Data-Driven Sustainability Assessment in Roadway Infrastructure Construction

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Abstract

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Rating systems and life cycle assessment frameworks have been extensively used to measure and evaluate the sustainability performance of roadway infrastructure. However, the existing literature lacks studies that use roadway construction data to evaluate the state of practice and establish performance benchmarks. To bridge the research gaps, this dissertation collected, organized, and analyzed data from 33 Greenroads-certified projects to establish the state of practice in sustainable roadway construction. Data from Greenroads scorecards are first analyzed to evaluate the most commonly pursued sustainable best practices and provide commentary on their level of achievement. This dissertation then conducts a pavement life cycle assessment (LCA) based on project submittals to Greenroads and integrates carbon and energy footprints into pay item lists to analyze correlations between the environmental impacts and financial costs of projects. A whole roadway LCA framework (one that considers all roadway elements beyond just pavements) is further developed and tested using actual construction data mined from 30 Greenroads-certified project documents. Finally, this dissertation introduces twelve data-driven sustainable performance benchmarks to establish the state of practice in roadway construction.

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1 Introduction

Climate change is highly referred to as the phenomenon attributed to the majority of recently experienced impacts on natural and human systems which might be directly or indirectly caused by human activities (IPCC, 2021). Especially, human-related activities (mainly in the form of releasing CO_2) are estimated to have caused a rise of 1°C in global temperature by 2017 (IPBES, 2019), which has and will have tremendous impacts on the ecosystem and its species. Such evidence prompted the global nations to rethink how our civilizations should develop moving forward so that future generations can enjoy the same -and even better- level of human wellbeing, economic prosperity, and a healthy planet (i.e., the three pillars of sustainability). Such a concept is frequently defined as *sustainable development*.

The construction sector assumed an influential role in promoting and implementing sustainable best practices as buildings and infrastructure comprise about 40% of the primary energy consumption globally (Global Alliance for Buildings and Construction, 2019). The U.S. Energy Information Administration (eia) further reports that the transportation sector is responsible for another 26% of energy consumption in the U.S. Such statistics motivated policymakers and environmentalists to reconsider how our built environment is designed and operated. Notably with the recently passed Bipartisan Infrastructure Law (BIL) by the Biden administration, there seems to be potential to take into account sustainability-oriented decisions in the construction and design of transportation infrastructure including roadways.

As Peter Drucker once wrote "what gets measured gets managed," to improve the sustainability of a system, we first need to provide meaningful measures that describe its state. Tracking sustainability using any tool or method would ultimately help evaluate the effectiveness of practices (Armstrong et al., 2013; Griffiths et al., 2018). Bueno et al. (2015) categorize current approaches to roadway sustainability measurement into 1) decision making techniques such as cost-benefit analysis (CBA), multicriteria decision analysis (MCDA) (e.g., Krajangsri and Pongpeng (2019) and Ramani et al. (2011)), life cycle assessment (LCA) (e.g., Chang et al. (2018) and Harrell et al. (2016)), 2) rating systems (e.g., Lee et al. (2013) and Anderson and Muench (2013)), and 3) frameworks, guidelines and models (e.g., Krajangsri and Pongpeng (2019)). Among many possible avenues, this dissertation concentrates on the use of rating systems and LCA as the two sustainability measurement tools for roadways.

To improve the performance of sustainable practices, we need some benchmarks to establish the state of practice. Once established, performance benchmarks can become the new yardsticks against which sustainability practices can be compared. However, the existing body of knowledge on sustainable performance benchmarks in roadway construction is lacking, especially when compared to its building counterparts. This is especially true for data-driven benchmarks that are directly obtained from actual roadway construction projects, the area in which this dissertation attempts to contribute. The following section uses the case of building rating systems as a reference and compares that against the roadways to highlight the research gaps in sustainable roadway construction.

1.1 Research Gaps

In the U.S., the building industry was a sustainability pioneer with the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) rating system development in the 1990s (Cole and Larsson, 1999) to measure and establish the state of practice in building construction. The transportation infrastructure sector, having started a decade after the building's counterpart and with slower progress, is less mature. The existing literature on roadway sustainability are overwhelmed with 1) identifying sustainability indicators and developing associated measurement tools or frameworks (e.g., (Armstrong et al., 2013; Boz and El-Adaway, 2015; Chang et al., 2018)), 2) reviewing existing rating systems and comparing scopes and applicability (e.g., (Clevenger et al., 2016; Mattinzioli et al., 2020; Oluwalaiye and Ozbek, 2019)), and 3) case studies that evaluate individual projects using a rating system or an LCA framework/tool (e.g., (Anderson and Muench, 2013; Lew et al., 2016; Tsai and Chang, 2012)).

To better understand the general trends of research on the state of practice in sustainability and performance benchmarks for building and infrastructure, a literature review using the Scopus database is conducted. Journal articles, conference papers, and review papers published between 2010 to 2022 are considered for review. The title and abstract of articles comprise the main attributes of the database. The search keywords include a combination of "building," "LEED," "rating system," "infrastructure," and "roadway," resulting in a total of 2,934 titles. Articles were first divided into two broad categories of *LEED for Buildings* and *Roadway Rating Systems*. After removing irrelevant articles, 1,075 articles remained for further analysis. Articles in both categories are further grouped into the following common research topics:

- Introduction. Describing a new rating system, model, tool, or framework including using it on one or more test projects to measure sustainability.
- Testing and replication. Using a rating system or sustainability assessment framework on a project to check functionality and performance.
- Critique. Provide a critique of a rating system or suggest new credits/ideas.
- Comparison. Compare multiple rating systems or some aspects of them.
- Benchmarking. Establish benchmarks in performance. Could be a rating system score, or a level of accomplishment.
- Economics. Studies that involve economic analysis of achieving sustainability goals described in rating systems.
- State of practice. Attempts to describe what is being accomplished in practice using a rating system as the measurement tool; can involve surveys and interviews.

Figure 1.1 is a summary of the literature review findings. At the first glance, there are three times more research articles published on some aspects of LEED (813 titles) than on roadway rating systems (262 titles). Research on LEED is rather evenly distributed over the seven topics, with more articles published on the *Testing and replication* and *State of practice* categories. However, the establishment of standard guidelines and performance benchmarks seem to be missing from most studies on infrastructure rating systems including roadways (less than 4% of research).

Despite extensive research on the state of the art in sustainable practices, the existing literature lacks studies that look at 1) the state of the practice in roadway sustainability (i.e., which practices are being done and with what frequency) and 2) the establishment of sustainability performance benchmarks (i.e., how much is considered good or bad). While meaningful when compared across projects, rating system indicators and scorecards alone are generally unable to set performance benchmarks and standard requirements.

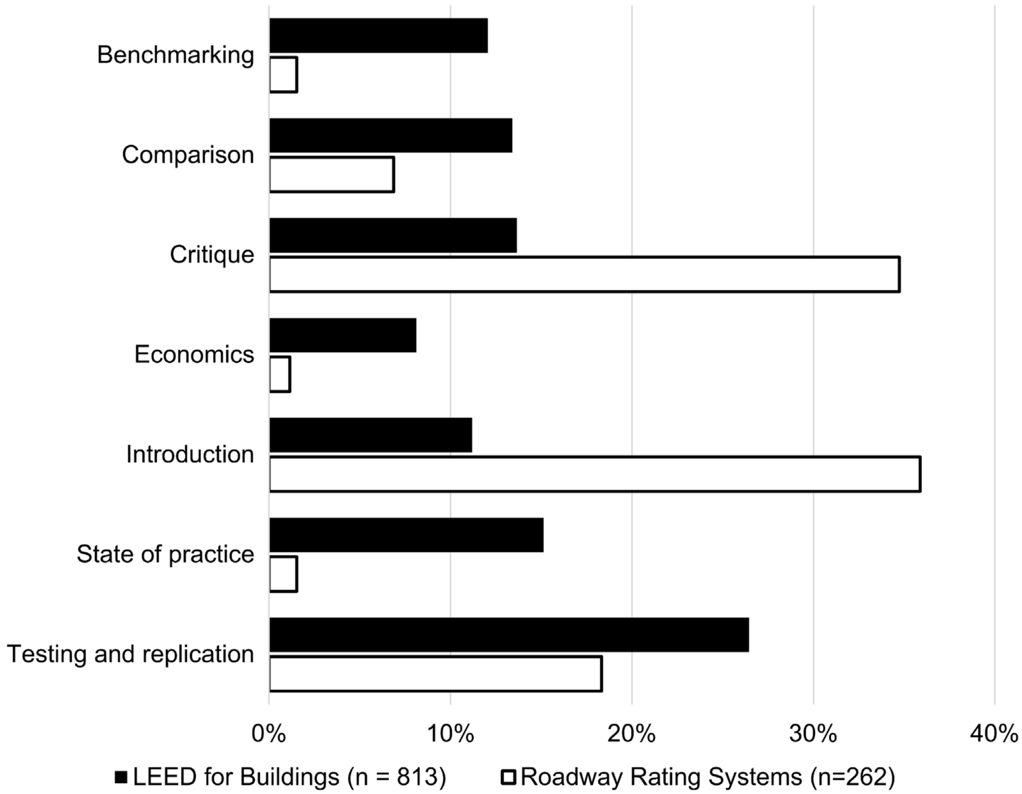

Figure 1.1 Literature review summary on the use of rating systems for buildings and roadway infrastructure broken down by research topics.

1.2 Research Questions and Scope

This dissertation asks, *what is the state of practice for sustainable roadway design and construction?* This is done by aggregating investigations of the following key questions:

1. What is the value of rating systems in measuring and assessing the state of practice in roadway construction? There has been extensive research and knowledge around particular sustainable roadway construction practices but a holistic view using actual project performance data is scarcely done. For example, what are the most commonly performed sustainable practices that roadway projects undertake? What other practices exist that projects either do not perform or have limited knowledge of? This dissertation uses rating system data and scorecards obtained from 33 Greenroads-certified projects to investigate the most and least commonly pursued sustainable roadway construction practices.
2. What are the quantitative environmental impacts of building a sustainable roadway project? While this has been answered using life cycle assessment (LCA) for singular projects, hypothetical

design parameters, or using aggregate LCA information for roadway projects in general, this dissertation uses multiple project datasets to establish trends and relationships with other key variables. For instance, what are the expected greenhouse gas emissions from the pavement structure of a $10 million sustainable project? To answer this question, LCI submittals from 32 Greenroads-certified projects are analyzed to perform a cradle-to-construction LCA on pavements. A whole roadway LCA framework is further developed based on a collection of construction data from 30 projects to expand the scope from pavements to all roadway elements.

3. <u>How can project data be used to establish performance benchmarks for sustainable best practices?</u> We usually know what to measure but have little information to judge relative achievement. For instance, does 10,000 gallons of water used on a $3 million arterial rebuild project constitute good performance or poor performance? This dissertation uses construction data from 33 Greenroads-certified projects and the whole roadway LCA models developed earlier to address the questions that were previously asked either from a single project or a small project set, or proposed theoretically using more generic, aggregate, or assumed information.

This dissertation leverages Greenroads resources because of the author's professional ties with the Greenroads CEO and its board of directors through involvement in Greenroads during two summer internships. Finally, it is worth noting that the dataset is limited to documents submitted by project teams for Greenroads certification purposes and is not necessarily an exhaustive list of all documents produced for project delivery.

1.3 Background

Although the diverse data needed to describe roadway infrastructure and its level of sustainability achievement exists (contracts, plans, specifications, tests, and inspections generated, collected, and archived as part of the design and construction process) such data are difficult to access given contemporary archiving methods (Yamaura, 2018). However, Greenroads International (now, Sustainable Transport Council), an independent 501(c)(3) non-profit corporation that was founded in 2010 and owns the Greenroads Rating System, has collected and retained a large repository of project data as part of its third-party certification mechanisms. The author had unique access to the Greenroads database during two summer internships in 2018 and 2019. This dissertation uses the data cleaning, validation, aggregation, and summarization efforts for 33 Greenroads-certified projects with a total construction cost of over $2.3 billion. This is the first time that such a large dataset is being used to create the state of the practice information on sustainable roadways and set data-driven performance benchmarks for individual and project-level sustainability achievements.

1.3.1 About the Greenroads Rating System

The Greenroads Rating System is a collection of sustainable roadway construction best practices (called credits) grouped into several categories based on sustainability theme areas. To date, Greenroads has released several versions with version 3 under review for publication. The majority (28 out of 33) of projects reviewed in this dissertation were certified using Greenroads version 1.5 (hereafter abbreviated to v1.5) (Muench et al., 2011), with the rest (5 out of 33) certified under version 2. Therefore, this dissertation uses v1.5 as a reference and converts project scores from version 2 (see **Section 8.1.2** for more details on the conversion).

1.3.2 Greenroads Credits Structure

Greenroads v1.5 consists of 11 project requirements and 37 voluntary credits (subdivided into 7 categories), and 13 custom credits (credits added after the initial version release based on project inputs). Project requirements are not worth any points, and voluntary credits are worth 1-5 points based on sustainability impact. Specifically, Greenroads v1.5 uses seven themes to allocate credit weights (from 1 to 5) to each credit based on their impact: 1) ecology, 2) equity, 3) LCA-based weighting, 4) incentive-based weighting, 5) developed area weighting, 6) durability weighting, and 7) aesthetics weighting.

To obtain Greenroads certification, projects must achieve all *Project Requirements* and may choose to pursue as many voluntary credits (called Core Credits in Greenroads) as they wish with certification levels corresponding to the number of voluntary credit points achieved: Bronze (32 to 42 points), Silver (43 to 53 points), Gold (54 to 63 points), and Evergreen (64 points and above). See **Table 8.1** for similar details on version 2. **Table 1.1** is a summary of Greenroads v1.5 credits, categories, brief descriptions, and score distributions. Refer to Greenroads v1.5 manual for more info.

Table 1.1 List of Greenroads credits, description, and score distribution.

No.	Credits	Pts.	Description and Criteria
Project Requirements (PR)		**All**	
PR-1	Environmental Review Process	req	Complete a comprehensive environmental review
PR-2	Lifecycle Cost Analysis (LCCA)	req	Perform LCCA for pavement section
PR-3	Lifecycle Inventory (LCI)	req	Provide LCI data for the pavement materials
PR-4	Quality Control Plan	req	Have a formal contractor quality control plan
PR-5	Noise Mitigation Plan	req	Have a construction noise mitigation plan
PR-6	Waste Management Plan	req	Have a plan to divert C&D waste from landfill
PR-7	Pollution Prevention Plan	req	Have an erosion or stormwater pollution control plan
PR-8	Low-Impact Development (LID)	req	Complete a LID feasibility study
PR-9	Pavement Management System	req	Have a pavement management system
PR-10	Site Maintenance Plan	req	Have a roadside maintenance plan
PR-11	Educational Outreach	req	Publicize sustainability information for the project
Environment & Water (EW)		**21**	
EW-1	Environmental Management System	2	ISO 14001 certification for the general contractor
EW-2	Runoff Flow Control	1-3	Do not increase runoff quantity by more than 20%
EW-3	Runoff Quality	1-3	Treat at least 80% of stormwater
EW-4	Stormwater Cost Analysis	1	Conduct an LCCA for stormwater elements
EW-5	Site Vegetation	1-3	Use native low/no water vegetation
EW-6	Habitat Restoration	3	Restore 5% more area than required or create one
EW-7	Ecological Connectivity	1-3	Install or upgrade existing habitat-friendly facilities
EW-8	Light Pollution	3	Dark-Sky compliant lighting fixtures
Access & Equity (AE)		**30**	
AE-1	Safety Audit	1-2	Perform roadway safety audit
AE-2	Intelligent Transportation Systems	2-5	Install at least 1 application in 2 ITS categories
AE-3	Context Sensitive Solutions	5	Fill out the CSS National Dialog form
AE-4	Traffic Emissions Reduction	5	Reduce emissions with congestion pricing
AE-5	Pedestrian Access	1-2	Provide/improve pedestrian accessibility
AE-6	Bicycle Access	1-2	Provide/improve bicycle accessibility
AE-7	Transit & HOV Access	1-5	Provide/improve transit accessibility
AE-8	Scenic Views	1-2	Project is part of the National Scenic Byways Program
AE-9	Cultural Outreach	1-2	At least 1% of budged is dedicated to art
Construction Activities (CA)		**14**	
CA-1	Quality Management System	2	ISO 9001 certification for the general contractor
CA-2	Environmental Training	1	Provide environmental training
CA-3	Site Recycling Plan	1	Have a plan to divert waste from landfill
CA-4	Fossil Fuel Reduction	1-2	Construction equipment alternative fuel usage is at least 15%
CA-5	Equipment Emission Reduction	1-2	EPA Tier 4 standards for at least 50% of equipment fleet hours
CA-6	Paving Emission Reduction	1	At least 90% of the HMA placed use a NIOSH-certified paver
CA-7	Water Use Tracking	2	Develop data on water use in construction
CA-8	Contractor Warranty	3	5-year minimum warranty on the constructed pavement

No.	Credits	Pts.	Description and Criteria
Materials & Resources (MR)		**23**	
MR-1	Lifecycle Assessment (LCA)	2	Conduct a detailed LCA of the entire project
MR-2	Pavement Reuse	1-5	Reuse at least 50% of existing pavement sections
MR-3	Earthwork Balance	1	Cut and fill difference ≤ 10%
MR-4	Recycled Materials	1-5	%Recycle pavement materials ≥ 10 or all project materials ≥ 20
MR-5	Regional Materials	1-5	Minimum 60% of material costs in a 50-mile radius of project
MR-6	Energy Efficiency	1-5	At least 20% of installed luminaires are energy efficient
Pavement Technologies (PT)		**20**	
PT-1	Long-Life Pavement	5	Design life of at least 75% of pavement area ≥ 40 years
PT-2	Permeable Pavement	3	Treat ≥ 50% of stormwater runoff to a TSS ≤ 25 mg/L
PT-3	Warm Mix Asphalt (WMA)	3	Reduce HMA temperature (>50F) and for > 50% of pavements
PT-4	Cool Pavement	5	Albedo >0.3 or porous pavement for more than 50% of area
PT-5	Quiet Pavement	2-3	Maximum average noise level < 99 dBA
PT-6	Pavement Performance Tracking	1	Collect construction quality and pavement condition data
Custom Credits (CC) (added later)		**10**	
CC-1	Sustainable Transportation Professional	1-5	Obtain STP for up to two project team members
CC-2	Workzone Safety	1-5	Minimize safety and health hazards of constructions
CC-3	Pavement Smoothness	1-5	Ensure satisfactory pavement roughness
CC-4	Roadside Revegetation	1-5	Reduce hardscape areas and increase greenspace
CC-5	Electric Vehicle Infrastructure	1-5	Provide charging stations for electric vehicles
CC-6	Alternative Energy	1-5	Reduce or avoid fossil fuel energy needs
CC-7	Freight Access	1-5	Provide dedicated lanes for freight
CC-8	Design for Disassembly	1-5	Design to facilitate future changes and dismantlement
CC-9	Volatile Organic Compounds Reduction	1-5	Ideas to reduce the VOC footprint of project materials
CC-10	Runoff Treatment Upgrades	1-5	Provide facilities to treat runoff water in-site
CC-11	Site Remediation	1-5	Treat contaminated soil in-site
CC-12	Safety Analysis	1-5	Support safety enhancements by data-driven methods
CC-13	Species Translocation	1-5	Improve biodiversity by dislocating native species
Total Possible Points		**118**	

1.3.3 Greenroads Certification Procedure

There are four main steps projects must take to earn certification. They are listed below:

- Application: Projects pursuing certification first submit a free *screening application* so that the Greenroads team can discuss with the project whether seeking certification is feasible given the scope of the project. Projects must be real property and serve a transportation purpose to become eligible to apply, with motorized facilities being the most common. Greenroads recommends the best path to participate in the rating program and creates an entry in the website database with basic information about the project and points of contact. Greenroads will contact project teams to discuss the project and provide an estimation of the fees. If approved, Greenroads staff set up the project to proceed to registration.

- Registration: Once registration fees are paid and registration agreements signed, the registration is complete and projects can access the Greenroads online platform (called workspace). Most importantly, the platform allows project teams to submit documents and track their progress. During registration, projects also indicate which Greenroads credits they might, or plan to, achieve points for; this will later be called *expected scores*.
- Pilot project assessment: Greenroads offers an initial assessment of projects based on some standard documents (mostly from the PR category) and interviews with project teams. For this assessment, projects are not required to provide detailed construction documents, rather demonstrating intent alone is sufficient. The final product of the initial assessment is a scorecard indicating potential scores projects can obtain in addition to feedback from Greenroads about the possibility of earning certification.
- Certification: Greenroads offers third-party assessment and certification for documented project activities. Project teams are responsible for selecting their desired Greenroads credits and uploading supporting documents to the Greenroads website for the review process. At least one Greenroads reviewer is assigned to the project. The main role of the reviewer is to evaluate projects' adherence to credit instructions and requirements and provide feedback for the submitted documents. The reviewer's findings would then need confirmation from a Greenroads board member. The final product of Greenroads evaluation is a scorecard (and a certification badge/sign accordingly) indicating which credits projects earned points for; we call this *awarded score*. Among registered projects, however, only a limited number make it to the certification level.

1.3.4 Scope of the Greenroads Rating System

Greenroads sets some eligibility criteria for projects to participate in certification. For example, projects must: legally comply with federal regulations, be part of a transportation master plan approved by all local public agencies, have at least one centerline and be located on real property, have more than 50% of funding approved and be expected to receive full funding within 2 years, include transportation-related improvements for a total disturbed area of more than 5,000 square feet, etc.

