (%)	Minimum Thickness of HMAC Surface Course (In.)	Minimum Thickness of Flexible Base Course (In.)	Terminal Serviceability Index (TSI)	Truck Factor (TF) (average City truck)	Lane Distribution Factor (LDF)
Local (Residential)									***Light Sections***				
SF-1 to SF-2		50	27		500	3.0%	20,000	2.0%	1½"	8"	1.0	0.40	100%
SF-3 to SF-6		56	33		500	3.0%	20,000	2.0%	1½"	8"	1.0	0.40	100%
Collectors									***Medium Sections***				
Residential		60	37		1,000	3.5%	80,000	3.2%	2"	10"	1.5	0.48	100%
Neighborhood		64	41		2,000	4.0%	290,000	5.5%	2"	10"	1.5	0.53	100%
Primary Collectors									***Heavy Sections***				
Commercial	COL	70	45		5,000	4.0%	1,240,000	8.6%	3½"	12"	2.0	0.58	90%
Industrial	COL	90	57		2,000	4.0%	930,000	16.1%	3"	12"	2.0	0.58	90%
Prim, Undiv, 4	COL	70	45		3,500	4.0%	650,000	7.0%	2½"	12"	2.0	0.53	90%
Prim, Undiv, 5	COL	90	57		3,500	4.0%	850,000	8.9%	3"	12"	2.0	0.58	90%
Prim, Div, 4-LN	COL	90	2 @21	16	6,000	4.0%	1,020,000	5.5%	3½"	12"	2.0	0.62	90%
Prim, Div, 6-LN	COL	120	2 @33	23	8,000	4.0%	2,010,000	9.2%	3½"	12"	2.0	0.62	80%
Minor Arterials													
Minor, Undiv.	MNR4	70	48		6,000	4.0%	1,020,000	5.5%	4"	12"	2.5	0.62	90%
Minor, Undiv, 5	MNR5	90	60		8,000	4.0%	2,680,000	11.5%	4"	12"	2.5	0.62	90%
Minor, Div, 4-LN	MAD4	90	2 @24	16	9,000	4.0%	3,020,000	10.9%	4"	12"	2.5	0.62	90%
Major Arterials													
Major, Undiv, 4*	MAU4	70	48		18,000	4.0%	4,000,000	7.2%	5"	12"	2.5	0.84	90%
Major, Div, 6-LN	MAD6	120	2 @36	23	18,000	4.0%	5,200,000	7.8%	5"	12"	2.5	0.84	80%
Major, Div, 8-LN	MAD8	150	2 @48	23	25,000	4.0%	6,300,000	8.3%	5"	12"	2.5	0.84	70%

Note: These values are minimums and are not to be used without verification by a computerized pavement design for specific site subgrade and local traffic conditions. *Major Arterial, Undivided, 4-Lane has been added for consistency with Austin Transportation Study (ATS) documents for proposed roadway configuration MAU4.

TRANSPORTATION 12/21/92 (unofficially modified 10/21/02) Page 3-43

A6: Traffic Volume Report of Todd Lane

Source: City of Austin

CITY OF AUSTIN
TRAFFIC DATA REPORT
VOLUME REPORT

Description 1: 4108 TODD LANE
Description 2: 298' South of Business Center Drive
Description 3: NORTHBOUND/SOUTHBOUND

Site: G26JDC
Date: 2/7/2011
Monday

24 Hour Volume

Begin	NB		SB		Combined		Begin	NB		SB		Combined	
1:00 PM	86	308	74	311	160	619	1:00 AM	11	25	11	21	22	46
1:15 PM	84		73		157		1:15 AM	5		2		7	
1:30 PM	75		68		143		1:30 AM	4		3		7	
1:45 PM	63		96		159		1:45 AM	5		5		10	
2:00 PM	81	309	76	295	157	604	2:00 AM	2	26	15	43	17	69
2:15 PM	63		71		134		2:15 AM	7		15		22	
2:30 PM	90		70		160		2:30 AM	3		7		10	
2:45 PM	75		78		153		2:45 AM	14		6		20	
3:00 PM	110	387	87	342	197	729	3:00 AM	10	27	4	15	14	42
3:15 PM	80		74		154		3:15 AM	5		5		10	
3:30 PM	117		79		196		3:30 AM	8		1		9	
3:45 PM	80		102		182		3:45 AM	4		5		9	
4:00 PM	105	428	89	362	194	790	4:00 AM	9	43	1	16	10	59
4:15 PM	81		97		178		4:15 AM	5		5		10	
4:30 PM	129		90		219		4:30 AM	15		2		17	
4:45 PM	113		86		199		4:45 AM	14		8		22	
5:00 PM	156	445	97	382	253	827	5:00 AM	16	96	15	107	31	203
5:15 PM	104		86		190		5:15 AM	21		18		39	
5:30 PM	92		108		200		5:30 AM	28		26		54	
5:45 PM	93		91		184		5:45 AM	31		48		79	
6:00 PM	110	337	90	308	200	645	6:00 AM	40	257	32	176	72	433
6:15 PM	82		80		162		6:15 AM	59		45		104	
6:30 PM	74		70		144		6:30 AM	71		40		111	
6:45 PM	71		68		139		6:45 AM	87		59		146	
7:00 PM	57	198	65	231	122	429	7:00 AM	99	480	59	291	158	771
7:15 PM	56		68		124		7:15 AM	106		83		189	
7:30 PM	44		48		92		7:30 AM	136		71		207	
7:45 PM	41		50		91		7:45 AM	139		78		217	
8:00 PM	46	138	38	157	84	295	8:00 AM	102	429	85	269	187	698
8:15 PM	37		45		82		8:15 AM	126		77		203	
8:30 PM	30		33		63		8:30 AM	105		56		161	
8:45 PM	25		41		66		8:45 AM	96		51		147	
9:00 PM	30	99	32	121	62	220	9:00 AM	88	307	63	217	151	524
9:15 PM	29		32		61		9:15 AM	76		62		138	
9:30 PM	18		33		51		9:30 AM	65		48		113	
9:45 PM	22		24		46		9:45 AM	78		44		122	
10:00 PM	13	76	45	131	58	207	10:00 AM	79	292	38	202	117	494
10:15 PM	21		31		52		10:15 AM	71		55		126	
10:30 PM	23		31		54		10:30 AM	71		49		120	
10:45 PM	19		24		43		10:45 AM	71		60		131	
11:00 PM	16	47	19	64	35	111	11:00 AM	59	264	70	240	129	504
11:15 PM	12		22		34		11:15 AM	57		50		107	
11:30 PM	15		10		25		11:30 AM	76		55		131	
11:45 PM	4		13		17		11:45 AM	72		65		137	
2/8/2011 12:00 AM	3	20	12	39	15	59	12:00 PM	103	326	57	286	160	612
12:15 AM	6		9		15		12:15 PM	70		73		143	
12:30 AM	7		10		17		12:30 PM	73		82		155	
12:45 AM	4		8		12		12:45 PM	80		74		154	