Furthermore, project boundaries must be determined prior to certification, preferably during the screening application process. Certification is only offered for projects with a continuous perimeter. Greenroads at least considers the limits of construction and the owner(s) of the real property under development when determining project boundaries. When project boundaries differ from construction limits, Greenroads breaks down the project into multiple certifiable segments that meet the continuity criteria and calls the collection of projects a *Program*. A Greenroads Program is certified when all its individual segments are certified.

1.3.5 Greenroads Data

Greenroads collects project documents using its online platform and stores them in Amazon Web Services (AWS) cloud storage. Overall, this dissertation evaluated 52 certified Greenroads projects that constitute about 13 gigabytes worth of information from over 4,300 documents submitted between 2011 and 2018. Greenroads divides large projects in terms of area or contract size (called *Programs*) into several pieces for the sake of defining certification boundaries, and recognizes each as a separate project (called project segments). Since programs sub-divided into segments share many identical documents, this dissertation aggregates all segments from the same project into one larger project for analysis. This resulted in 33 analyzed projects. Data collection took place over two summer internships in 2018 and 2019 at Greenroads International in Redmond, Washington.

This dissertation uses three main data types available from the Greenroads platform. First, the project portfolios provided descriptive information about each project (size, budget, scope of work, contractor, client, etc.). Second, the Greenroads web-based platform produces two scorecard spreadsheets per project summarizing *expected scores* (as claimed by project teams) and *achieved scores* (as evaluated by Greenroads). These scorecards also include the feedback from Greenroads on why a credit did not achieve an expected score, or whether further supporting documents were required to award points. Third, projects pursuing certification submit to Greenroads, through the web interface, supporting documents or information as evidence for satisfying Greenroads project requirements and voluntary credits. Project submittals in the form of pdf (scanned or digitized), word documents, pictures, and spreadsheets account for the bulk of this data. It was sometimes the case that projects submitted more documents than required either voluntarily, mistakenly, or upon request. All project documents were used for data collection and analysis.

1.3.5.1 Data Tiers

The quality of documents submitted for Greenroads certification (i.e., the third type of data explained above) varies depending on the type of information inquired. Generally, data types can be grouped into three tier categories: primary, secondary, and tertiary. Approved or as-built project plans and documents are assumed primary data. Secondary data are those that were not required for project delivery or were not officially approved by any other entity than the project teams or Greenroads. Submittals that required some amount of calculations and were largely not included in any project documents are considered tertiary data. However, this dissertation does not perform a numerical quality assessment of data for the first and second studies (**Chapters 2** and **3**) and only provides a qualitative assessment of data quality in the original dataset. The third study (**Chapter 4**) is more involved with data (mostly primary and secondary) and presents a separate LCA data quality assessment (**Section 8.2.2.3.1**). The following provides a brief introduction of the three data tiers with example documents:

- Primary: Documents and plans prepared by the project team for the sake of design or construction.
    - Examples: project specifications, project submittals such as pavement mix designs, as-built or design drawings, waste management plans, as-built pay item lists, stormwater and erosion control plans (or pollution prevention plans), spill plans, environmental impact statements, and quality control plans.
- Secondary: Documents prepared mainly for the sake of Greenroads certification or satisfying required credits. This mostly includes documents showing evidence of activities. Also included under this category are unofficial and provisionary documents.
    - Examples: engineer's estimate of pay items, noise mitigation plans, public and cultural outreach plans, long-life pavement design evidence, context sensitive solutions,

construction water tracking documents, pavement management system records, site maintenance plans, and internal memorandums that state evidence of using particular products such as light-emitting diode (LED) lights and Darksky luminaires or the use of warm mix asphalt (WMA) technologies.

- Tertiary: Documents required to achieve scores for a mandatory or voluntary credit. These documents typically require project teams to collect information or provide evidence while undertaking additional calculations/estimates not necessary for project delivery.
    - Examples: lifecycle inventory (LCI) and lifecycle assessment (LCA), lifecycle cost analysis (LCCA), material supplier tracking, recycled materials content, pavement reuse content, earthwork balance, and evidence of pedestrian/bicycle/transit access.

1.3.5.2 Greenroads Data Availability and Anonymity

As part of the agreement between Greenroads and project teams upon signing the contract, project data are not publicly available. I had unique access to use the Greenroads database for educational purposes during my two internships. In this dissertation, the anonymity of project data is preserved and project identities are not disclosed. The final datasets are packaged into several Excel worksheets and are partially became available (see **Chapter 9**). Finally, this dissertation follows the data collection processes and data sources explained above for all sections unless specified within the relevant chapter. Subsequent chapters are divided up based on the nature of the analysis carried out on this data.

1.4 Contributions

This dissertation offers contributions in five main areas:

- Define the state of the practice for sustainable roadway projects using the Greenroads rating system. Greenroads scorecard data are used as a metric for sustainability achievement and analyze the gaps between expectation and achievement. This is primarily an update and expansion on Lew et al. (2016).
- Estimate greenhouse gas emissions and energy consumption associated with sustainable roadway projects. This dissertation uses pay item lists (similar to Mukherjee et al. (2013)) and project documents to extract material types and quantities, transportation distances, and

construction equipment runtime to conduct LCA on entire roadway systems. The analysis also identifies the limitations of performing LCA on a whole roadway (e.g., the percentage of project costs that can be included in LCA) as well as some rules of thumb correlations based on costs, emissions, energy, material types, and construction categories.

- Set benchmarks for quantifiable sustainability measurements. Measurable sustainable practices within Greenroads (e.g., the total amount of local materials, recycled materials, or water used) are collected and summarized with suggested performance benchmarks.
- Provide critical feedback to the Greenroads rating system on its functionality. Rating systems like any other tools or software require revisions and modifications. After spending so much time digging into Greenroads data and its working mechanism, this dissertation will contribute in part to the improvement of the Greenroads rating system. Upon its completion, this dissertation is an opportunity to express feedback on the strengths and weaknesses observed in Greenroads and rating systems in general.
- Produce and publicize a ready-to-use dataset for future research endeavors on roadway sustainability. The data collected as part of this dissertation is invaluable. Several person-hours were spent on collecting and preparing the datasets in use of this dissertation. Such a dataset is worth exploring by other researchers and this dissertation contributes to the body of knowledge by providing open access to its main datasets.

1.5 Dissertation Format

This dissertation contains the following chapters:

- **Chapter 1** introduced research gaps within the literature, research scope, contributions of this dissertation, and a summary of data collection efforts.
- **Chapter 2** summarizes the data collection results and introduces the state of the practice for roadway construction projects pursuing sustainability. It will also discuss the differences between projects' perceptions and achievement of sustainability best practices.

- **Chapter 3** uses life cycle inventory (LCI) submittals from project teams to evaluate greenhouse gas emissions and energy consumption of roadway paving materials and investigates the possibility of integrating LCA frameworks into pay item lists to better communicate LCA results.
- **Chapter 4** develops a data-driven approach to providing quantitative measures for sustainable best practices. This chapter would then introduce twelve sustainable performance benchmarks based on the collected project data that encompass several aspects of a sustainable roadway design and construction. A whole roadway lifecycle assessment (LCA) framework that integrates with projects' pay item lists is also developed in this chapter. It will also manage to find the environmental footprints and financial costs associated with different construction categories and material types.
- **Chapter 5** uses an example research project funded by the Washington State Department of Transportation (WSDOT) to showcase the implications of the whole roadway LCA framework and its associated models built as part of **Chapter 4** in estimating state-wide greenhouse gas inventories related to roadway infrastructure construction.
- **Chapter 6** discusses the findings and limitations of the methods and analysis.
- **Chapter 7** summarizes the dissertation chapters and provides overall conclusions.
- **Chapter 8** includes supplementary materials about different Greenroads versions, Greenroads Rating System structure, data collection, pay item list analysis, and LCA background data.
- **Chapter 9** explains the accessible datasets created in this dissertation. It also explains the type of data made available in an online data repository and provides metadata and context about those datasets.
- **Chapter 10** lists the bibliographical information.

2 Application of the Greenroads Rating System in Establishing the State of the Practice in Sustainable Roadway Construction

2.1 Preface

It was discussed in the previous chapter that the existing literature lacks studies that use actual roadway project performance data to investigate the state of the practice in sustainable construction. This chapter describes the power of rating systems in quantifying, assessing, and communicating the state of practice by using data from 33 Greenroads-certified projects. Although a rating system like Greenroads might be perceived as a certification mechanism to help projects gain recognition for sustainable performance, it manifests itself as a data collection tool with ample implications in research and development. This chapter takes advantage of data generated and collected by Greenroads during the certification process of roadway projects to investigate the state of practice in sustainability.

As of August 2022, a substantial amount of this chapter and **Chapter 3** is submitted for publication in *Transportation Research Record*. A few sections under this chapter are excluded from the submitted paper due to the journal's word limit. The excluded sections are those related to the questions about expected vs. achieved sustainability performance and sustainability benefits mapping (**Sections 2.6.3**, **2.6.4**, **2.7.2**, **2.7.3**, **2.8.4**, and **2.8.5**) and their sub-sections.

2.2 Abstract

This chapter highlights the application of the Greenroads Rating System in collecting and measuring sustainable best practice data in the context of roadway infrastructure construction. Once measured, meaningful comparisons between common practice and what goes above and beyond routine can be recognized, educated, advertised, spread, and finally, implemented. This chapter collected, organized, and analyzed rating system data from 33 Greenroads-certified roadway construction projects completed between 2011 and 2018 with a total value of over $2 billion. It can be argued that such a database is scarce within the literature and is worth exploring.

Greenroads scorecards, which indicate the level of achievement in sustainable construction practices, were analyzed to show the frequency in which best practices are pursued or left unattended. This chapter

also compares project teams' perception of sustainability and its actual achievement by performing a gap analysis between the expected and awarded Greenroads scores. Findings suggest that projects typically perform activities that can be considered common practice and avoid activities that fall outside of their prior experience realm. Finally, a mapping algorithm is proposed in this chapter that can be used to translate sustainability indicators across different definitions, for example, from the realm of rating system indicators to a broader context of tangible sustainability benefits or the Sustainable Society Index.

2.3 Introduction

The Greenroads Rating Systems (Greenroads, 2022) has been used to rate and certify roadway projects for sustainability for over 10 years. In doing so, it has become a good proxy for what can be considered sustainability best practices, and it has built up a substantial database of sustainable roadway infrastructure design and construction information that can be mined to determine the state of practice for roadway sustainability and provide benchmarks for the future. Now, as climate change concerns have pushed the world toward greenhouse gas emission reduction targets (e.g., the 2015 Paris Agreement (UNFCCC, 2015)), and national legislation has begun to provide substantial funding for sustainability efforts (e.g., the Bipartisan Infrastructure Law), it is appropriate to revisit the state of practice for roadway infrastructure sustainability as we begin to set baselines for sustainability and targets for improvement.

2.3.1 Literature Review

To better understand the background of research on rating systems within the broader area of construction, the following sections provide a brief review of the evolution of rating systems in the building and infrastructure contexts while using some example articles to demonstrate the purpose.

2.3.1.1 Sustainability Implementation in Construction

The building industry acts as the pioneer of sustainability implementation in construction with the advent of the Leadership in Energy and Environmental Design (LEED) rating and evaluation system in 1998 (Bocchini et al., 2014). LEED is a credit-based system consisting of a series of activities and requirements for project teams to partake in and implement. In the decade following the emergence of LEED, similar sustainability evaluation and rating systems have been developed to assess and measure the sustainability of infrastructure construction projects (Griffiths et al., 2019). Those systems span over the fields of transportation, ecology, water and wastewater management, among others. Infrastructure sustainability rating systems are usually centered around the transportation sector and its infrastructural elements including but not limited to roads, traffic, and water and wastewater collection systems.

Sustainability consideration is not an alien topic in many of the missions and visions of the Departments of Transportation (DOTs), however. Ramani et al. (2011) proclaim that while sustainability might not be explicitly required within state DOTs' visions, issues such as environmental impact, future needs, and social equity are touched upon in many instances. Moreover, as guided by the National Environmental Policy Act (NEPA), federal-level mandates are enforced on some major projects where an Environmental Impact Statement (EIS) is required (Zietsman et al., 2011). Regulations such as NEPA, Clean Water Act, Clean Air Act, and the Federal Highway Administration's (FHWA) MAP-21 already imposed many standard practices on project development (Armstrong et al., 2013; Clevenger et al., 2016). Nevertheless, a clear measure of sustainability and its associated performance metrics are missing from current state or federal level regulations.

2.3.1.2 Infrastructure Sustainability Rating Systems

Indicators and criteria defined to constraint sustainability in the context of infrastructure construction are vast and are typically unquantifiable. Sustainability rating systems, in this essence, are structured to assign quantifiable points to a variety of best practices categorized into a limited number of rating criteria (Muench et al., 2010). Despite being different in their scope, rating systems share many common goals; among those are: the creation of a rating scheme and point system for quantitative evaluation of qualitative measures; promoting sustainability, accountability, and informed decision making; advocating construction best practices as baseline standards; and adhering to standard regulations while going above and beyond common practice (Bocchini et al., 2014; Chang et al., 2018; Gupta et al., 2016; Lew et al., 2016; Muench et al., 2012a, 2010).

2.3.1.2.1 Roadway Rating System Case Studies

There have been a few studies that employed rating systems (mostly Greenroads as it relates to this dissertation) and/or data from actual roadway construction projects to evaluate their sustainability achievement. They are typically limited to one or a few projects data or use rating system scores for analysis. Tsai & Chang (2012) are among the first that used information from four actual construction projects, with contract amounts between $270,000 to $5,630,000, in evaluating their sustainability efforts. Although not quantitatively analyzed, they allege that sustainability indicators were incorporated by project teams and that the designers expressed sufficiency of those indicators for consideration in highway construction projects. Muench, Armstrong, et al. (2012) deployed Greenroads to evaluate seven Federal Land Highway projects. In their study, sustainability practices were evaluated against Greenroads v1.5 credits to figure out the most commonly achieved practices; however, no performance measures were reported.

In another study, Muench, Scarsella (now Lemeire), et al. (2012) used Greenroads to rate three Oregon DOT projects to exemplify and assess the alignment of Greenroads direction to their agency priorities. That study, again, relied on the Greenroads credit scheme and minimal project information and did not provide any actual performance measures. Anderson & Muench (2013) used information from 40 projects identified as sustainable and 65 conventional projects and concluded that Greenroads can differentiate their sustainability performance. They further state that there is a lack of performance data to set baselines and reference points to compare current practices against sustainable ones. Lew et al. (2016) have probably conducted the most comprehensive study to date on the performance of 19 Greenroads-certified projects, aiming at identifying performance trends using Greenroads as the scale and informing the state of practice in roadway sustainability rating systems. Although unique in using a dataset of certified projects, the primary information analyzed in their study relied on the Greenroads scoring system as a proxy to actual sustainability performance with a focus on credit achievement rates.

2.3.2 Research Gaps

The transportation infrastructure sector, having started a decade after LEED and with slower progress, is less mature. Majority of journal articles published on sustainability measurement and rating system applications in transportation infrastructure revolve around the following:

- Establishing sustainability goals, indicators, and metrics through literature review and surveys mostly from transportation professionals (e.g., Litman, (2007)).

- Conceptual design and development of sustainability assessment frameworks and rating systems (e.g., Boz and El-Adaway (2015)).
- Critical review and comparison of the scope and structure of rating systems (e.g., Mattinzioli et al. (2020)).
- Using rating system structures and scorecards to investigate the state of the practice in sustainable roadway projects (e.g., Lew et al. (2016)).

Despite extensive research on the state of the art in sustainable practices, the existing literature lacks studies that use actual construction data to explore the state of the practice in roadway sustainability (i.e., which practices are being done and with what frequency). This dissertation builds upon previous research by Lew et al. (2016), which itself expanded on Anderson and Muench (2013), to examine sustainability in roadway construction. Besides, this dissertation adds data from 14 more projects than Lew et al. (2016).

2.4 Problem Statement and Scope

The overarching question of this chapter is *what is the state of the practice for sustainable roadway design and construction?* This chapter would then pose three sub-questions: 1) What are the most and least pursued sustainable practices by roadway construction projects and why? 2) In what aspects do the projects' expectations of achieving sustainable practices differ from the way they are evaluated using the Greenroads Rating System? 3) Is there a structured way to translate sustainability achievements expressed by Greenroads to another set of indicators? This chapter concentrates on the use of rating systems as a data collection and management tool. Greenroads-certified project scorecards will be used to answer the three sub-questions. A pairwise comparison of achieved and expected Greenroads scores for all certified projects would help address the first and second sub-questions. For the third sub-question, this chapter proposes a method to map Greenroads project scores to a set of sustainability benefits defined in Greenroads.

Collectively, this chapter would contribute to the body of knowledge by first defining the state of practice for a unique selection of sustainable roadway construction projects, and second, setting sustainable performance benchmarks based on real project data. However, the scope is limited to the Greenroads-certified projects who self-declared to be sustainable. This poses two limitations to the results; first, the data might be biased as they come from the project teams (they might oversell their products), and second, the results cannot be simply overgeneralized to an average project with no to minimal sustainability agendas.

2.5 Background

2.5.1 About Greenroads

The Greenroads Rating System is a voluntary third-party transportation infrastructure project certification program administered by the Sustainable Transport Council (STC, we will use its former name Greenroads International), a private non-profit company. In order to be certified by Greenroads, projects must 1) meet a series of minimum requirements (termed *project requirements*), and 2) earn points by accomplishing voluntary sustainable best practices (termed *voluntary credits*). If a project meets the requirements for a voluntary credit they receive the associated points. Certification levels are awarded based on achieving all project requirements and a minimum number of voluntary credit points. Importantly, there are more voluntary credit points available in the rating system than need to be obtained even for the highest certification level, so projects can choose which voluntary credits to pursue based on project context.

Since its inception in 2011, Greenroads has released several versions of the Greenroads Rating System. Currently, Version 2 is in use with Version 3 planned for the near future. The majority of projects reviewed in this dissertation were certified using Greenroads Version 1.5 (hereafter abbreviated to v1.5) (Muench et al., 2011), therefore, this dissertation uses v1.5 as the reference Greenroads Rating System. Greenroads v1.5 consists of 11 project requirements and 37 voluntary credits, and 13 custom credits (essentially, voluntary credits added after the initial version release based on project input). Voluntary and custom credits are worth 1-5 points based on sustainability impact (Muench et al., 2011). Certification levels corresponding to the number of voluntary credit points achieved are Bronze (32 to 42 points), Silver (43 to 53 points), Gold (54 to 63 points), and Evergreen (64 points and above) from a total available of 118. **Table 2.1** gives a summary of Greenroads v1.5 categories, credits, and score distributions. See **Table 1.1** for more detailed descriptions of Greenroads credits.

Table 2.1 List of Greenroads credits and score distribution.

No.	Credits	Points	No.	Credits	Points
Project Requirements (PR)		**All**	**Construction Activities (CA)**		**14**
PR-1	Environmental Review Process	req	CA-1	Quality Management System	2
PR-2	Lifecycle Cost Analysis (LCCA)	req	CA-2	Environmental Training	1
PR-3	Lifecycle Inventory (LCI)	req	CA-3	Site Recycling Plan	1
PR-4	Quality Control Plan	req	CA-4	Fossil Fuel Reduction	2
PR-5	Noise Mitigation Plan	req	CA-5	Equipment Emission Reduction	2
PR-6	Waste Management Plan	req	CA-6	Paving Emission Reduction	1
PR-7	Pollution Prevention Plan	req	CA-7	Water Use Tracking	2
PR-8	Low-Impact Development (LID)	req	CA-8	Contractor Warranty	3
PR-9	Pavement Management System	req			
PR-10	Site Maintenance Plan	req			
PR-11	Educational Outreach	req			
Environment & Water (EW)		**21**	**Materials & Resources (MR)**		**23**
EW-1	Environmental Management System	2	MR-1	Lifecycle Assessment (LCA)	2
EW-2	Runoff Flow Control	3	MR-2	Pavement Reuse	5
EW-3	Runoff Quality	3	MR-3	Earthwork Balance	1
EW-4	Stormwater Cost Analysis	1	MR-4	Recycled Materials	5
EW-5	Site Vegetation	3	MR-5	Regional Materials	5
EW-6	Habitat Restoration	3	MR-6	Energy Efficiency	5
EW-7	Ecological Connectivity	3			
EW-8	Light Pollution	3			
Access & Equity (AE)		**30**	**Custom Credits (CC)**		**10**
AE-1	Safety Audit	2	CC-1	Sustainable Transportation	5
AE-2	Intelligent Transportation Systems	5	CC-2	Workzone Safety	5
AE-3	Context Sensitive Solutions	5	CC-3	Pavement Smoothness	5
AE-4	Traffic Emissions Reduction	5	CC-4	Roadside Revegetation	5
AE-5	Pedestrian Access	2	CC-5	Electric Vehicle Infrastructure	5
AE-6	Bicycle Access	2	CC-6	Alternative Energy	5
AE-7	Transit & HOV Access	5	CC-7	Freight Access	5
AE-8	Scenic Views	2	CC-8	Design for Disassembly	5
AE-9	Cultural Outreach	2	CC-9	Volatile Organic Compounds	5
Pavement Technologies (PT)		**20**	CC-10	Runoff Treatment Upgrades	5
PT-1	Long-Life Pavement	5	CC-11	Site Remediation	5
PT-2	Permeable Pavement	3	CC-12	Safety Analysis	5
PT-3	Warm Mix Asphalt (WMA)	3	CC-13	Species Translocation	5
PT-4	Cool Pavement	5			
PT-5	Quiet Pavement	3			
PT-6	Pavement Performance Tracking	1			
	Total Possible Points			**118**	

2.6 Method

This section first describes the data collection process from the Greenroads database. It will then provide general information about the type of projects the database represents. The analysis involves the processing of information primarily collected from Greenroads scorecards and project documents. Firstly, a comparative analysis of project expectations and achievement level of Greenroads credits will be performed. Secondly, this chapter develops a methodology to map Greenroads credits and project scores into a series of 22 sustainability benefit indicators as defined in the Greenroads Rating System v1.5.

2.6.1 Data Collection

Data collection took place over two summer internships in 2018 and 2019 at Greenroads International. Greenroads collects project documents using its online platform and stores them in an Amazon Web Services (AWS) cloud storage. This dissertation uses the data cleaning, validation, aggregation, and summarization efforts for 33 Greenroads-certified projects with a total construction value of over $2 billion. This is the first time such a large dataset is being used to synthesize the state of the practice information on sustainable roadways and set data-driven performance measures for individual and project-level sustainability achievement.

2.6.2 Data Sources

This dissertation uses three main data sources available from the Greenroads platform. First, the project portfolios provided descriptive information about each project (size, budget, scope of work, contractor, client, etc.). Second, the Greenroads web-based platform produces two scorecard spreadsheets per project summarizing expected scores (as suggested by project teams during registration) and awarded scores (as evaluated by Greenroads upon certification). Third, projects pursuing certification submit to Greenroads, through the web interface, supporting documents or information as evidence for satisfying Greenroads project requirements and voluntary credits.

2.6.2.1 Projects Metadata

Table 2.2 shows an overview of information from the 33 Greenroads-certified projects gathered herein. Most of the data presented in **Table 2.2** comes from project team entries into the Greenroads platform when registered for certification. The total monetary value of project constructions is $2.3 billion, covering about 1,083 acres of land spun over 162 lane-miles. Scope of projects extends from small resurfacing projects (e.g., Projects #4 and #14) and stormwater enhancement projects (e.g., Projects #6 and #31) over to large reconstruction or new construction projects (e.g., Projects #9 and #11 which involve the construction of a new bridge and tunnels).

Table 2.2 Projects summary information.

Project ID	Certification Level	Score	Location	Completion Year	Bid Price (Million$)	Certification Area (Acres)	Lane-Miles	AADT
1	Bronze	35	San Jose, CA	2011	$3.7	15.7	8.25	45,320
2	Silver	45	Houston, TX	2013	$11.5	6.6	1.24	9,575
3	Silver	43	Oak Harbor, WA	2011	$8.5	2.9	0.42	8,400
4	Silver	44	Bellingham, WA	2011	$1.3	3.0	0.63	3,900
5	Bronze	33	Auburn, WA	2012	$6.1	2.2	0.38	3,300
6	Silver	43	Tacoma, WA	2011	$1.8	13.8	0.82	1,319
7	Silver	44	Tacoma, WA	2012	$4.5	6.9	2.2	6,800
8	Bronze	35	Santa Ana, CA	2014	$7.8	6.6	3.6	34,487
9	Bronze	35	San Francisco, CA	2013	$558.6	30.4	6.3	122,800
10	Bronze	32	Denver, CO	2012	$10.9	8.4	2.25	24,900
11	Bronze	47	Portland, OR	2016	$247.7	15.1	1.7	29,774
12	Silver	46	Kirkland, WA	2014	$3.0	1.4	0.33	10,000
13	Silver	43	Bellingham, WA	2015	$3.5	3.1	0.75	11,500
14	Silver	45	Tacoma, WA	2012	$1.3	1.2	0.52	500
15	Bronze	36	Tacoma, WA	2012	$0.6	0.7	0.22	100
16	Bronze	40	Des Moines, WA	2013	$6.2	5.7	1.6	11,000
17	Silver	43	Bothell, WA	2013	$18.1	12.8	2	42,000
18	Silver	43	Campbell, CA	2015	$5.7	7.5	1.8	8,600
19	Bronze	37	San Francisco, CA	2015	$660.6	69.5	9	110,000
20	Silver	43	Arlington, WA	2015	$5.2	1.3	0.2	166
21	Silver	45	Bellingham, WA	2014	$1.5	1.5	0.44	3,545
22	Bronze	38	Bothell, WA	2015	$5.0	1.1	0.3	900
23	Bronze	36	Bellingham, WA	2014	$0.7	8.7	0.89	N/A
24	Bronze	39	Seattle, WA	2013	$57.1	22.7	10.4	42,300
25	Bronze	32	Delta, Canada	2014	$624.1	766.3	84.6	30,000
26	Silver	51	Raleigh, NC	2017	$7.5	13.8	3.81	8,600
27	Silver	44	Austin, TX	2016	$8.0	9.3	2.42	13,300
28	Bronze	32	Seattle, WA	2017	$28.9	12.2	4.35	17,015
29	Bronze	34	New Zealand	2016	$14.9	21.6	6.21	1,450
30	Bronze	33	Fairfield, OH	2016	$2.3	2.4	1.88	21,000
31	Bronze	35	Fayetteville, NC	2016	$1.5	2.6	0.5	9,500
32	Bronze	34	Grays Harbor, WA	2018	$2.3	0.7	0.2	7,900
33	Bronze	33	Bothell, WA	2016	$9.9	5.2	1.7	20,000
			Total		*$2,330*	*1,083*	*162*	*659,951*

To help understand project summary information, below is an explanation of different attributes used to create **Table 2.2**:

- Project ID: A unique identifier assigned to each project. The numbers are ascending in the order of the project registration date. Numeric values are used to maintain confidentiality in project data.
- Certification: Based on the total points achieved, certification levels are official ways that Greenroads acknowledges project accomplishment.
- V1.5 Equivalent Score: 5 projects included in the database pursued certification thru Greenroads v2.0 released in 2015. To simplify analysis and avoid confusion from using different versions, all final scores have been converted to Version 1.5 and tabulated under this column (see **Section 8.1.2**).
- Location: Geographic location of projects expressed by the name of city and state, if located in the U.S., or province and country if outside the U.S.
- Completion Year: The year in which construction finished and the road opened to traffic.
- Bid Price (2020 $M): The construction costs as expressed in the bid tab, either from the engineer's estimate or as-built records. Most bid prices exclude owner-incurred administrative expenses (e.g., design cost, administrative costs, right-of-way acquisition, etc.) and post-bid price adjustments due to change orders. The Engineering News-Record Construction Cost Index is used to inflation-adjust all bid prices to 2020 dollars. Due to the lack of sufficient information, a single adjustment factor is used for all projects completed during a calendar year, regardless of location, completion month, or specific pay items that may have different rates of inflation. See **Table 2.3** for a list of ENR cost indices used.

Table 2.3 Average ENR cost index values per project completion year used to convert bid prices to 2020 USD value.

Project Completion Year	Average ENR Cost Index
2011	1.256
2012	1.224
2013	1.193
2014	1.162
2015	1.135
2016	1.107
2017	1.061
2018	1.030

- Certification Area (Acres): The area disturbed by the project construction expressed in acres. This is one of the most challenging pieces of information to collect. Area calculations are typically reported in Wastewater Management Plans, Pollution Prevention Plans, or through the transportation master plans. In some instances, however, aerial satellite images from Google Earth were used to calculate disturbed areas if no project information was available.
- Length (Lane-Miles): Project length expressed in lane-miles, mostly collected from the Greenroads website platform. When absent from the database, Google Earth satellite images were used to measure project lengths.
- AADT: Average annual daily traffic at the project completion year. To put projects into the perspective of the number of users and thus budget allocation, AADT can indicate the importance of a road segment. AADTs were mostly found from pavement design documents where traffic level is used as an input for thickness selection and life cycle cost analysis.

2.6.2.2 Project Portfolios

When applying and registering for Greenroads evaluation, project teams are required to give out general information about the project. These information would make up a *portfolio* for projects, which are also accessible via the Greenroads website. Portfolio data collected here will later be used to populate and classify projects based on frequency and budget size following these six descriptive characteristics:

- Delivery Method: Project delivery methods are design-bid-build (DBB), public-private-partnership (PPP), and construction management/general contractor (CMGC).
- Purpose: Greenroads recognizes project scopes as reconstruction, maintenance, or new construction.
- Motivation: Greenroads divides project motivations into economic, preservation, environmental, safety, mobility, and utility upgrades.
- Location: Dependent on population density and city structure, geographic areas are categorized into three classes: urban, rural, and small urban lands.
- Functional Class: Arterial, collector, local, or other classes comprise functional classes.

- Zoning: Greenroads divides land use functionality into commercial, central business district (CBD), residential, mixed/multiple, underdeveloped, and industrial zones.

Figure 2.1 illustrates the distribution of project characteristics described by the six portfolio classes, populated by frequency of occurrence (counts of projects) and construction costs. Starting from the delivery method, although most projects adopt the design-bid-build contract, those are usually low-budget projects with a limited scope of work like resurfacing and maintenance. Public-private-partnership contracting, on the other hand, is most prevalent for extensive projects with broad scopes that involve new construction. Reconstruction projects dominate projects' purpose both in terms of popularity and cost. This is while, as expected, new construction projects, although not taking place as often, require higher budgets.

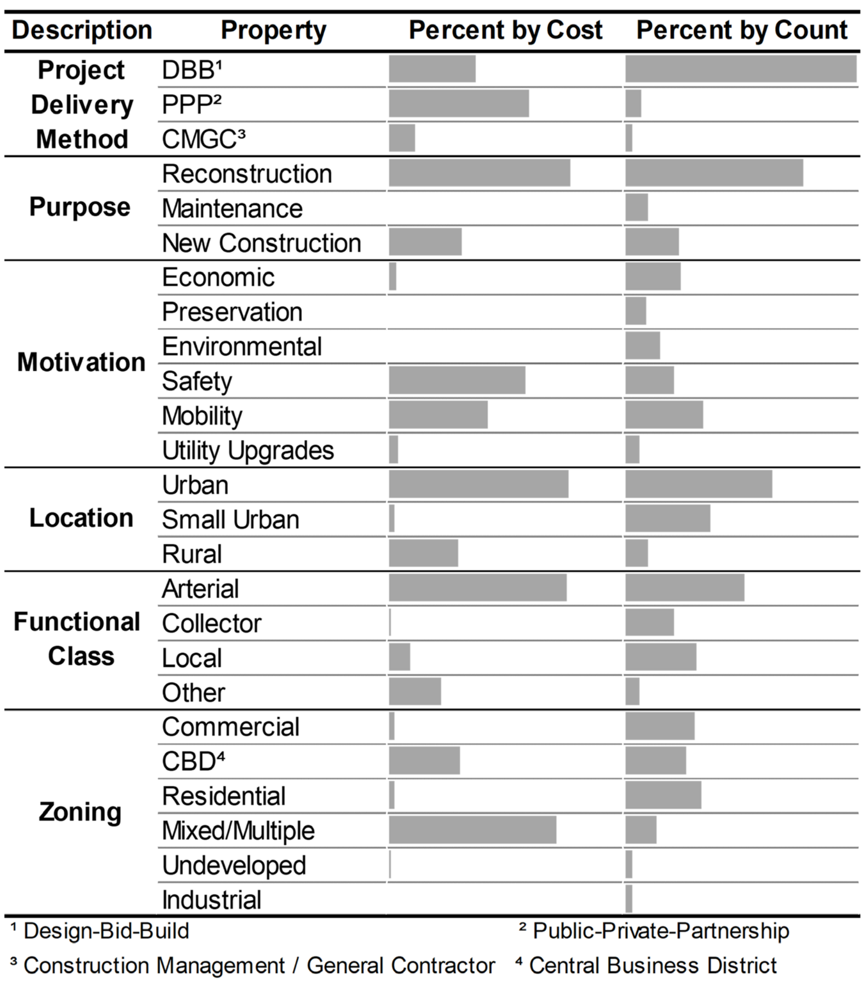

Figure 2.1 Project portfolios indicating the distribution of project counts and costs over the six descriptive properties.

Despite a rather uniform distribution of project motivations, those motivated by mobility and safety goals are shown to expect more budget allocations. This very fact suggests that best practices that consider social aspects of sustainability incur more expenditures than those involved with environmental or economic aspects. Higher frequency and budget needs for projects located in urban areas are also expected since those areas require more regular maintenance and preservation. Experiencing higher traffic volumes in arterial segments is one possible reason why this functional class demands more costs than other classes despite showing a rather uniform frequency of project counts. Finally, central-business-district and mixed/multiple roads dominate project costs in terms of zoning, although almost evenly spread out regarding project counts.

2.6.2.3 Greenroads Scorecards

Greenroads produces an awarded scorecard after the formal certification of projects. Scorecards from all projects were compiled into a single matrix with columns showing project IDs and rows showing each Greenroads credit. Numbers in this matrix indicate awarded scores. **Figure 2.2** shows detailed scorecards for the 33 projects under study. This figure illustrates the breakdown of credit scores awarded to each project and the certification level each project has achieved. For instance, project #26 is silver-certified and was awarded a total score of 51 (the highest in the dataset).

Also depicted is a breakdown of the scores based on Greenroads credits indicating the most and least commonly awarded credit categories. The credit categories responsible for the most points over all 33 projects are Context Sensitive Solutions (AE-3) at 13%, Regional Materials (MR-5) at 7%, Energy Efficiency (MR-6) and Long-Life Pavement (PT-1) at 6%, Site Vegetation (EW-5) at 5%, and Pedestrian Access (AE-5), Runoff Flow Control (EW-2), and Light Pollution (EW-8) at 4%. Overall, these 8 credits make up for over 50% of the total Greenroads scores earned by project teams.

2.6.3 Expected vs. Achieved Sustainability Performance

When registering for Greenroads, project teams submit a scorecard completed with the Greenroads credits and scores they intend to attempt. The scorecards filled this way are called *expected* scorecards in this dissertation. This usually helps Greenroads identify credits that are applicable to the scope of a project. This information is most often provided by one or several project team members who have some -

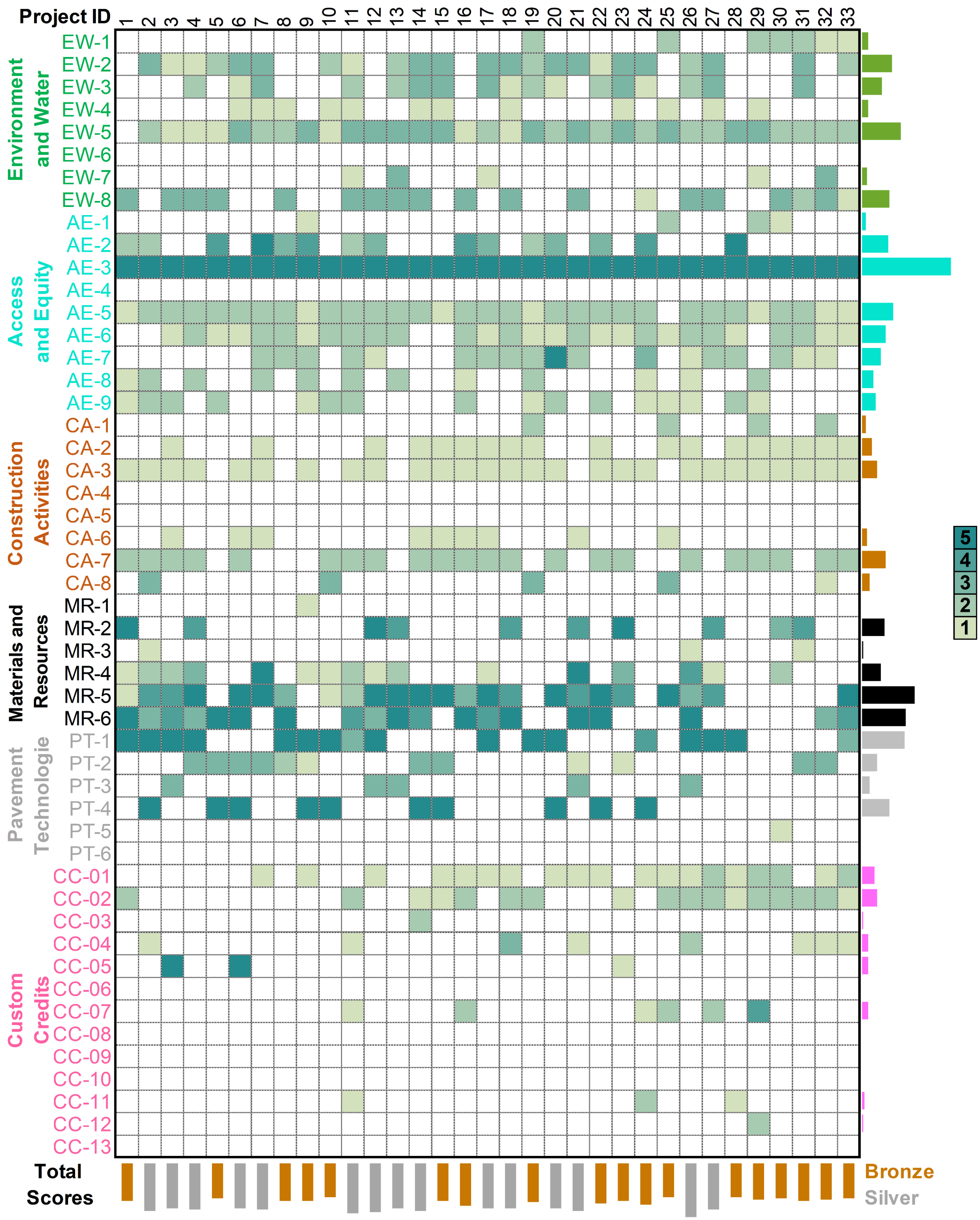

Figure 2.2 Scorecard for the Greenroads-certified projects studied in this dissertation. Vertical and horizontal data bars indicate total scores per project and per Greenroads credit, respectively.

level of proficiency in the Greenroads manual (or sustainability rating systems in general), including its categories, criteria, and requirements. While some rating systems (like INVEST) only require self-assessment of project performance according to a set of criteria, Greenroads acts as a third-party certification firm that validates project expectations. This is mainly why Greenroads compels projects to submit supporting documents to demonstrate their due diligence.

Although deviation from expectations can have many underlying reasons, it can also reveal interesting facts about project perceptions of sustainability and understanding of rating systems. To shed more light on the areas projects' expectations on sustainability achievement deviate from actual performance, this section takes a closer look at two different scorecards: final credit scores achieved after certification by Greenroads personnel (i.e., *awarded scores*), and the scores project teams expected to achieve before them being evaluated by Greenroads (i.e., *expected scores*). In mathematical form, Score Deviation is expressed using **Equation (2-1)**:

$$SD_{i,j} = AS_{i,j} - ES_{i,j} \tag{2-1}$$

Where,

$SD_{i,j}$ = Score Deviation (discrepancy) for project *i* pursuing Greenroads credit *j*,

$AS_{i,j}$ = Awarded Score for project *i* pursuing Greenroads credit *j*, and

$ES_{i,j}$ = Expected Score for project *i* pursuing Greenroads credit *j*.

2.6.4 Sustainability Benefits Mapping

Greenroads v1.5 introduces 22 sustainability benefits associated with the achievement of each of its credits. Credits in Greenroads refer to certain activities a road construction project can carry out and earn scores for. Sustainability benefits, on the other hand, are strongly tied into the definition of sustainability and these seven aspects: ecology, equity, economy, extent, expectations, experience, and exposure. Despite credits being purposefully designed to fit into the infrastructure construction context, sustainability benefits defined in Greenroads are broad in context and understandable by most sustainability practitioners. Rather than being activity-based, sustainability benefits reflect the outcome of accomplishing an activity or construction practice. Achievement of credits in Greenroads can result in at least one of the 22 following eco-centric or anthropocentric benefits (i.e., outcomes) with the abbreviations used here:

- Eco-centric benefits:
    - Reduce raw materials use (-RAW)
    - Reduce fossil fuel use (-FUEL)
    - Create energy (+KWH)
    - Reduce water use (-H2O)
    - Reduce air emissions (-AIR)
    - Reduce greenhouse gases (-GHG)
    - Reduce water pollution (-TSS)
    - Reduce solid waste (-WTL)
    - Restore habitat (REHAB)
    - Create habitat (+HAB)
    - Reduce manmade footprint (-AREA)
- Anthropocentric benefits:
    - Improve access (+USER)
    - Improve mobility (+MOB)
    - Increase service life (+LIFE)
    - Improve human health & safety (+H&S)
    - Improve local economies (LOCAL)
    - Reduce first costs (-1ST$)
    - Reduce lifecycle costs (-LC$)
    - Improve accountability (ACCT)
    - Increase awareness (EDU)
    - Increase aesthetics (+AES)
    - Create new information (DATA)

2.6.4.1 Mapping Matrix

As a result of tracing each Greenroads voluntary credit (vector **c**) to its anticipated sustainability benefit (vector **b**), this chapter introduces a mapping matrix ($\mathbf{M}_{b\times c}$), where *b* denotes the index of the row (i.e., benefit) and *c* the index of the column (i.e., credit). Each Greenroads credit can be linked to any of the 22 sustainability benefits, and each sustainability benefit can be linked to any of the 50 Greenroads voluntary and custom credits. The mapping matrix contains only values of 0, when a Greenroads credit is not linked to any of the sustainability benefits, and 1 when there is a sustainability benefit related to a Greenroads credit. Mathematically notating:

$$\mathbf{M}_{b\times c} = \begin{bmatrix} \mathrm{m}_{11} & \cdots & \mathrm{m}_{1\mathrm{c}} \\ \vdots & \ddots & \vdots \\ \mathrm{m}_{\mathrm{b}1} & \cdots & \mathrm{m}_{\mathrm{bc}} \end{bmatrix}; \mathrm{m}_{ij} = \begin{cases} 0 & \text{if } \exists_{i:1 \text{ to } 22;\ j:1 \text{ to } 50} \big| \mathrm{b}_i \notin \mathrm{c}_j \\ 1 & \text{if } \exists_{i:1 \text{ to } 22;\ j:1 \text{ to } 50} \big| \mathrm{b}_i \in \mathrm{c}_j \end{cases} \quad \textbf{(2-2)}$$

Using 0's and 1's implies that sustainability benefits, unlike Greenroads credits, are not weighted towards their impact on the overall achievement of sustainability. Rather, all sustainability benefits are weighted similarly. The introduction of a mapping matrix would then facilitate many mathematical operations when converting sustainability indicators based on different domains (e.g., from one rating system to another, or as in the case of this dissertation, to an unweighted vector of sustainability benefits).