	NB	SB	Combined
24 Hour Volume	5364 (53.7%)	4626 (46.3%)	9990

	12:00 AM - 12:00 PM			12:00 PM - 12:00 AM		
	NB	SB	Combined	NB	SB	Combined
Count	2266	1636	3902	3098	2990	6088
	58.1 %	41.9 %		50.9 %	49.1 %	
Peak Hour	7:30 AM	7:15 AM	7:30 AM	4:30 PM	5:00 PM	4:30 PM
Volume	503	317	814	502	382	861
Factor	0.90	0.93	0.94	0.80	0.88	0.85

A7: Average Percentage of RAP in Texas Districts

Source: Texas Department of Transportation

DISTRICT	RAP (Tonnage)	Average Percentage (%)
ABILENE	6,127	4.2%
AMARILLO	63,490	16.6%
LUBBOCK	31,099	13.2%
CHILDRESS	5,304	2.5%
EL PASO	28,201	18.4%
ODESSA	9,254	6.2%
SAN ANGELO	0	0.0%
ATLANTA	13,547	10.7%
BROWNWOOD	7,488	13.1%
DALLAS	136,284	15.9%
FORT WORTH	62,525	15.4%
PARIS	8,020	3.4%
TYLER	35,226	12.2%
WACO	66,055	14.4%
WICHITA FALLS	22,898	11.5%
AUSTIN	64,029	9.8%
CORPUS CHRISTI	90,161	19.6%
LAREDO	81,693	16.2%
PHARR	113,763	18.7%
SAN ANTONIO	44,911	10.8%
YOAKUM	52,804	14.7%
BEAUMONT	26,206	18.4%
BRYAN	34,639	11.3%
HOUSTON	83,447	17.1%
LUFKIN	0	0.0%

A8: Average Percentage of WMA in Texas Districts

Source: Texas Department of Transportation

DISTRICT	WMA (Tonnage)	Average Percentage (%)
ABILENE	108	0.1%
AMARILLO	85,080	22.3%
LUBBOCK	22,709	17.9%
CHILDRESS	63,585	9.8%
EL PASO	79,782	55.9%
ODESSA	8,652	15.2%
SAN ANGELO	11,834	3.9%
ATLANTA	0	0.0%
BROWNWOOD	196,692	42.7%
DALLAS	204,070	23.8%
FORT WORTH	107,743	70.2%
PARIS	105,989	26.2%
TYLER	86,316	17.7%
WACO	87,818	17.5%
WICHITA FALLS	117,451	49.7%
AUSTIN	0	0.0%
CORPUS CHRISTI	0	0.0%
LAREDO	77,979	32.7%
PHARR	1,680	0.3%
SAN ANTONIO	0	0.0%
YOAKUM	74,896	17.9%
BEAUMONT	153,153	52.9%
BRYAN	0	0.0%
HOUSTON	122,934	61.5%
LUFKIN	83,690	23.3%

A9: Tire/Pavement Noise Level on Different Types of Pavement Surface

Source: Texas Department of Transportation

Pavement Type	Noise Level (dBA)	
	Average	Range
Permeable Friction Course (PFC)	101.1	98 – 108
Asphalt Rubber PFC	100.1	94.8 – 103.1
Continuously Reinforced Concrete Pavement (CRCP)	104.1	101.2 – 108.8
Untined CRCP	102.3	101 – 104.7
Hot Mix Asphalt – Type C/D	103.3	101.3 – 104.9
Thin Overlay Mixture	99.1	96.3 – 100
HMA - Coarse Matrix-High Binder (CMHB-C)	103.2	N/A
Crack Attenuating Mixture	100.8	N/A
Microsurfacing	100.3	97 – 105.2
Stone Matrix Asphalt	101.5	100.8 – 102
Grade 3 Surface Treatment	106.2	104.2 – 108.2
Grade 4 Surface Treatment	105.8	104 – 109.3
Grade 5 Surface Treatment	104.3	103.5 – 105

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