Figure 2.3, in detail, illustrates the mapping matrix (**M**) for all Greenroads credits. The purpose of showing such a matrix in the form of graphs is not merely illustrating the matrix itself, rather it is to highlight the credits and benefits that are emphasized the most within the Greenroads rating system and their interrelationship. For example, EW-1 (i.e., environmental management systems) is tied to the greatest number of sustainability benefits. On the benefits side, -AIR and -GHG (reducing air pollution and greenhouse gas emissions, respectively) comprise the major benefits when pursuing Greenroads.

2.6.4.2 Benefits Matrix

Translation of Greenroads credits to another set of sustainability indicators (or benefits in this case) can become useful when interpreting the performance of projects. The mapping matrix (**M**) introduced in the prior section can be used to convey such translation from Greenroads scores to the more sensible definition of sustainability benefits explained earlier. Doing so requires some algebraic operations to map the project scorecards matrix ($\mathbf{S}_{c\times p}$) to a so-called benefits matrix ($\mathbf{B}_{b\times p}$), where *c* and *b* denote the same -

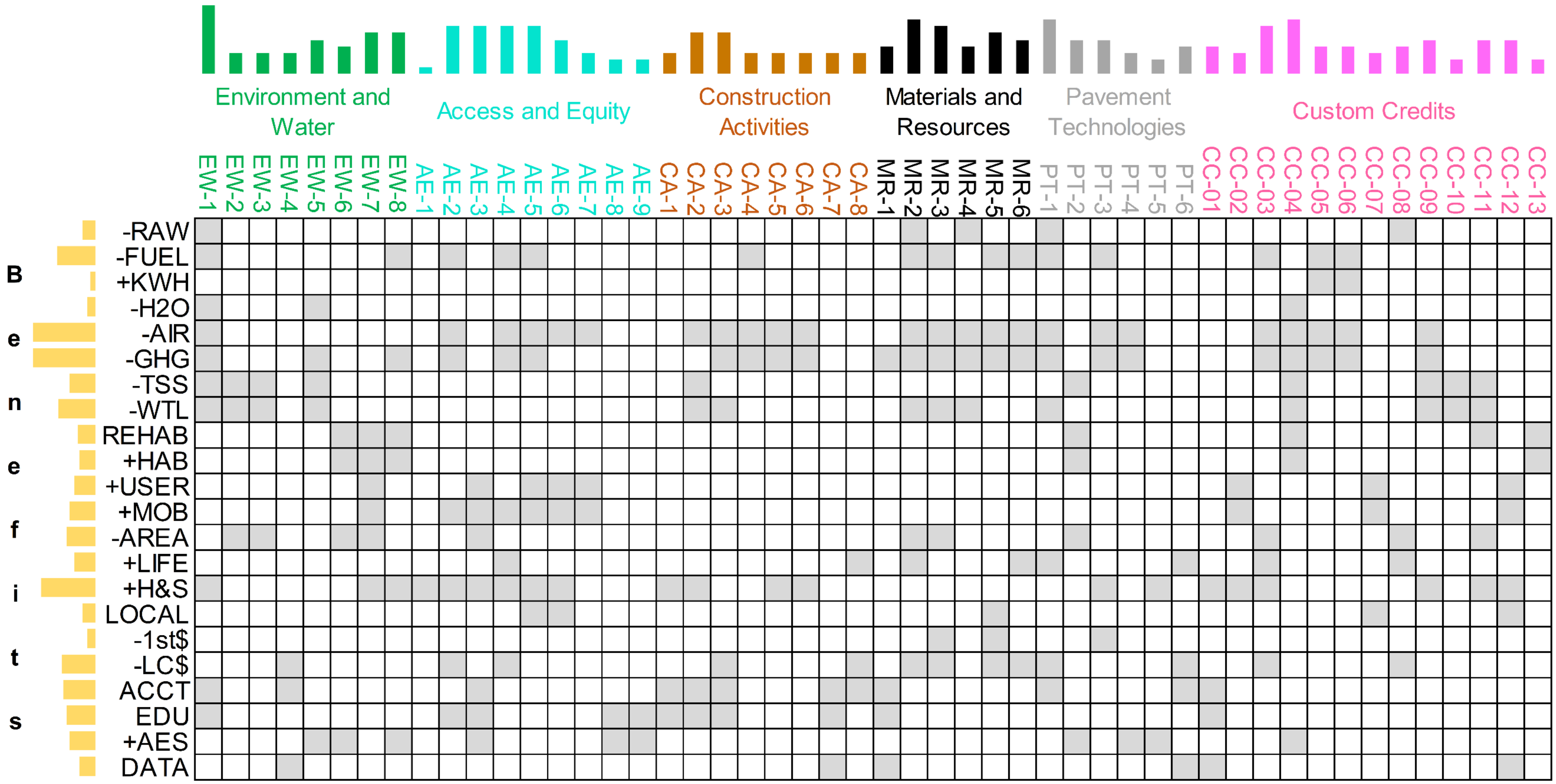

Figure 2.3 Benefits mapping matrix (M). Shaded cells indicate instances where a Greenroads credit (columns) is associated with a sustainability benefit (rows). The vertical and horizontal bars demonstrate the total count of sustainability benefits related to a Greenroads credit and the total number of Greenroads credits related to a sustainability benefit, respectively.

indices as previously stated, and *p* denotes any of the 33 Greenroads-certified projects considered here. In other words, the **B** matrix represents the sustainability benefits attained by each project based on the scores they achieved after Greenroads certification. Algebraic formulation of such mapping follows **Equation (2-3)**:

$$\mathbf{B}_{b\times p} = \mathbf{M}_{b\times c} \times \mathbf{S}_{c\times p} \quad \textbf{(2-3)}$$

Where:

$\mathbf{B}_{b\times p}$ = Benefits matrix showing the sustainability benefits (*b*) achieved by each project (*p*),

$\mathbf{M}_{b\times c}$ = Mapping matrix used to convert Greenroads credits (*c*) to sustainability benefits (*b*), and

$\mathbf{S}_{c\times p}$ = Scorecard matrix summarizing Greenroads credits (*c*) achieved by each project (*p*).

2.6.4.2.1 Normalization

Since sustainability benefits and Greenroads scoring systems follow two different weighting algorithms, a direct comparison of the two seems impossible. Thus, this chapter (similar to some other studies like A. S. Chang & Tsai (2015)) employs a normalization approach to express both matrices in terms of a common metric. The algorithm uses an arbitrary *best project* as a reference for normalization which produces two vectors; one representing a project that earns the highest Greenroads scores ($\mathbf{s}_c$) and another representing a project that obtains the most possible sustainability benefits ($\mathbf{b}_b$). The best project is one that has been awarded the maximum Greenroads score from the *awarded scorecard* (this is not necessarily equating to the maximum Greenroads score for all credits, rather, it is derived from the existing scorecards from the 33 certified projects). Each element of the scorecard and sustainability benefits matrices will then be divided by the relevant denominator values represented by the *best project* expressed as a percentage. The following summarizes the algorithm:

1. Define: $s = \sum_{\boldsymbol{c}} \mathbf{s}_{\boldsymbol{c}}$; $\mathbf{s}_{\boldsymbol{c}} = max\{\mathbf{S}_{c\times p}: p = 1,\ldots,33\}$
2. Define: $b = \sum_{\boldsymbol{b}} \mathbf{b}_{\boldsymbol{b}}$; $\mathbf{b}_{\boldsymbol{b}} = \mathbf{M}_{b\times c} \times \mathbf{s}_{\boldsymbol{c}}$
3. $\widehat{\mathbf{S}_{c\times p}} = \mathbf{S}_{c\times p}/\boldsymbol{s}$
4. $\widehat{\mathbf{B}_{b\times p}} = \mathbf{B}_{b\times p}/\boldsymbol{b}$

Where,

s = Normalization factor for the scorecard matrix **S**,

b = Normalization factor for the benefits matrix **B**,

$\mathbf{s}_c$ = Scorecard vector representing a project that earned the Max scores across all credits,

$\mathbf{b}_b$ = Benefits vector representation of the project with a scorecard of $\mathbf{s}_c$,

$\widehat{\mathbf{S}_{c\times p}}$ = Normalized scorecard matrix, and

$\widehat{\mathbf{B}_{b\times p}}$ = Normalized benefits matrix.

2.7 Results

2.7.1 Sustainable Best Practices

Figure 2.2 shows that the credit categories responsible for the most points over all 33 projects are Context Sensitive Solutions (AE-3) at 13%, Regional Materials (MR-5) at 7%, Energy Efficiency (MR-6) and Long-Life Pavement (PT-1) at 6%, Site Vegetation (EW-5) at 5%, and Pedestrian Access (AE-5), Runoff Flow Control (EW-2), and Light Pollution (EW-8) at 4%. Overall, these 8 credits make up for over 50% of the total Greenroads scores earned by project teams.

2.7.2 Expected vs. Awarded Scores

Figure 2.4 shows, in the most detailed way possible, the deviation from what scores projects have been awarded and what they had expected during project registration (see **Section 0**). Each cell on this figure indicates the numerical difference between awarded and expected scores arranged by project IDs and Greenroads credits. **Figure 2.4** is color-coded to help interpret deviations visually. Darker shades show higher absolute deviations, while yellow-shaded cells indicate no deviation between awarded and expected scores. Green-shaded cells indicate circumstances where a project achieved more score(s) for a credit than they expected. Conversely, red-shaded cells illustrate instances where a project performed worse than their expectations in terms of Greenroads credit score achievement. **Figure 2.4** is dominated by yellow-shaded cells, suggesting that project teams in most cases met their expected scores. Credits that no projects have attempted or earned points for are left blank.

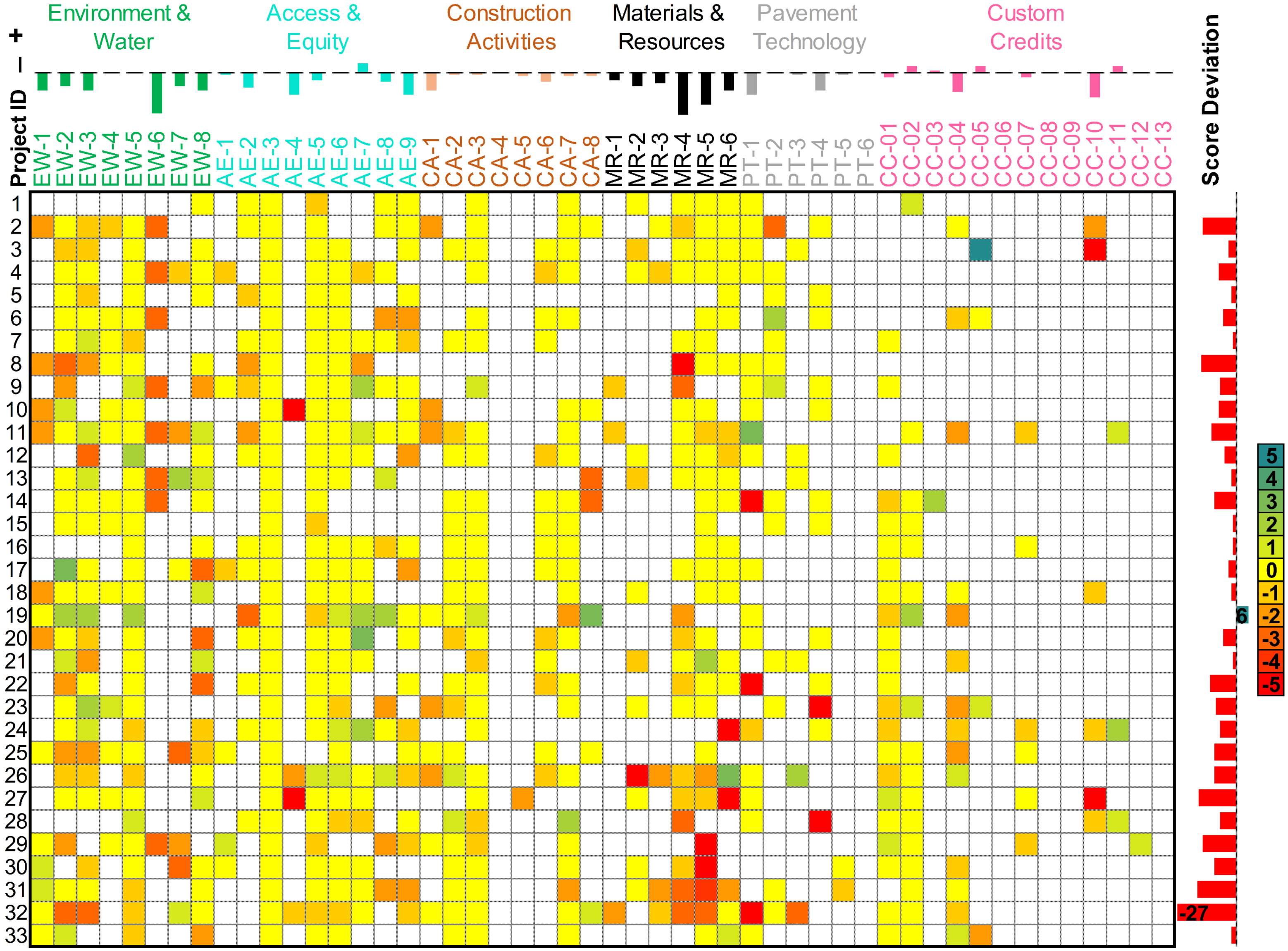

Figure 2.4 Score Deviations by project and Greenroads credit. Red numbers indicate credits that achieved fewer scores than expected. Vertical and horizontal bars indicate total score deviations per Greenroads credits and per project, respectively.

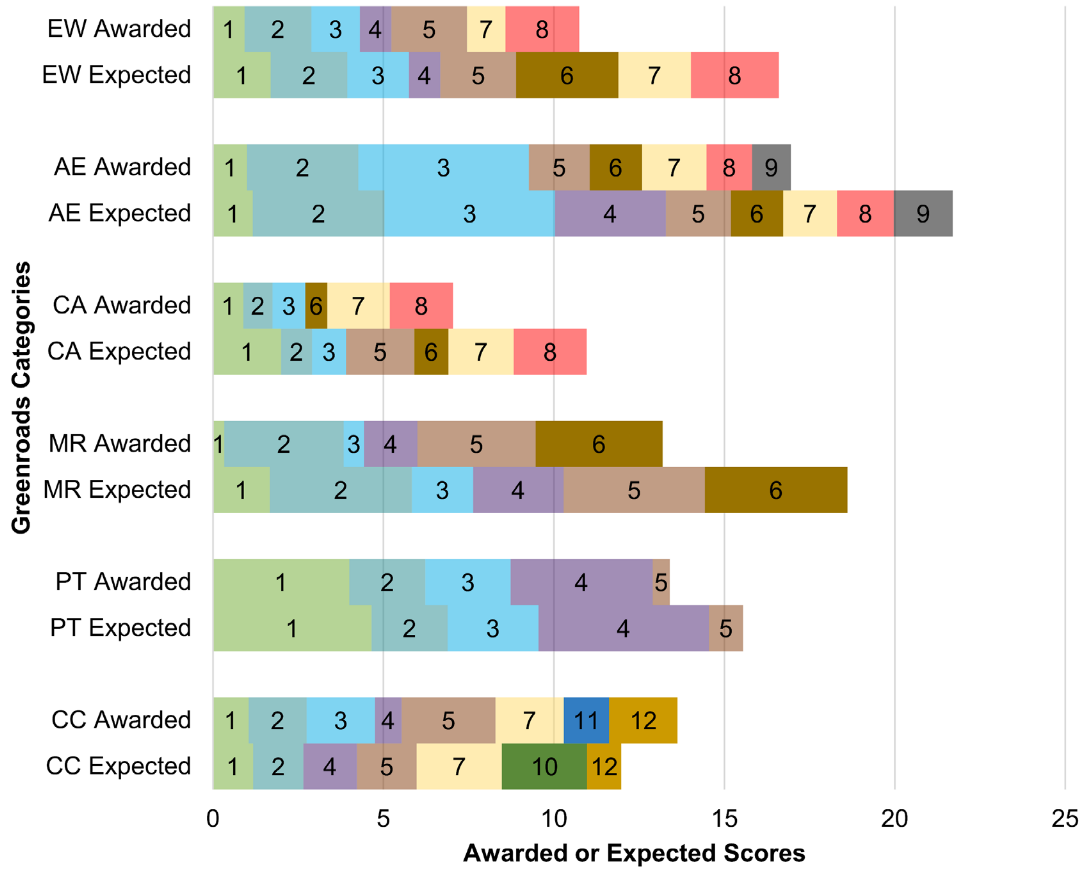

Figure 2.5 Average awarded and expected scores populated by Greenroads categories and credits (labels indicate Greenroads credit numbers, for example, EW-1).

The illustration in **Figure 2.4** also shows the total score deviation per project and Greenroads credit with horizontal and vertical bars, respectively. Accordingly, scores awarded for MR-4 (recycled materials), EW-6 (habitat restoration), and MR-5 (regional materials) seem to deviate the most from what project teams expected in general. On the other hand, projects in pursuit of AE-7 (transit & HOV access) and CC-2 (workzone safety) credits were awarded more scores than they expected. Custom Credits are also depicted in **Figure 2.4**; however, this might raise some questions regarding their inclusion in the analysis. Custom Credits are those that project teams developed and offered for inclusion in the Greenroads Rating System (except for CC-1 and CC-2 which were originally part of the rating system). This means that most of the Custom Credits were not available to all project teams before their existence. For this reason, we will narrow down our discussion on score deviation to voluntary credits only.

Aggregated by Greenroads categories, **Figure 2.5** shows the average awarded and expected scores populated by certified projects. This figure is further broken down by Greenroads credits and presents a one-by-one comparison of Score Deviations. Evident from **Figure 2.5** is that, on average, projects expected to earn more voluntary credit scores than what they have been awarded. While for some credits this deviation is more significant (e.g., EW-6), the trend flips for some Custom Credits category credits (e.g., CC-3). Although these discrepancies might have originated from either party (i.e., Greenroads or the project teams), this chapter will later discuss and provide some possible reasoning and arguments to expound on the observations.

2.7.3 Sustainability Benefits Mapping

After normalization, both the scorecard and sustainability benefits matrices can be sketched based on a common axis to visualize their interrelationship. **Figure 2.6** is one of several illustration techniques to visually compare the achievement of sustainability benefits across projects. The numbers shown on the perimeter of the spider graph in **Figure 2.6** represent the 33 Greenroads-certified projects. Normalized sustainability benefits associated with project scores are summed up over projects and then sorted from largest (innermost section of **Figure 2.6**) to lowest (the outermost slice of **Figure 2.6**). Reduction in air pollution (-AIR) and greenhouse gas emissions (-GHG) deliver the most sustainability benefits projects obtained overall. This was somehow anticipated since these two benefits are associated with more Greenroads credits than others. On the least achieved benefits stays the creation of energy (+KWH) and new information (DATA). **Figure 2.7** illustrates the sustainability benefits mapping results in higher resolution where the association between each project and the particular sustainability benefits they achieved is clear.

Also depicted in **Figure 2.6** are the total normalized scores (red solid line) each project achieved across all Greenroads credits. Comparing the outermost line of the spider graph (total normalized benefits associated with project scores) with the solid red line (normalized project scores) from **Figure 2.6** or the horizontal data bars in **Figure 2.7**, one can immediately realize that projects' achieved scores moderately correlate with their sustainability benefits counterparts (R^2 = 0.77). This very observation suggests that other metrics than the ones adopted by a rating system can also convey rather similar rankings among projects. When certification levels are considered, both rating approaches (based on Greenroads credit scores and the number of sustainability benefits they relate to) yield the same outcomes. Meaning that -

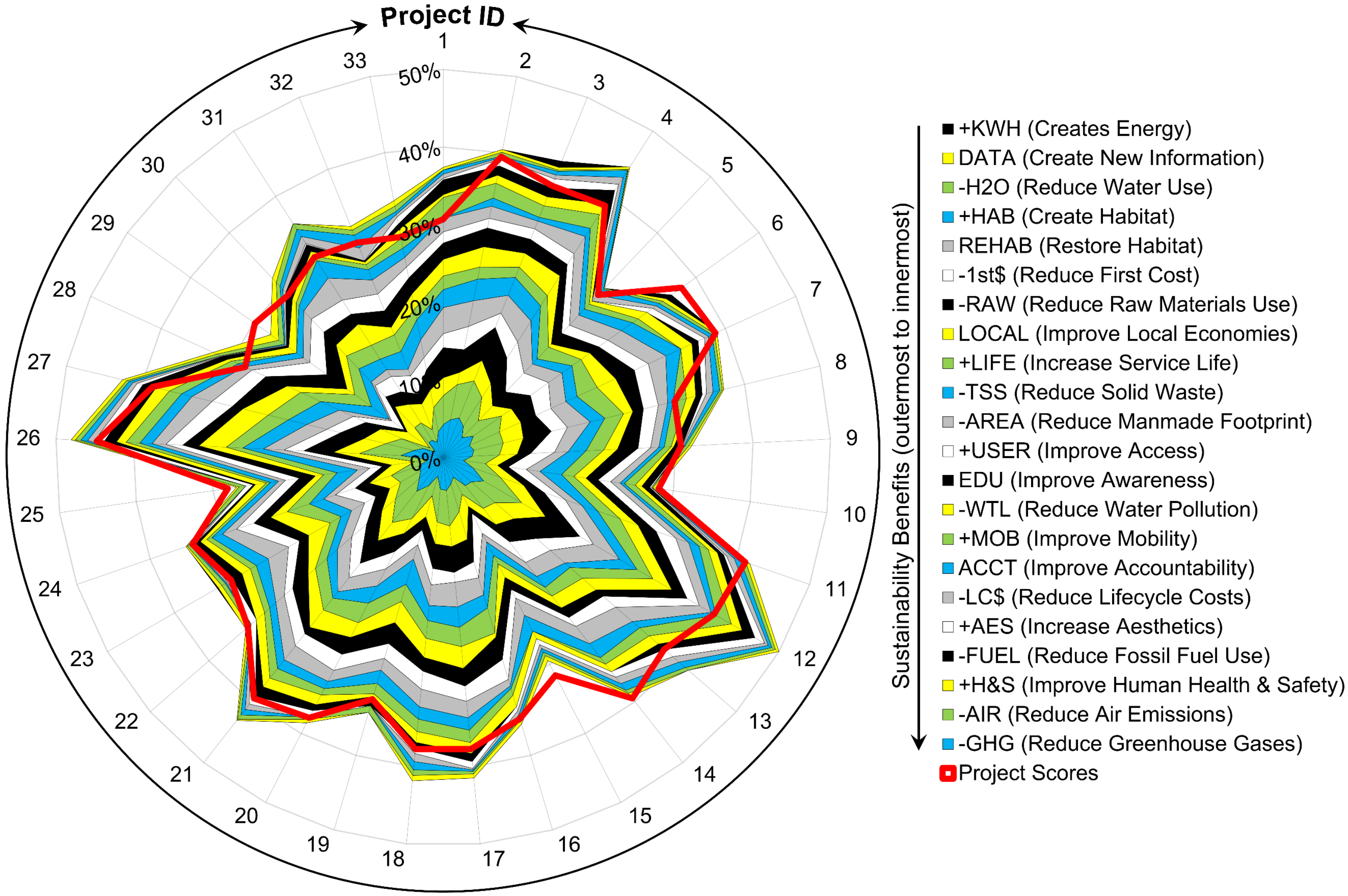

Figure 2.6 From scorecards to sustainability benefits: Greenroads projects performance evaluation based on the definition of sustainability benefits.

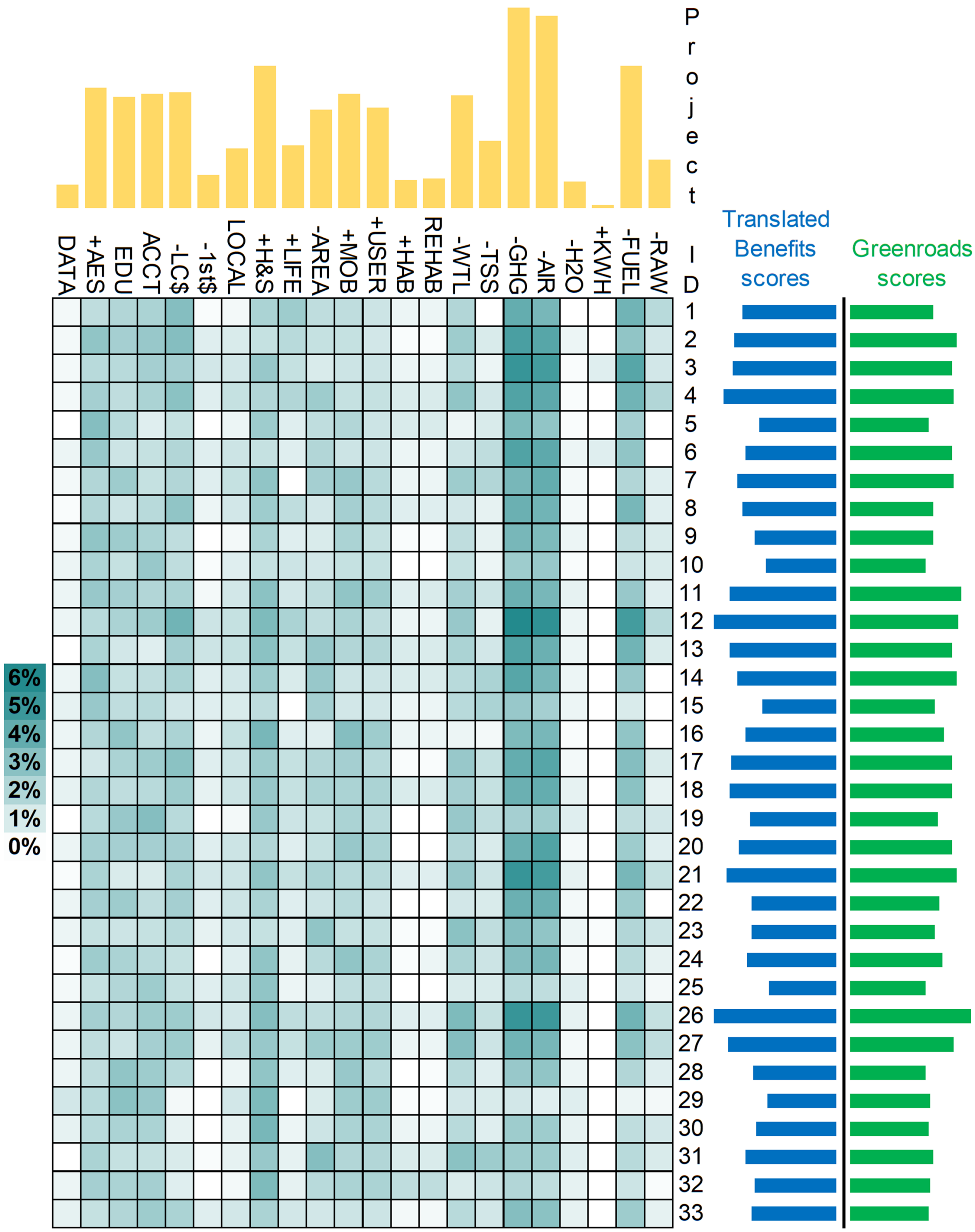

Figure 2.7 Detailed mapping of Greenroads project scorecards to sustainability benefits. The color intensity of cells correlates with the relative normalized sustainability benefit. Vertical bars on the top of this graph show the total normalized sustainability benefits received from each project. Blue horizontal bars indicate the total sustainability benefits each project has contributed to. Green horizontal bars indicate the total Greenroads score each project is awarded.

projects earning a bronze level certification (achieving 30 to 40% of total points) also earn the same certification level when examined against the sustainability benefits basin. Another implication of such analysis is in comparing rating systems. For example, a mapping matrix can be developed to convert Greenroads credits to their INVEST equivalent. The same normalization approach can then be adopted to directly compare both systems and investigate their level of agreement.

2.8 Discussion and Limitations

Thus far this chapter presented several aspects of how data acquired from construction projects in pursuit of Greenroads certification can become helpful in understanding their sustainability performance. This section takes a closer look at the results and discusses the findings. Points of discussion include the value of using rating systems to streamline and measure the state of the practice in sustainable roadway construction, the disconnect between perception and achievement of sustainability goals and possible solutions to bridge the gap, and translating sustainability as defined by Greenroads to other sets of indicators.

2.8.1 Greenroads Scores are Data-Driven

Rating systems like Greenroads are valuable tools to set performance benchmarks either as scores or project data. Although scoring systems in some cases use actual project performance metrics as criteria, the final representation of sustainability efforts is nevertheless expressed as hollow unitless numbers (integers of 1 thru 5 in Greenroads). On one hand, this very fact devalues the ability of a rating system to set performance-based benchmarks for other projects to adhere to. On the other hand, using actual performance metrics can jeopardize the useability and simplicity of rating systems to some extent, and the use of arbitrary scoring schemes seems justifiable (Bueno et al., 2015).

2.8.2 Greenroads is a Powerful Data Collection and Management Tool

What makes Greenroads and other third-party evaluation systems unique is their data collection capacity. That means Greenroads scores are based on actual project performance data, and the underlying documents to verify the level of sustainability achievement are accessible. This is contrary to some other sustainability assessment tools that usually translate sustainable performance into a single metric (e.g., carbon footprint) or use rating systems with self-assessment features that do not collect nor acquire supporting documents to establish metrics reflecting the state of the practice. In this chapter, we only explored two [from several] types of data collected and made available by Greenroads, namely the project portfolios and scorecards. More importantly, our data only pertains to roadway projects that are certified as sustainable (several hundred other projects apply for Greenroads but never get certified). More engagement of projects in Greenroads simply means more access to screened data that can be used to establish the state of the practice in sustainable roadway construction.

2.8.3 Sustainability Trends in Roadway Construction

Examining the scorecards suggest that the most popular credits are typically those that project teams were either fully familiar with or had already pursued as required by the project specification. For example, all Greenroads projects earned points for the AE-3 credit (context sensitive solutions) since it is mostly regulated and mandated by many agencies as part of their National or State Environmental Policy Acts (NEPA and SEPA). Another good example is the MR-5 credit (regional materials) which essentially requires a record of material suppliers' information and the majority of projects already keep track of that.

On the other hand, the scorecards show that some credits such as EW-6 (habitat restoration), CA-4 fossil fuel reduction), CA-5 equipment emission reduction), PT-5 (quiet pavement), and PT-6 (pavement performance tracking) have never been awarded any points. We presume four reasons for this: 1) project teams were largely unfamiliar with or misunderstood those credits and their requirements, 2) project teams have found pursuing these credits difficult, 3) those practices did not fall within the scope of projects due to specificity, and 4) minimum Greenroads requirements were too strict and fell well above and beyond common practice.

In most cases, however, project teams did not take an extra step to modify their design or construction practice. Projects typically earned points for credits that only required documentation efforts without a change in design. Even more so, Greenroads typically asked project teams to retain data that was indeed collected but otherwise discarded or left unattended. For example, PT-1 credit (long-life pavement) only asked for a document showing perpetual pavement design. As another example, CA-7 credit (water use tracking), which is in fact the highest scored credit in the Construction Activities category, only required a document showing the water meter records or water truck receipts, both of which are readily available to contractors. On the other hand, credits that required an additional step beyond documentation were less attractive. Good examples are MR-1 credit (LCA) for which only one project had an internally produced LCA report and CA-1 credit (quality management system) for which projects were required to provide ISO 9001 certification that can be an extra burden to contractors.

2.8.4 Sustainability Perception

This section discusses the results depicted in **Figure 2.4** and **Figure 2.5**, contrasting projects' expectations of sustainability achievement as obtained during the Greenroads certification process. Except for a few credits, project teams show some level of misconception about how sustainable their practices were. However, it sounds reasonable to set the goals high regardless of how confidently those goals can be reached. In that, overoptimism in self-assessment is not unprecedented in human natural distinct. As Lew et al. (2016) hypothesize, lack of data and documentation method, misinterpretation of Greenroads credits, the inexperience of project teams with the concept of rating systems, and contextualization are among the underlying reasons why projects expect better sustainability performance than they practically carry out.

MR-4, MR-5, and PT-1 are among the credits with the highest score deviations. The challenges involved with calculating and finding out the correct number of points projects could achieve are believed to be the main source of score deviation. For example, the denominator for which the percentages of recycled or regional materials, or areas designed with long-life pavement, are calculated is sometimes ambiguous to choose. It was common to see projects ignoring a big portion of materials used during construction (i.e., high expectation) which caused the denominator to raise significantly and thus resulted in lower Greenroads scores (i.e., low achievement). A rather same story holds for the EW-6 credit (i.e., habitat restoration), where the area of preserved or restored natural habitat in comparison to the total project area was miscalculated.

Misunderstanding a Greenroads credit is another contributor to score deviations. For example, AE-4 and AE-9 credits seem to lack clarity in their definition at the first sight. The main approach to achieving scores in AE-4 credit is having a congestion pricing scheme in place to reduce traffic emissions, while most projects attempting this credit sought other approaches that did not necessarily result in reduced emissions. The misperception of *art* as part of the AE-9 credit can be described as the main source of ambiguity. Later versions of Greenroads recognized these interpretation issues and provided more specific instructions to reduce misconceptions.

On the other end of the spectrum are the credits which experienced the least deviation, or even positive deviation, between achievement and expectation; namely AE-7, PT-2, AE-6, AE-3, EW-5, and EW-4. CC credits are left out of the discussion because "not every project has had an equal opportunity to achieve a custom credit" (Lew et al., 2016). Achieving AE-6, AE-7, and EW-4 credit scores typically involves minimal effort, both in terms of design and expenditure. Moreover, the approaches are well established and understood by transportation and traffic designers. For instance, context sensitive solutions (AE-3) are mostly regulated and mandated by many agencies as part of their National or State Environmental Policy Acts (NEPA and SEPA). Additionally, this credit only involves documentation practices in the form of a statement of purpose, which the majority of projects already have in their possession. For some credits like PT-2 with only one possible option to earn all scores, score deviation tends to be small; for example, projects either designed for permeable pavement sections or not (achieved either 0 or 3 points). Since almost all Greenroads projects included a landscaping scope, 32 out of the 33 projects pursued EW-5 credit and earned points by using non-invasive or native plant species. The choice of native plants, however, makes the most economic sense and construction projects are most often bid based on the lowest price. This could in part explain the low score deviations for EW-5 credit.

2.8.5 From Sustainability Indicators to Sustainability Benefits

The number of sustainability indicators to account for, measure, and document sustainability activities is skyrocketing. Being broad in definition, sustainability indicators are specified following the context they are in use. Despite meeting the triple bottom line definition of sustainability while sharing many common traits, such as having a concise definition, measurability, reliant on accessible data, and being evaluated based on some benchmark values, the depth and breadth of indicators hinder their immediate implementation and translation into a unified set of sustainability goals and benefits (Merino-Saum et al., 2020). To address the issues of universality, this chapter presented an approach to translating sustainability indicators and their numeric measures (in the case of the Greenroads rating system) to what was defined as a series of sustainability benefits.

Greenroads divides sustainability benefits into two distinct categories: 1) ecological benefits, with a focus on reducing emissions and consumption, and 2) human-centric benefits, focusing on the user, performance, and interaction improvements (Muench et al., 2010). Sustainability benefits, as opposed to indicators, are not necessarily measurable and benchmarked to standard values. Rather, these sustainability benefits qualitatively reflect the *outcome* of implementing sustainable practices measured by indicators. This chapter argues that any system of sustainability indicators, related to roadway construction and urban design can be viewed from the more universal lens of sustainability benefits. Given the myriad of sustainability rating systems available to evaluate infrastructure construction projects, the introduction of sustainability benefits can become a solution to unify and map the variety of sustainability indicators into a finite set of understandable qualities. Even though the attribution of each indicator to a subset of benefits poses the issue of subjectivity, this chapter proposed a rigorous mathematical solution to their mapping function.

There are several reasons why projects achieved some sustainability benefits over others. Among those are: 1) construction practices related to a particular sustainability benefit are more (or less) emphasized by Greenroads indicators, 2) some construction practices for reaching a specific benefit are either cumbersome or economically infeasible to carry out, 3) projects typically do what is common practice and is regarded as standard and avoid new and emerging technologies, 4) design-bid-build contracts (which dominate Greenroads-certified projects) may impede projects from actively engaging in innovative solutions and unconventional practices (Anderson and Muench, 2013), 5) projects are usually motivated by safety and mobility goals which in turn limit those benefits driven by environmental considerations, 6) majority of Greenroads projects are of arterial class and located in and around urban areas which poses many limitations over project scopes and innovative solutions, 7) the weighting of Greenroads credits might be biased towards certain benefits, and 8) sustainability benefits defined here are unweighted and only reflect the number of Greenroads credits they relate to. Although controversial, three possible solutions to address the predicaments expressed above are: a) eliminating the existing Greenroads credits that are never pursued by any projects historically and incorporating CC credits proposed by project teams as voluntary credits, b) revising the Greenroads rating system weighting mechanism based on project data to balance the emphasis on the three pillars of sustainability, and c) assigning weights to sustainability benefits to distribute importance equally over all 22 benefits.

2.8.6 Other Limitations

Observations and conclusions are limited by the choice of dataset (33 self-selected Greenroads-certified projects), choice of measurement tool (Greenroads v1.5), and mathematical approaches. First, this dissertation draws conclusions about all sustainable road infrastructure based on the design and construction of 33 Greenroads-certified projects. We believe that while there is a risk to this generalization, the comprehensive findings of Lew et al. (2016) and Anderson & Muench (2013) and this research lend some credibility to such generalization. Second, Greenroads v1.5 is one of many sustainability rating systems (or indicator systems) for roadways. While different roadway rating systems measure many of the same things (Mattinzioli et al., 2020) they do have differences, so basing a definition of sustainability on one system risks excluding items. For instance, since Greenroads v1.5 was developed about 10 years ago, it does not have credits directly addressing climate change adaptation or resilience, two popular research topics today.

2.9 Summary and Conclusions

To answer the research question of whether project data can be used to establish the state of the practice in sustainable roadway construction, this dissertation collected and organized construction and rating system data from 33 Greenroads-certified roadway construction projects. The total bid price of projects was $2.3 billion spun over 162 lane-miles of roadway. By investigating the effectiveness of the Greenroads Rating System to act as a data collection and sustainability measurement platform, the objectives of this chapter were to find the most commonly pursued construction best practices, investigate the effectiveness of Greenroads rating system to act as a data collection and sustainability measurement platform, contrast projects' perception of sustainability against Greenroads evaluation, and proposing a method for mapping sustainability indicators from one domain to another. The following bullet points conclude this chapter:

- Greenroads is a useful data collection and management tool. Much of the data generated during roadway design and construction is ephemeral: it is used (i.e., to describe required construction and materials, document testing, and provide a basis for billing), but its long-term storage is either non-existent or difficult to access (Yamaura, 2018). Greenroads maintains this data and more (e.g., water use, material transportation distances, etc.) in an accessible format, which can be used in deeper post-construction analysis such as this research.
- There seems to be a standard set of sustainable practices that are achieved most often. Just 17 of the 50 credits in Greenroads v1.5 are achieved by at least half the certified projects (EW-2, EW-3, EW-5, EW-8, AE-3, AE-5, AE-6, AE-7, AE-9, CA-2, CA-3, MR-4, MR-5, MR-6, PT-1, CC-1, CC-2). This constitutes the baseline for sustainable road infrastructure, with other credits being achieved periodically as scope and effort allow. In short, the sustainable road does this (at least over half the time): control runoff flow and quality, use native vegetation, make light-emitting diode luminaires that are Dark Sky compliant, use of context sensitive solutions while improving high occupancy vehicle (HOV) access, include art and community values, do construction environmental training, recycle things on the construction site, monitor construction water use, use local and recycled materials, design pavement for at least 40 years, and practice good workzone safety.
- Good documentation is key to success. Analysis of Greenroads scorecards suggests that the majority of sustainable practices that projects were awarded points for are those that can be achieved with minimal to no additional efforts or modifications to original project plans. For instance, although providing pedestrian and bicycle facilities or using ecologically friendly luminaires helped several projects to earn Greenroads credits, these were the practices that projects would have done regardless. In some cases, however, Greenroads urged projects to take an additional step to document their practices and have them evaluated using Greenroads criteria. Good examples are measuring construction water use, reporting recycled material contents, tracking material suppliers, and encouraging life cycle thinking by requiring LCA and LCCA, all of which can be considered documentation efforts.

- Project teams typically expect to achieve more points than awarded. Misunderstanding of credits (e.g., what is considered art), the vagueness of credit requirements and descriptions (e.g., reduction in fossil fuel reduction by traffic pricing), difficulties in estimating or measuring values asked by Greenroads credits when not initially documented by projects (e.g., percent recycled content or the portion of project pavements designed for long-life performance) are among the main reasons to explain discrepancies. However, it might be prudent to set the goals high when the price is just reporting a higher expected score.
- Project teams with prior experience with Greenroads performed better. Knowledgeable members can help set realistic sustainability goals. Comparing credit achievement rates for projects with similar contractors provided evidence of 1) improvement in final awarded scores and 2) lower deviation between expected and achieved scores. This signifies the value of Greenroads in sustainability training and education, especially given the infancy of sustainable thinking in the infrastructure construction realm.
- Urban reconstruction projects dominate the type of Greenroads-certified projects. There seem to be more opportunities for reconstruction projects to obtain Greenroads certification. New construction projects are typically more involved and provide fewer opportunities for pursuing sustainability. It can be speculated that restrictions lead to innovations, and sustainability is mostly about doing things beyond common practice. Another reason might be the inclination of Greenroads credits towards practices that are more applicable to urban environments, and those projects are mostly reconstruction.
- The impact of credit weights on the achievement of certification levels is unclear. This chapter mapped Greenroads credits to several weightless sustainability benefits and the results showed no significant difference in the final certification level. It can be argued that any arbitrary selection of credit weights can still produce the same final results. More research on the sensitivity of rating systems to credit weights is therefore warranted.

3 Life Cycle Assessment of Pavement Construction

3.1 Preface

The previous chapter used Greenroads scorecard results from 33 certified projects to investigate the state of practice in sustainable roadway construction. The interpretation of rating system scorecards, however, requires some mastery of the rating system structure since the scores are not direct performance measures and use proxy numbers to translate the level of sustainability achievement. Therefore, this chapter, by recognizing carbon and energy footprints as two critical performance measures of projects' environmental impacts, uses 32 project submittals as part of the Greenroads' life cycle inventory (PR-3 credit) requirements to quantify those impacts using LCA methods. Moreover, this chapter integrates LCA results into pay item lists to explore correlations between environmental impacts and the financial cost of projects and materials. The scope of this chapter is limited to pavement sections in alignment with the Greenroads' PR-3 credit scope.

As previously mentioned, a combination of all contents in this chapter and part of **Chapter 2** was submitted for publication in *Transportation Research Record* as of August 2022.

3.2 Abstract

Realizing that roadway surfaces including pavement structures often contribute to a high proportion of a roadway project's sustainability efforts, this chapter is dedicated to the life cycle assessment of paving materials. This chapter leverages life cycle inventory (LCI) data from 32 Greenroads-certified projects as conducted and reported by project teams to run LCA on pavement sections and paving materials. Integrating life cycle assessment results with financial information from pay item lists, correlation analyses between carbon and energy footprints and the price of major paving materials such as asphalt mixtures and portland cement concrete were carried out. Results show that the quantified environmental footprints of projects and the materials used to build them strongly correlate with the total price of projects and the price of constituent materials, respectively.

3.3 Introduction

The bidding process and selection of the best alternatives for construction projects are almost always driven by financial factors. Although implicitly, the environmental and social impacts of project construction are also baked into project economics. For example, outsourcing materials from farther regions incurs more financial burden over projects in most cases. For this reason, not only is supplying projects from regional sources reduce transportation costs, but it can also stimulate local economies and decrease fuel consumption due to shorter transportation trips. However, monetization of all environmental and societal footprints of a project poses serious challenges due mainly to a lack of data and quantification methods, spatial variation, and selection of impact categories and indicators (Bueno et al., 2015).

Environmental impacts of any production process can be tracked over a wide range of impact recipients and categories including air pollution and emission, water use and quality, land use, energy consumption, etc., and their impacts on human health, ecosystem, and other habitats. Life cycle assessment (LCA) is a standardized methodology (ISO14040:2006 and ISO14044:2006) developed to quantify the environmental impacts of processes. LCA has been applied in a wide variety of disciplines and processes involved in them, mainly to track and quantify a select number of indicators. Among LCA metrics, global warming potential (GWP) measured in the unit of carbon dioxide equivalent (CO_2-eq, or simply carbon footprint), which is a combined weighted measure from three non-fluorinated gases of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and energy consumption (or simply, energy footprint) measured in common units of energy (e.g., Joule or British Thermal Unit (BTU)) are two of the most commonly reported environmental impact categories. In general, an LCA framework according to the ISO standards consists of four elements: 1) goal and scope definition, 2) lifecycle inventory (LCI), 3) lifecycle impact assessment (LCIA), and 4) interpretation, and two optional stages called normalization and weighting.

3.4 Background

3.4.1 LCA in Roadway Construction

The majority of existing literature on roadway LCA is limited to pavement sections. Harvey et al. (2016) produced one of the most comprehensive pavement LCA frameworks; however, such a framework seems non-existent for an entire roadway system which consists of many other elements than pavements. Most roadway-related LCA studies consider either a hypothetical design or in some cases use actual construction data for a single or a few paving projects. Nevertheless, carbon footprint and energy consumption are the two main environmental impact categories. Functional units for pavement LCAs are dominated by definitions using a unit of length (e.g., lane-mile or lane-kilometer) or area (e.g., square foot or square meter) which are also typically used to normalize LCA results.

Muench (2010) provides a summary of 14 LCA studies on pavement sections reporting energy consumption and CO_2-eq emissions of 3 to 7 TJ/lane-mile and 200 to 600 tons/lane-mile (Muench, 2010). These values have undergone some changes since 2010 due mainly to technological advancements and changes in the electricity mix as well as the data availability. More recent studies report carbon footprints ranging from 87 to 4,160 tons CO_2-eq per lane-mile (i.e., 87 (Santos et al., 2015), 406 (Mao et al., 2017), 801 (Mao et al., 2017), 886 (Liu et al., 2017), 958 (Galatioto et al., 2015), 1,037 (Mao et al., 2017), 2,058 (Liu et al., 2017), and 4,160 (Guo et al., 2017). Although more scarce, those that conducted whole roadway LCAs reported CO_2-eq emissions from 486 (Li et al., 2020) and 1,664 (Noland and Hanson, 2015) to 11,240 (Wang et al., 2015) tons/lane-mile.

Overall, the studies reviewed here reveal two major limitations: 1) the system boundaries are not well defined to allow for a meaningful comparison among projects of various scopes, resulting in a wide range of carbon footprints, and 2) the analyzed projects, whether designed or constructed, were not always identified as sustainable and in most cases lacked actual construction data. By integrating data from Greenroads-certified projects with LCA results, this research endeavor aims to close those gaps and make quantitative environmental impacts comparable across a larger population of sustainable roadway construction projects.

3.4.1.1 LCA in Greenroads

Greenroads Rating System also recognizes LCA as an important asset to the sustainability evaluation of infrastructure construction by requiring projects (as part of its PR-3 credit in v1.5) to submit a lifecycle inventory (LCI) and further encouraging a full LCA study (as part of its MR-1 credit in v1.5) by awarding 2 points. LCA is not yet an immediately implementable tool when it comes to adopting construction best practices and its main functionality is in quantifying environmental impacts and, to some extent, in decision-making processes. The idea behind requiring partial LCA in Greenroads is, hence, not its implementation into the design and planning procedures, rather it is mainly an accounting tool at this point for future projects to become considerate and educated in the environmental impacts of material selections and construction activities.

Following the research trends explained earlier, Greenroads v1.5 narrows down the LCA boundary to the pavement section of projects. This is mainly due to the fact that the pavement industry has been one of the biggest advocates and developers of LCA frameworks compared to other fields involved in the construction of transportation infrastructures (Harvey et al., 2016; Horvath and Hendrickson, 1998). This is somewhat anticipated from the Federal Highway Administration's (FHWA) use of lifecycle cost analysis (LCCA) in the design and procurement of paving projects in 1998 (Walls III and Smith, 1998). Greenroads further requires a cradle-to-grave LCA approach to account for the weight and type of virgin and recycled materials, materials transportation to and from construction sites (i.e., waste materials), construction equipment usage, and maintenance activities expected during the design life of projects.

3.4.1.2 Integrating LCA into Pay Item Lists

Material quantities are the most important input to any LCA model. Such information for construction projects are usually listed under three forms of documents provided by project teams depending on the construction stage: 1) design estimates, 2) bid documents provided by the contractor(s), and 3) final invoice for a contract (Harrell et al., 2016). Muench, Scarsella (now Lemeire), et al. (2012) attempted on using bid tabulation information to assign each item to a Greenroads credit to quantify their lifecycle costs and benefits. They found such assignment tasks challenging since a single pay item can be attributed to many processes, materials, and construction activities. A. S. Chang et al. (2018) followed a rather similar approach to assign bid items to Greenroads credit while also performing LCA on individual pay items. They showed that the environmental and economic impacts of some Greenroads credits can be linked to the level of difficulty in achieving or performing their related activities.

Supplemented with other information such as transportation mode and hauling distances as well as equipment usage data logs, several studies leveraged a form of bid tabulation (whether estimate or final) to perform a partial or full LCA. The first step in using bid tabulation data to carry out LCA usually involves the assignment of bid items to a material type, construction activity, or any other appropriate module. In a case study of a project, A. S. Chang et al. (2018) divided materials into crushed stone, steel reinforcement, concrete, and asphalt and argued that they account for 74% of the total carbon emission of the project. Mukherjee et al. (2013) have gone even further and developed a tool (i.e., PE-2) that uses bid tabulation data from 14 construction projects in Michigan to perform LCA on highway construction projects, where they divide materials into concretic and asphaltic. Ozer et al. (2017) performed one of the most comprehensive studies on linking environmental and economic costs of paving projects using a database of 464 asphalt and 461 concrete mix designs. However, using estimated material costs in their study magnifies the importance of integrating bid tabulation data into the analysis.

3.5 Scope

The primary question of this chapter is about the quantifiable environmental impacts of building a roadway project. The goal is to go beyond an individual project and expand into a collection of projects to investigate relationships and trends. The overarching question of this chapter is *what are the greenhouse gas emissions (i.e., carbon footprint) and energy consumption of roadway construction projects?* The scope is mostly limited to the pavement sections and materials used to build them. This chapter then asks whether there is a relationship between the environmental impacts and financial costs of roadway projects. We hypothesize that project bid price can act as a proxy to project size and LCA results can be normalized according to the project's bid price to draw more consistent and comprehensive conclusions To answer these questions, Greenroads LCA submittals from 32 certified projects are analyzed and integrated into pay item list submittals to investigate our hypothesis.

3.6 Method

3.6.1 Life Cycle Assessment (LCA)

Greenroads encourages projects to use an in-house modified version of the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) for satisfying the PR-3 credit requirement (hereafter referred to as the PR-3 Tool). This Microsoft Excel spreadsheet tool takes advantage of an emission factor inventory for material production and material transportation. The PR-3 Tool is also capable of estimating the environmental impacts of equipment usage based on engine size, fuel type and consumption rates, productivity, and efficiency information provided by several manufacturers (Horvath, 2004). Project teams in most cases submitted a complete spreadsheet with the life cycle inventory inputs and LCA results. As a result, only minimal data cleaning was needed. It is also worth noting that LCA submission was missing from Project #25 (see **Table 2.2**) which reduced our LCA sample population to 32.

In practice, the PR-3 Tool requires four major pieces of information to perform LCA: 1) material types and quantities expressed in units of volume or weight, 2) transportation modes and distances, 3) construction equipment information (number, type, and engine size), and 4) maintenance activities throughout the lifecycle of projects (maintenance activities are excluded for this study). A formal explanation of the four LCA steps (i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation) is beyond the scope of this chapter and the reader is referred to the PR-3 credit description in Greenroads Manual (Muench et al., 2011).

The system boundary of this LCA is limited to and is defined by the project scope and context, while the functional unit is not explicitly stated. The scope of the PR-3 Tool is limited to the pavement sections; however, it can technically be used for any other road element that shares similar material properties with pavements such as sidewalks, driveways, and even structures. Here, we define the functional unit as *the initial construction of the road surface structure of a given project including materials excavation, production (e.g., hot mix asphalt, concrete, steel, aggregate bases), transportation, and placement*. The system boundary entails cradle-to-construction LCA (use and end-of-life phases excluded) of earthwork operations, waste management, materials production, materials transportation, and construction activities. Material types are limited to asphalt mixes, portland cement concrete (PCC), aggregates used as base layers, soil used as subgrade, and structural or reinforcing steel.

3.6.1.1 Pay Item List Integration

The methodology outlined above only required one additional step, which is the process of identifying the pay item(s) that are related to the LCA results. This was done by matching material types and volumes from the PR-3 submittals and the pay item lists. Doing so will enable the analyses to show the coverage of LCA in terms of the total bid price of included items. The goal of integrating LCA results with associated pay items was to examine how material prices (including production, transportation, and placement) relate to their carbon footprint and energy consumption (similar to Ozer et al. (2017) and Mukherjee et al. (2013) but using real project data).

Combining LCA results with the financial information documented during the bidding process (i.e., pay item lists) reveals interesting insights into how environmental and economic aspects of sustainability can become integrated. As Ozer et al. (2017) postulated, GWP (measured in CO_2-eq) and energy consumption are found to be highly correlated with financial costs since higher emissions and energy consumption are tied to higher fuel combustion which incurs more costs in return (Ozer et al., 2017). However, this dissertation addresses the shortcomings of Ozer et al. (2017) by 1) using actual material prices as recorded by project teams (as opposed to estimated prices), 2) considering more applications of portland cement concrete than just in pavements (e.g., concrete sidewalks, driveways, and some general use of concrete), and 3) going beyond the geographic coverage of one state (i.e., Illinois) to a much larger intercontinental area.

3.6.1.2 Normalization

ISO 14044 standard on LCA defines normalization as “calculating the magnitude of category indicator results relative to reference information.” Despite normalization being an optional step in the standard LCA process, it can be valuable in terms of data interpretation and communication. Normalization based on a unit of measure defined in the functional unit is also possible, but it may be biased and does not produce the most consistent and comparable results. In fact, functional unit and normalization reference are often used interchangeably. This chapter proposes that unit price can serve as a fair normalization reference and will compare LCA results normalized by other commonly used references (e.g., lane-mile and square foot). **Equation (3-1)** below is the mathematical expression of the normalization process (Langfitt and Haselbach, 2017):

$$N_i = {S_i}/{R_i} \quad \textbf{(3-1)}$$

where i is the environmental impact category, N_i is the normalized result, S_i is the characterized impact of the product, and R_i is the normalization reference.

3.7 LCA Results

There are multiple ways LCA results can be normalized, analyzed, and visualized. To remain consistent with the literature, the PR-3 Tool LCA results were initially normalized using lane-milage and square footage of projects. Given that, the median carbon footprint for Greenroads-certified projects is 535 (ranging from 65 to 13,505) tons CO_2-eq/lane-mile and 3.72 (ranging from 0.03 to 34.90) kg CO_2-eq/ft^2. The median energy consumption is 6.2 (ranging from 0.9 to 143.9) TJ/lane-mile and 68.6 (ranging from 0.3 to 372.0) MJ/ft^2. Our findings are comparable to other LCAs on road construction projects, pavements in particular. Overall, the literature reviewed previously showed an average footprint of 2,138 tons CO_2-eq/lane-mile which falls within the range of values found here.

3.7.1 Correlation with Bid Price

Figure 3.1 illustrates the results of a combined LCA and pay item list analysis and the correlation between the itemized bid prices and the environmental footprints of materials expressed in GWP (measured in CO_2-eq) and energy consumption (measured in MJ). 95% confidence intervals for the power regression lines are also indicated in **Figure 3.1**. The data points are further stratified based on the purpose of roadway construction projects (i.e., maintenance, reconstruction, and new construction). The use of a log-log scatterplot and power functions to regress bid prices to environmental impacts seems more appropriate due to the high variability of material weights (and hence footprints and prices) that exists within the database.

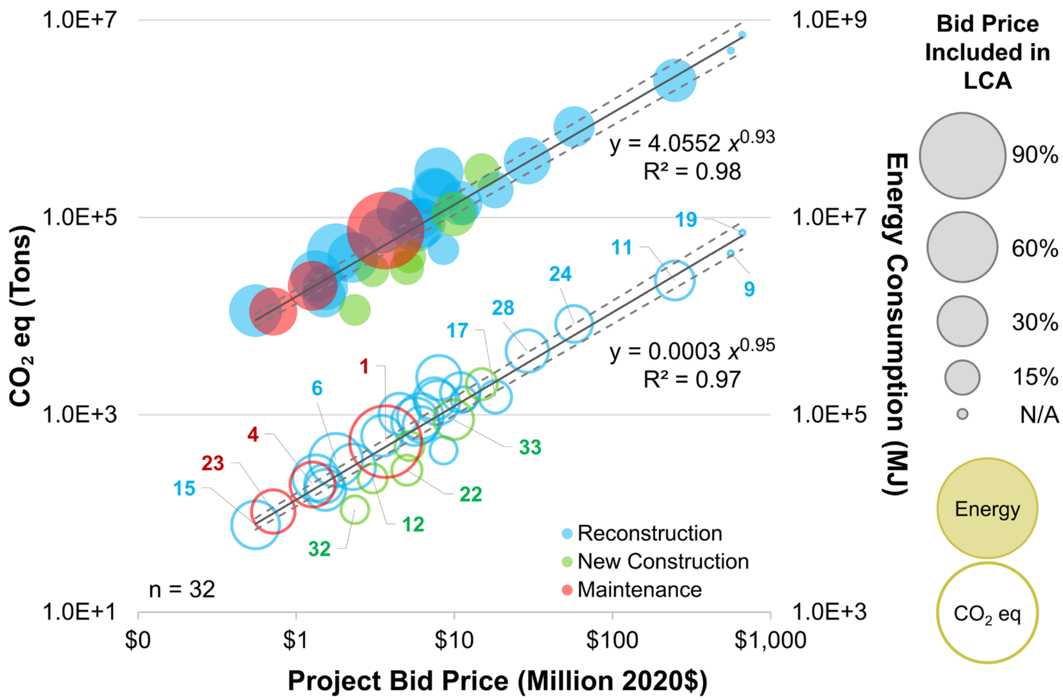

Figure 3.1 Carbon footprint and energy consumption of roadway surfaces correlated with project bid price and construction type. Circle areas correspond to the percent of projects' bid price covered in the LCA. Solid lines show linear regression results, and the dashed lines indicate 95% confidence intervals. Data labels indicate Project ID.

As expected, larger projects use larger quantities of materials and thus result in higher footprints**. Figure 3.1** and its regressed power line can serve as a reference for future paving projects to guesstimate their environmental footprints based on the total bid price. With a majority of project bid prices falling between $1 to $10 million, the trendline is most accurate for medium size road maintenance and reconstruction projects. To exemplify, a $10 million roadway construction project emits about 1,340 tons of CO_2-eq and consumes about 13 TJ of energy related to its surface structures including pavement sublayers.

Also shown in **Figure 3.1** is the percentage of project bid prices included in the LCA; in that, larger circles show a higher proportion of a project's bid price included in the analysis. It can be observed that maintenance and reconstruction projects typically involve more pavement-related activities than new construction projects and hence have a higher percentage of their bid price covered in the LCA. The scope of new construction projects is often broader than paving activities and can expand to structures (e.g., bridge and tunnel elements), water and wastewater infrastructure (e.g., pipes, culverts, catch basins, etc.), among others. On average, 32% of projects' bid prices are captured in this LCA.

3.7.1.1 Asphalt and Concrete Materials

LCA results can also be broken down by material types or roadway elements like sidewalks, driveways, curbs and gutters, etc. **Figure 3.2** and **Figure 3.3** scatter plots correlate carbon footprints with the pay item price of asphalt and concrete materials, respectively. The general trends are similar to the case when the LCA results were aggregated by projects; in that, a higher price of materials correlates with higher carbon footprints. Despite PR-3 Tool's inability to account for geographic location and electricity grid mix, **Figure 3.2** and **Figure 3.3** suggest differences in footprints for the same type of material. There are three justifications for this observation: 1) price variability within regions, 2) different material compositions (e.g., mix design and recycled content), and 3) varying material transportation distances.

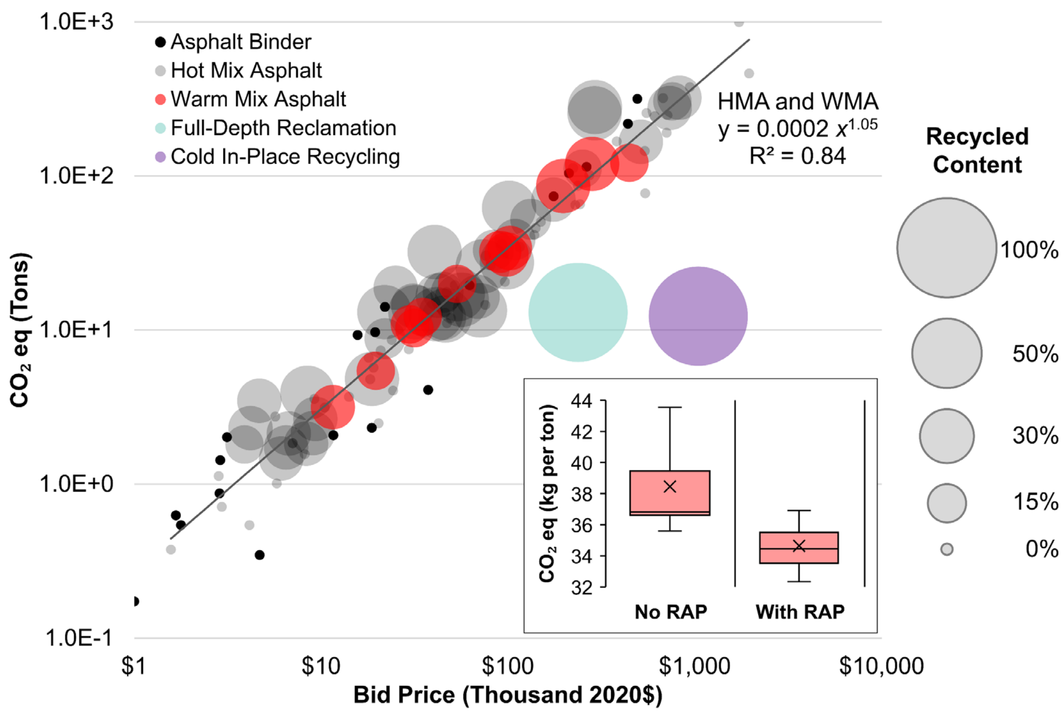

Figure 3.2 Carbon footprint of asphalt-related pay items correlated with their bid price. Circle areas correspond to the percentage of reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), or reused pavement materials incorporated into asphalt mixtures. The regression line indicates the association between hot or warm mix asphalt with their bid price. The box plot shows the carbon footprint per mass of asphalt mixes made with and without RAP.

The size of circles in **Figure 3.2** and **Figure 3.3** is proportional to the percentage of recycled content in asphalt and fly ash (a by-product from coal power plants) in the portland cement concrete mix design, respectively. These figures also illustrate the carbon footprint per mass of RAP and fly ash and suggest that on a per mass basis, the substitution of virgin materials with recycled or by-product materials may result in lower carbon footprints. It is also worth noting that Full-Depth Reclamation (FDR) and Cold In-Place Recycling (CIR) practices in **Figure 3.2** suggest lower overall carbon footprints compared to typical HMA and warm mix asphalt (WMA) applications. It is worth noting, however, that the system boundary of our LCA excludes use phase and workzone traffic. It is well known that FDR and CIR practices require longer road closures and strong conclusions cannot be drawn without a more comprehensive LCA scope to consider the emissions associated with workzone traffic.

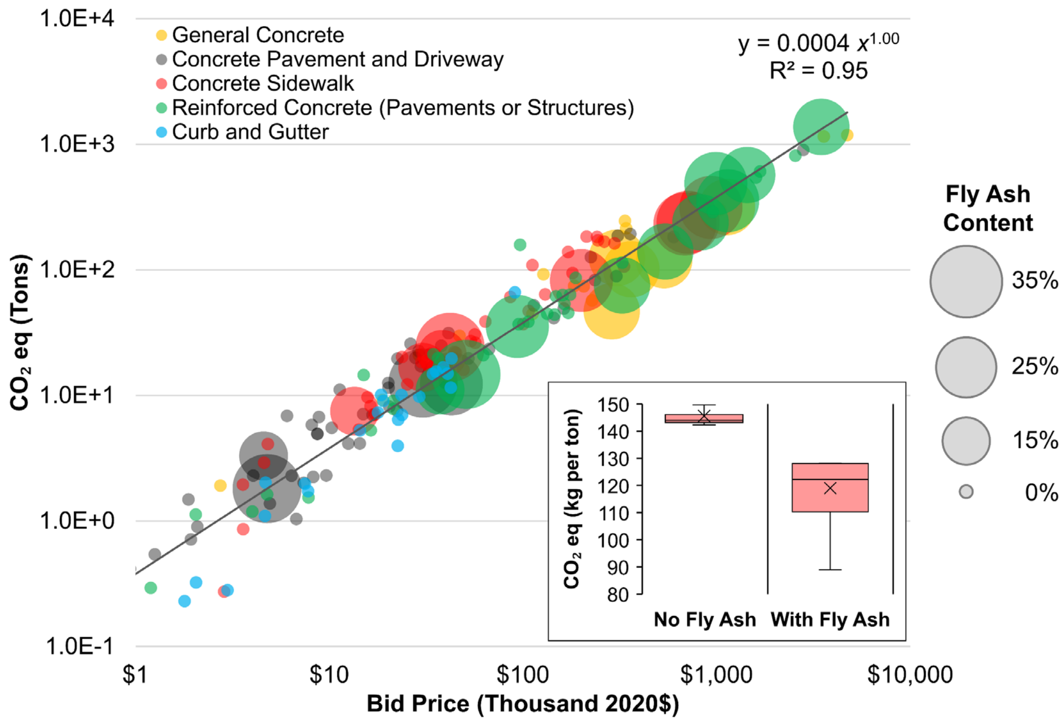

Figure 3.3 Carbon footprint of portland cement concrete items correlated with their bid price. Circle areas correspond to the percentage of fly ash used in the mix design. The box plot shows the carbon footprint per mass of concrete made with and without fly ash.

Finally, **Figure 3.4** compares LCA results for asphalt and concrete used in pavements, sidewalks, and driveways. Carbon footprints are correlated with both mass and bid price of asphalt and concrete items. On a per-mass basis, concrete shows a higher carbon footprint than asphalt. This could mainly be attributed to the energy-intensive cement manufacturing process and its high proportion in concrete mix designs. However, on a per-price basis, both material types seem to trend very similarly. This serves as another evidence that normalization of LCA results based on the mass of materials or geometric properties of the roadway (e.g., length or area) can become misleading. In contrast, since several aspects of material production, construction activities, and material longevity are considered in the financial accounting of projects, pay item price seems to be a better denominator to normalize LCA results against. Overall, our results show no significant difference between the carbon footprint per bid price of asphalt and concrete items.

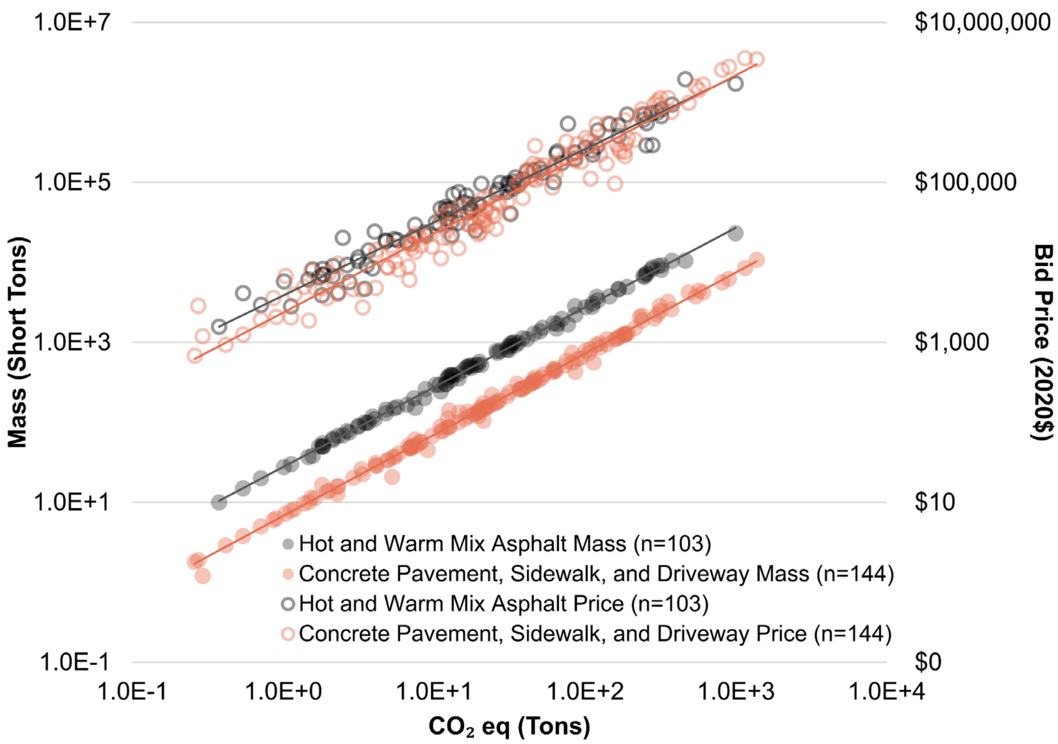

Figure 3.4 Pairwise comparison between the carbon footprint of HMA/WMA and Portland cement concrete used in roadway surfaces correlated with their mass and bid price.

3.7.2 LCA Normalization

The wide range of normalized LCA results per lane-miles or square footage of projects is in part due to the variability of project scopes, functional classes, traffic levels, and designated service lives. For example, it is unfair to compare a lane-mile of a bridge structure to a pavement section although they may both be called a roadway. To address the scope-sensitivity issue, the LCA results are further normalized to bid price to act as a proxy to project size. As a result, the median carbon footprint of Greenroads projects was found to be 138 (ranging from 47 to 297) tons CO_2-eq per million USD. For energy consumption, a median value of 1.4 (ranging from 0.5 to 3.6) TJ per million USD was obtained. For both metrics, we observe a range difference of less than one order of magnitude as compared to three orders of magnitude differences in the range of carbon footprint and energy consumption per lane-mile or square foot (see **Figure 3.5**). This observation also suggests a strong association between the financial costs of projects and their environmental footprints.

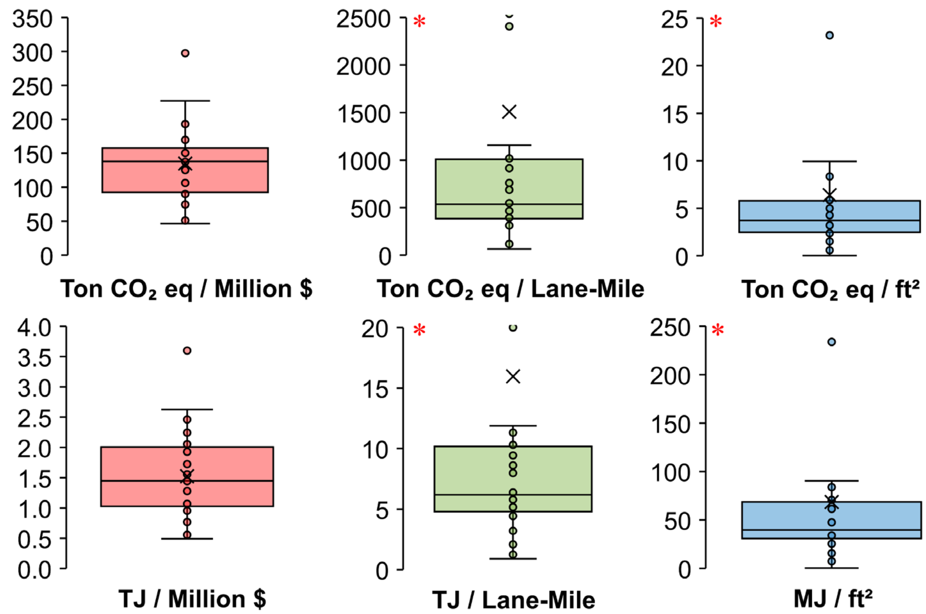

Figure 3.5 Carbon footprint and energy consumption of projects normalized by the bid price, lane-mile, and square footage. Numbers above the red asterisk (*) are not shown. The middle horizontal line in the box plot indicates median and the cross sign (x) indicates average. The height of each box indicates the interquartile range (IQR) and the length of bottom and top whiskers indicate difference between the IQR to 1.5 times the first and third quartiles, respectively.

3.8 Discussion

3.8.1 Carbon and Energy Footprints are Highly Correlated with Price

In agreement with Ozer et al. (2017), findings from **Figure 3.2**, **Figure 3.3**, and **Figure 3.4** show that carbon and energy footprints for pavements and constituent materials are highly correlated with the price of projects, materials, and pavement structures. Consequently, it may be that prices represent a relatively quick and cheap way to estimate carbon and energy footprints. This may be of use to agencies that own and operate large roadway networks such as State Departments of Transportations (DOTs) and need to produce greenhouse gas inventories rather quickly but possess only price information. So far, this correlation is specific to pavements and constituent materials, and its generalization to all roadway features (e.g., bridges, walls, pipes, catch basins, signs, etc.) is an ongoing research effort. We suspect, based on similar materials (i.e., both pavements and entire roadway projects use the same basic materials) this correlation will hold for entire roadway project material inventories.

3.8.2 Implications of LCA Normalization based on Price

In line with most studies, **Figure 3.2** and **Figure 3.3** show that using recycled materials in asphalt and concrete mixtures reduces the carbon intensity (i.e., carbon footprint per mass of material). However, that reduction appears minimal (< 10%) and when carbon footprints are normalized against price, the differences are less noticeable (see **Figure 3.2**, **Figure 3.3**, and **Figure 3.5**). One possible interpretation is that the inclusion of recycled content makes the material less expensive to produce on a per weight basis, therefore, market forces result in it being priced lower. This is often hypothesized and has been shown true in many cases (Ozer et al., 2017).

Similarly, **Figure 3.4** suggests that when the carbon footprint of asphalt and concrete pavements are normalized to their price, the differences in their environmental impacts become relatively insignificant. This is in contrast to most previous pavement LCA studies that normalize results to unit mass (e.g., kg), roadway geometrics (e.g., length or area), and/or structural design parameters. This may be because our LCA is cradle-to-construction only. It may be that the increased price for concrete is a proxy for its perceived longevity, which in turn makes normalized LCA results comparable.

3.8.3 Full-Depth Reclamation (FDR) and Cold In-Place Recycling Are Outliers

Figure 3.2 shows FDR and CIR have significantly lower carbon and energy footprints for their price than HMA or WMA. However, FDR and CIR are intended as alternatives to a full pavement reconstruction, which is generally only necessary in a preservation context if an existing pavement has been neglected long enough where a non-structural overlay is no longer viable. In most cases, regular non-structural overlays (e.g., only 1-2 inches thick) as part of a pavement preservation program are less carbon/energy-intensive than periodic FDR or CIR to maintain an equivalent condition. Therefore, FDR and CIR should be considered less carbon/energy-intensive when compared to full pavement reconstruction.

3.8.4 Limitations

There are two major limitations associated with this chapter. First, the in-house LCA process used here is limited because it does not allow for the inclusion of Environmental Product Declarations (EPDs) for specific materials, limiting its ability to differentiate between similar materials. Second, normalization based on price is susceptible to changes in price due to inflation. While using inflation-adjusted real dollars in a baseline year can compensate for much of this, differential inflation between construction materials is difficult to account for. For instance, current price fluctuations in the petroleum market (Cardinal et al., 2021) which are reflected in asphalt prices are not indicative of risking carbon or energy footprints.

3.9 Summary and Conclusions

Regardless of size and scope, the bidding process of construction projects is almost always driven by economic factors. Pay item lists are the place to document and summarize the economic accounting outcomes. On the other hand, with the raising concerns over the environmental impacts of material manufacturing and streamlined processes, a mere concentration on project economics in the alternative selection process appears ignorant. This chapter, following the suggestion by previous researchers, attempted at supplementing pay item lists with several other pieces of information to make them appropriate for environmental impact assessment using the LCA methodology.

Limiting the system boundary to cradle-to-construction (as explained in Ozer et al. (2017)), the LCA of roadway construction projects can be split up into three main categories of materials production, materials transportation, and construction activities. Subsequently, this chapter introduced a modified version of pay item lists to act as a reference for further environmental impact analysis. The following bullet points conclude this chapter:

- Project pay item lists can be integrated into an LCA framework to report results. A median carbon footprint and energy consumption for the pavement sections of road infrastructure is about 140 (range of 50 to 300) tons of CO_2-eq and 1.5 (range of 0.5 to 3.6) TJ per million USD spent, respectively.
- Carbon and energy footprints are highly correlated with the price of pavements and their constituent materials. This correlation is expected for three reasons. First, pavements are quite similar between projects. Their only substantial difference is asphalt or concrete and slight differences in their mix design. Second, the underlying LCA data are the same. The PR-3 tool uses the same standard emission factors for materials production and transportation and does not capture most differences between projects. Third, results are normalized by price, which

accounts for the most common project differences (e.g., size or amount of material, asphalt vs. concrete).

- Project bid price serves as a good proxy to project size. The variation in LCA results is substantially reduced when project bid prices are used as the normalization reference. Normalization based on geometric features such as roadway length or area is unable to capture differences in project scope and functionality (e.g., highway pavements vs. local roads pavements).
- More expensive projects are correlated with higher environmental impacts. This chapter found a power relationship between projects' bid price and the carbon and energy footprints of paving materials and related construction activities. Confidence intervals were further generated to better describe the range of possible environmental footprints based on projects' bid prices. For example, a $1 million and a $10 million project have carbon footprints of 150 and 1,000 metric tons associated with their paving materials.
- Pavement LCA captures an average of about 30% of a roadway bid price. This chapter found that, on average, about 30% of projects' bid prices can be included in the environmental impact assessment of pavement sections and pavement materials. This suggests that a whole roadway LCA framework would require non-pavement items such as earthwork and site preparation activities, water and stormwater infrastructure, structural elements like walls, bridges, and tunnels, etc. to draw a full picture of a roadway's quantifiable environmental impact.
- LCA cannot capture all environmental impacts. Although the high correlation between price and environmental impacts supports the notion of integrating them for the bidding process of construction projects, there are numerous environmental impacts not captured by GHG emissions or energy consumption. LCA is powerful in quantifying project impacts but is less powerful in quantifying human aspects of projects. This very argument highlights the power of rating systems in capturing and quantifying sustainability achievements.
- Bidding mechanisms can include environmental impacts besides financial project costs. This chapter suggests that an integrated economic and environmental impact framework for the bidding process of roadway projects might soon replace the traditional project delivery

mechanisms. Especially with the recent urge to develop and require Environmental Product Declarations (EPDs) for construction materials as well as green procurement initiatives (Rangelov et al., 2021b), agency-level consideration of environmental impacts in bidding processes does not seem far-fetched.

4 Data-Driven Sustainable Performance Benchmarks in Roadway Construction

4.1 Preface

So far, this dissertation used Greenroads scorecards as a proxy measure to project performance and explored the state of practice in sustainable roadway construction using that (see **Chapter 2**). **Chapter 3** argued that other metrics such as carbon and energy footprints estimated using LCA methods can serve as data-driven performance measures that would complement rating system scores in defining the state of practice. This chapter combines the ideas from the two previous chapters and establishes performance benchmarks for the state of practice in roadway construction using actual construction data (as opposed to rating system scorecards or partially performed pavement LCA). This was done by mining data from several construction documents collected during the Greenroads certification process for 33 projects to introduce and establish quantifiable sustainable performance measures. This chapter would then mine and collect a significant amount of construction data to carry out a whole roadway LCA (as opposed to the already available Greenroads' pavement LCA submittals) and add the carbon and energy footprint of an entire roadway to the mix of performance benchmarks.

A substantial amount of what is presented in this chapter is formatted as a journal paper and it is currently (as of August 2022) under review for publication in the journal of *Cleaner Production*. Methods, findings, and discussions related to **Section 4.6** and its sub-sections are excluded from the submitted paper due to word and scope limitations.

4.2 Abstract

For the $100 billion per year road construction industry, effective sustainability management is hampered because there are few established sustainability benchmarks with which to judge best practices. This dissertation uses data from the 33 Greenroads-certified projects to develop 12 roadway construction sustainability benchmarks: water use, vegetated area, stormwater runoff treatment, lighting power, construction waste generation, local materials use, pedestrian area, bicycle facilities, recycled content, pavement reuse, project CO_2 emissions, and project energy consumption. For the last two benchmarks,

this dissertation introduces and develops a *whole roadway LCA* framework that works alongside projects' pay item lists to further investigate financial costs with the quantitative environmental impacts.

4.3 Introduction

Continued interest in sustainable development (United Nations, 2015) has pushed most infrastructure sectors to acknowledge at least parts of it as business, organization, or industry goals, and therefore, in some manner manage these parts as a concept (Chester, 2019; Griffiths et al., 2018; Thacker et al., 2019). Globally, participation in the Paris Agreement has focused recent sustainability management efforts on limiting global warming by reducing greenhouse gas emissions (UNFCCC, 2015) making their measurement particularly urgent. Nationally, the Infrastructure Investment and Jobs Act (IIJA) (H.R. 3684, 2021) contains multiple funded sections addressing sustainability including Subtitle D – Climate Change, as well as funding for reconnecting communities, permeable pavements, stormwater management best practices, invasive plant elimination, bus tolling equity, pollinator-friendly roadside practices, active transportation, and a variety of sustainability-oriented research. Furthermore, several government agencies have recently pursued or passed procurement policies (e.g., Buy Clean Acts in California (California Public Contracts Code, 2018), Colorado (Colorado General Assembly, 2021), and Oregon (Oregon Legislative Assembly, 2022)) and design standards (e.g., the U.S. General Services Administration's Standard (GSA, 2022)) to account for and reduce the greenhouse gas emissions of select construction materials such as portland cement concrete, asphalt, and steel.

Because of this attention, infrastructure has become more focused on sustainability; specifically on best practices, measurement and management. Measurement and management are primarily accomplished through 1) indicator-based metrics, also known as rating systems, that account for a wide range of practices and provide a generic score (e.g., Leadership in Energy and Environmental Design (LEED), Living Building Challenge, Envision, Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), Greenroads, etc.,) and 2) life cycle assessment (LCA, an accounting process that quantifies specific emissions and environmental impacts).

4.3.1 Problem Statement

Road infrastructure is an industry that puts nearly $100 billion of construction value in place each year (U.S. Census Bureau 2022). Despite this industry size and over 20 years of attention to roadway sustainability, there is still little information on appropriate benchmarks. For instance, what are the average CO_2 emissions associated with a given type of road construction project? Or what is an acceptable target for water use in road construction? Even more basically, what metrics should we use so that these questions can be answered consistently for different types of road projects?

It appears the industry may be hampered by a still-immature research field, and a lack of quality field data. Research on roadway sustainability is new enough that a majority of work still focuses on introducing and critiquing new systems and concepts rather than more industry-wide subjects like benchmarking and state of the practice (see **Section 4.3.3**). Also, actual completed project data can be hard to obtain. Most roadway sustainability research use singular case studies, focus on a subsystem of the whole road (e.g., pavement), and use design/conceptual information only (see **Section 4.3.3**).

4.3.2 Research Scope and Significance

This study uses extensive data from 33 different road construction projects to produce 12 roadway sustainability benchmarks that address: water use, vegetated area, stormwater treatment, lighting power use, waste generation, local materials, pedestrian area, bicycle facilities, recycled content, pavement reused, carbon footprint (greenhouse gas emissions associated with project construction), and energy footprint (energy use associated with project construction). We use the Greenroads Rating System (Muench et al., 2011) as a data collection tool because it collects commonly available public road construction records (e.g., plans, specifications, bid prices) and also detailed data specific to the Greenroads rating process that would not otherwise be collected or archived. Furthermore, this dissertation develops a *whole roadway LCA* framework (accounting for all infrastructure associated with a roadway project) based on publicly available contract pay item lists. These methods and results are significant because 1) this is the first large-scale (33 projects) sustainability review of as-built road projects (all projects are actual completed work), 2) as such, it can provide some first insights into the state of the practice, and 3) it provides some of the first quantifiable benchmarks for 12 different metrics based on real-world data.

4.3.3 Literature Review

The following two literature sections investigate the scope and limitations of roadway sustainability research. In the first, a review of research on sustainable roadway construction shows few articles that address performance metrics and benchmarks. In the second, a review of roadway LCA articles shows that most limit their scope to pavements and use theoretical or design case studies instead of as-built information and prices.

4.3.3.1 Rating System Research

This dissertation used the Scopus database to review journal articles, conference papers, and review papers published between 2010 and 2022. Article titles and abstracts were searched for keywords including a combination of "sustainable," "road," and "construction," and obtained 941 titles. After removing irrelevant articles, the remaining 247 articles were further analyzed to determine common research themes. The main irrelevant topics to the scope of this dissertation were those that looked at the performance of a sustainable material design, experimental studies to characterize material properties, and those with a focus on the development of particular sustainable construction practices.

A total of 55 research theme categories were identified to characterize relevant articles, among those are life cycle assessment (LCA), pavements, tool or framework development, case studies, rating systems, review papers, recycling, qualitative analysis, etc. A combination of up to four research themes was used to categorize each article. As a result, only 11 research themes were found to repeat in more than 5% of the articles. The following list describes each of these 11 research categories (plus one that relates to this chapter and is thus included in the list) in the order of frequency and in addition to the percentage they appeared in our characterization effort:

- Life Cycle Assessment (LCA): 47%. The use of LCA on a variety of roadway elements (mainly pavements at 32%) using a theoretical (14%) or real (4%) case study. Hypothetical case studies apply LCA to design parameters while real case studies use some aspect of a construction project to perform LCA. Comparing two scenarios or materials (9%) and whole roadway LCA (6%) are the other two popular LCA-related research themes.

- Pavement (41%). Pavements as one of the main features of a roadway are one of the most popular research topics. The majority of research on roadway sustainability has focused on the pavement section.
- Roadway (30%). Describes research on entire roadway structure which can include pavements among other roadway features.
- Tool or Framework Development (28%). Development of a sustainability assessment tool or a framework to indicate sustainability in a roadway system. This may or may not include LCA.
- Case Study (27%). The use of theoretical or real case studies to investigate sustainability aspects of a roadway. Typically used to test an LCA framework/tool or a sustainability assessment framework of some sort (e.g., rating systems).
- Rating System (13%). Studies that either applied a rating system scheme on roadway projects, reviewed and compared different rating systems, or attempted to develop one for roadways.
- Review Articles (12%). These are primarily literature review articles with a focus on roadway sustainability to identify research gaps and future directions.
- Recycling (11%). Describes sustainable practices dealing with material recycling and its impact on the environment or design life. Examples are the use of supplementary cementitious materials in portland cement concrete and reclaimed asphalt pavement (RAP) in asphalt mixes.
- Qualitative Analysis (10%). Studies that use qualitative methods to describe roadway sustainability. The use of surveys and interviews to collect opinions and multi-criteria decision making (MCDM) are two main components of this research category.
- Bridge Construction (7%). Describes the sustainable design or a construction practice related to bridge structures.
- State of Practice (5%). Describes the current practice in sustainable roadway construction. This could be through the review of literature, application of rating systems on a construction project or structured surveys to seek sustainability trends.

- Benchmarking (2%). This research theme contributes to less than 5% of research on sustainable roadways and is included here to indicate the research gap on this topic. Benchmarking studies use a sustainability assessment tool (e.g., a rating system or LCA) to establish performance reference values.

Figure 4.1 shows the frequency with which these research themes appeared in the literature reviewed here. Sustainable road construction research shows a heavy emphasis on LCA application, with little work in the areas of benchmarking, state-of-practice, and real case studies (i.e., application on construction projects). Therefore, there is not much information to answer such basic questions as 1) what is the state of the practice in sustainable roadway construction and how can the achievement of those be quantified as performance benchmarks for future projects to follow, and 2) can LCA be used on a whole roadway structure (i.e., whole roadway LCA) to establish roadway construction performance benchmarks? Since LCA research in the world of sustainable roadway construction is attracting more attention, the following section provides a more in-depth review of the literature on roadway LCA.

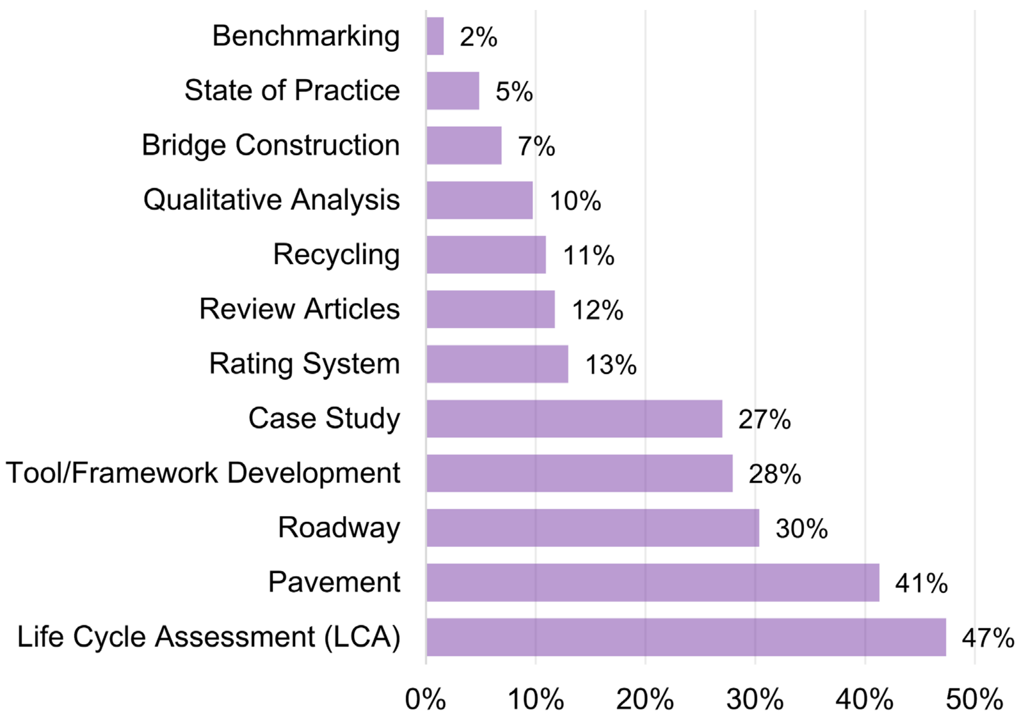

Figure 4.1 Comparing the most frequently published articles on sustainable roadway construction broken down by research topics. A total of 247 articles were analyzed.

4.3.3.2 Life Cycle Assessment (LCA) in Road Construction

Roadway construction LCA is dominated by studies that consider pavement sections and materials, albeit being different in their scope. Those studies either perform a review of existing literature, develop LCA tools and frameworks and apply them to hypothetical design parameters, or, less frequently, use them on a case study of a built or designed project. However, studies that conduct LCA on whole roadway structures (either a hypothetical design or a real project) are scarce in the literature. Regardless, the use of greenhouse gas emissions (i.e., carbon footprint) and energy consumption (i.e., energy footprint) in reporting LCA results and establishing benchmarks is widespread.

Table 4.1 summarizes the meta-analysis of 19 roadway LCA articles that specifically provide metrics and benchmarks for roadway construction. General trends observed are: 1) LCA systems boundaries are most often limited to the pavement structure only, 2) because of this pavement focus, most often results are normalized using functional units related to length or area (e.g., per lane-mile), and 3) articles analyzing as-built material quantities and prices (e.g., Noland and Hanson (2015) and Ozer et al. (2017)) are rare. Most rely upon hypothetical or real design values only.

4.4 Methods

4.4.1 Greenroads: The Data Source

This chapter uses existing project data collected and stored by the *Sustainable Transport Council* (STC), formerly *Greenroads International*, as part of their Greenroads Rating System project review process (Muench et al., 2011). Specifically, this effort uses stored data within the Greenroads Rating system from 33 projects, totaling $2.3 billion in construction cost, that were completed and certified through the Greenroads Rating System process between 2011 and 2018. These represent a range of project types, sizes, and locations.

Table 4.1 Meta-analysis of LCA scopes and results from select literature.

Source	Location	System Boundary: Initial Construction	System Boundary: Maintenance	System Boundary: Operation	System Boundary: Traffic	Roadway Components: Pavement	Roadway Components: Non-Pavement	Roadway Components: Bridge	Roadway Components: Tunnel	Roadway Components: Whole Roadway	Study Method: Hypothetical Design	Study Method: Case Study	Study Method: Meta-Analysis	Functional Unit	CO_2eq (1,000 Metric Tons per Lane Mile)	Energy Consumption (TJ per Lane-Mile)
Stripple (2001)	Sweden	✓	✓	✓		✓	✓			✓	✓			P	1.9 - 2.7	37 - 43
Muench (2010)	Variable	✓	o			✓							✓	o	0.3 - 0.8	3 - 11
Martinez Caraballo et al. (2013)	Spain	✓	✓	✓		✓	✓			✓	✓			o	7.4	x
Martinez Caraballo et al. (2013)	Spain	✓	✓	✓		✓	✓	✓		✓	✓			o	17.1	x
Galatioto et al. (2015)	The U.K.		✓			✓					✓	✓		P	0.5	x
Noland & Hanson (2015)	The U.S.	✓				✓	✓			✓	✓	✓		P	1.7	x
Rasdorf et al. (2015)	The U.S.	✓				✓	✓			✓		✓		P	0.9	x
Rasdorf et al. (2015)	The U.S.	✓				✓						✓		P	0.2	x
Wang et al. (2015)	China	✓				✓		✓			✓	✓		P	2.2 - 3.0	x
Wang et al. (2015)	China	✓				✓		✓	✓		✓	✓		P	10.6 - 11.8	x
Guo et al. (2017)	China	✓				✓					✓	✓		km	0.6	x
Mao et al. (2017)	China	✓	✓			✓					✓	✓		m^2	0.4 - 1.2	x
Pasetto et al. (2017)	Italy	✓	✓	✓		✓					✓	✓		km	11.5 - 12.9	210 - 232
Penadés et al. (2017)	Spain	✓	✓	✓	✓	✓		✓			✓			m	4.8 - 5.6	x
Trigaux et al. (2017)	Belgium	✓	✓	✓		✓	✓			✓	✓			m	3.2 - 4.5	x
Milani & Kripka (2019)	Brazil	✓				✓		✓			✓			m^2	1.1 - 2.1	x
Li et al. (2020)	China	✓				✓	✓			✓	✓	✓		m^2	1.7	x
Ek et al. (2020)	Sweden	✓	✓	✓				✓			✓	✓		m	0.3 - 0.4	5 - 6
Hasan et al. (2020)	U.A.E.	✓	✓			✓						✓		P	0.9 - 1.3	15 - 25
Barbieri et al. (2021)	Norway	✓	✓	✓		✓					✓			km	7.3 - 7.5	x
Blaauw & Maina (2021)	South Africa	✓				✓					✓			km	1.1 - 1.2	8 - 8.6
Cristiano (2022)	Italy	✓				✓	✓	✓	✓	✓		✓		P	4.0	115

✓*: Considered* o*: Variable* x*: Not Available/Not Specified* P*: Project Level*

4.4.1.1 About the Greenroads Rating System and its Data

The Greenroads Rating System is an independent third-party sustainability rating system for roadways. Version 1.5, used for the projects reviewed in this study, consists of 50 sustainability best practices for roadway design and construction (Muench et al., 2011). Roadway projects can choose to engage Greenroads, for a fee, to measure their sustainability efforts through a certification process. To obtain a Greenroads certification, a project chooses which best practices within the system to pursue, submits documentation of their attainment, is awarded points based on their accomplishments, and, ultimately, a certification level based on Greenroads staff verification. As part of the certification process, Greenroads maintains a database that identifies what sustainable practices a roadway achieved, and contains the documentation and quantities associated with those practices as well as general project information. This database is critical to our effort because while much of the data reviewed is produced for the standard road construction process (usually for specification, inspection, or payment reasons), little of it is archived in an accessible form for later analysis such as this (Lew et al., 2016; Thacker et al., 2019; Yamaura and Muench, 2018). Furthermore, some of the data used in this dissertation are only produced to meet Greenroads requirements and, otherwise, would not exist.

4.4.1.2 About The Projects

We reviewed 33 Greenroads-certified projects (see **Figure 4.2** and **Table 2.2** for information about project contexts) that were completed between 2011 and 2018 using the Greenroads Rating System, Version 1.5 (Muench et al., 2011) as the certification standard. Median project values are 1.7 lane miles, a $6.1 million bid price, and 10,000 average annual daily traffic (AADT). The most popular project descriptors are project delivery method: design-bid-build (30 projects), purpose: reconstruction (23), motivation: mobility (12), location: urban (19), functional class: arterial (17), and zoning: residential (10), with numbers in parentheses denoting the number of projects.

4.4.2 Data Collection

Greenroads collects and stores project documentation using a custom online platform constructed in Amazon Web Services (AWS). Overall, the stored data for the 33 evaluated Greenroads projects constitute about 13 gigabytes of data from over 4,300 documents. Data can be grouped into two main categories (see **Section 9.2** for details):

4. Project portfolio (**Figure 4.2**). Descriptive information about the project including price, budget, the scope of work, contractor, owner, geographic location, among others.
5. Supporting evidence. Documentation submitted by project teams for Greenroads evaluation. Most of this is in the form of scanned documents, PDFs, word documents, pictures, and spreadsheets.

The resulting dataset is extensive, but not uniform. This is because the Greenroads Rating System offers more credits than are needed even for the highest certification level. Therefore, different projects choose different credits to pursue, some being more popular than others (Anderson and Muench, 2013; Lew et al., 2016). Hence, not all project datasets contain information in the same categories.

4.4.3 Sustainability Performance Benchmarks

Using Greenroads data, we searched for potential performance benchmarks based on information we defined as *primary* (direct information taken from documents submitted by project teams to meet Greenroads credit requirements, e.g., reported project water use), *secondary* (calculations made by the researchers based on submitted documents, e.g., using submitted plans to calculate paved area), or *tertiary* (using submitted documents supplemented by further data obtained by the researchers outside of the Greenroads project submission process, e.g., using project documents to identify items included in construction, then researching their carbon and energy footprints elsewhere). From this search, we were able to create twelve performance benchmarks based on the following criteria: 1) data for the benchmark must be available from at least one-third (11 of 33) of the projects, and 2) benchmarks must be quantitative instead of binary yes/no information.

Figure 4.3 shows which projects contributed to which performance benchmarks. The following section describes each performance benchmark and the general information collected and the method used to obtain the measurement. Data sources are distinguished as 1) standard project documents (can be obtained from any project if required documents are accessible), 2) Greenroads-specific data (information not generally available from standard project documents and, therefore, asked for specifically by the Greenroads Rating process), or 3) a combination of the previous two.

Project ID	Lane Miles	Bid Price (Million USD)	Average Annual Daily Traffic (Thousand AADT)	Delivery Method			Purpose			Motivation						Location			Functional Class				Zoning					
				DBB [1]	CMCG [2]	PPP [3]	Maintenance	Reconstruction	New Construction	Preservation	Economic	Mobility	Environmental	Safety	Utility Upgrades	Urban	Small Urban	Rural	Arterial	Collector	Local	Other	Commercial	CBD [4]	Residential	Mixed/Multiple	Industrial	Underdeveloped
1	8.3	3.7	45.3	X			X			X						X			X				X					
2	1.2	11.5	9.6	X				X			X					X			X					X				
3	0.4	8.5	8.4	X				X			X						X			X				X				
4	0.6	1.3	3.9	X			X					X					X		X						X			
5	0.4	6.1	3.3	X				X			X						X		X					X				
6	0.8	1.8	1.3	X				X					X			X					X		X					
7	2.2	4.5	6.8	X				X		X						X				X					X			
8	3.6	7.8	34.5	X				X				X				X			X							X		
9	6.3	558.6	122.8	X				X				X		X		X			X					X				
10	2.3	10.9	24.9	X				X			X					X			X					X				
11	1.7	247.7	29.8		X			X				X				X			X		X					X		
12	0.3	3.0	10.0	X					X			X				X					X		X					
13	0.8	3.5	11.5	X				X						X			X			X					X			
14	0.5	1.3	0.5	X				X					X			X					X				X			
15	0.2	0.6	0.1	X				X					X			X					X				X			
16	1.6	6.2	11.0	X				X			X						X		X				X					
17	2.0	18.1	42.0	X				X			X					X			X				X					
18	1.8	5.7	8.6	X				X		X		X					X			X					X			
19	9.0	660.6	110.0			X		X						X		X			X							X		
20	0.2	5.2	0.2	X					X			X					X					X	X					
21	0.4	1.5	3.5	X				X					X				X			X					X			
22	0.3	5.0	0.9	X					X			X				X					X		X					
23	0.9	0.7	0.0	X			X						X				X		X		X			X				
24	10.4	57.1	42.3	X				X						X	X	X			X					X				
25	84.6	624.1	30.0			X			X			X						X	X							X		
26	3.8	7.5	8.6	X				X				X					X			X					X			
27	2.4	8.0	13.3	X				X			X					X				X							X	
28	4.4	28.9	17.0	X				X				X			X	X			X						X			
29	6.2	14.9	1.5	X					X					X				X	X									X
30	1.9	2.3	21.0	X				X						X			X		X				X					
31	0.5	1.5	9.5	X				X			X					X					X			X				
32	0.2	2.3	7.9	X					X					X				X			X				X			
33	1.7	9.9	20.0	X					X			X				X					X		X					

[1] DBB: Design-Bid-Build
[2] CMCG: Construction Management/General Contractor
[3] PPP: Public-Private-Partnership
[4] CBD: Central Business District

Figure 4.2 Project portfolio information from the 33 projects reviewed in this study.

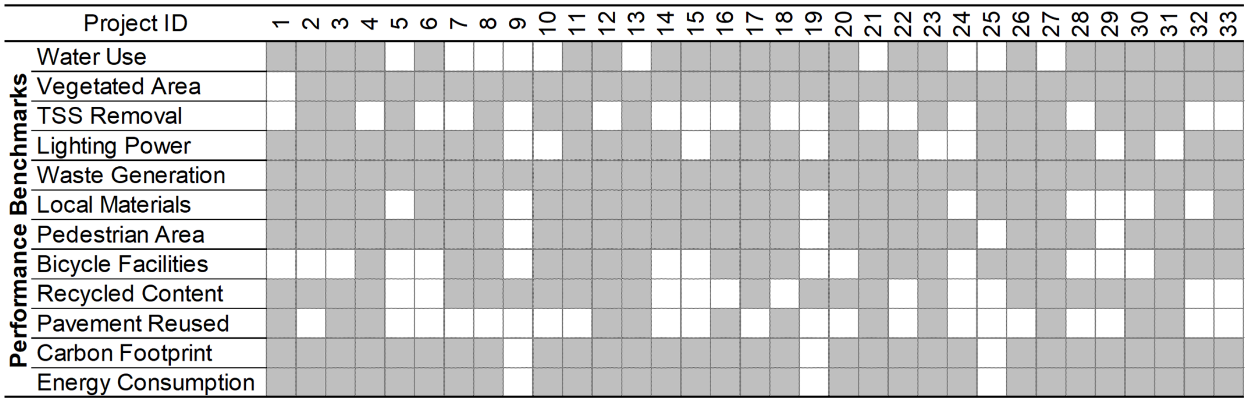

Figure 4.3 Selected sustainability performance benchmarks broken down by projects. Gray cells indicate the inclusion of a project for the establishment of a sustainability performance benchmark.

4.4.3.1 Water Use

- Description: The total amount of water used on the construction site for construction activities. Typical water uses are for saw cutting and grinding pavement, grading and compacting soil, dust control, vegetation establishment watering, in-place pavement recycling, and concrete washout. This total includes both potable and non-potable water and is most often tracked by metering the on-site water source (such as a hydrant) or inventorying water delivery trucks.
- Data source: Greenroads-specific data. Projects typically collected water use information to meet the Water Tracking (CA-7) credit requirements by metering their water use from municipal hydrants and/or collecting their water truck receipts.
- Calculation: None.

4.4.3.2 Fraction Of Vegetated Area

- Description: The fraction of a project's total construction area that is ultimately vegetated (i.e., not paved). The fraction of vegetated area reflects a project's specific efforts to preserve/create green space within its boundaries. Although the fraction of vegetated length is also introduced as a metric (Kristle Nathan and Reddy, 2013), we believe the fraction of vegetated area serves as a better measure to capture landscaping efforts.
- Data source: Standard project documents. Landscape plans were reviewed for the number, species, size, and area covered by vegetation.

- Calculation: Canopy area of trees and shrubs was calculated assuming a circular growth pattern. The vegetated area of other plants was directly obtained from landscaping plans. Total vegetated area is then divided by the total project area.

4.4.3.3 Total Suspended Solids (TSS) Removal

- Description: A performance measure describing one aspect of stormwater treatment efforts. "Suspended solids" are solids in water that can be collected/removed with a filter. Collectively referred to as best management practices, retention/detention ponds, bioretention, biofiltration, and bioswale systems are some common methods for removing suspended solids from stormwater runoff (Eckart et al., 2017). Although not specifically stated in our data, 80% TSS removal is often set as the minimum performance goal based on local interpretations of the Clean Water Act.
- Data source: standard project documents. TSS removal rates were obtained from stormwater pollution prevention plans (SWPP) submitted for Pollution Prevention Plan (PR-7) project requirement, or, if permeable pavement was used, from documents submitted for the Permeable Pavements (PT-2) credit.
- Calculations: None.

4.4.3.4 Lighting Power

- Description: A measure of total roadway lighting energy requirements. Design standards (e.g., ANSI/IES RP-8-18) typically provide illumination requirements, while designers may choose lighting types, styles, and power consumption. Sixty-four percent of Greenroads projects used LED lighting, which consumes less power than older high-pressure sodium lighting (Boyce et al., 2009).
- Data source: Standard project documents. Lighting data came from project lighting plans and specifications.
- Calculations: The total rated power for all street lighting is divided by the project lane miles.

4.4.3.5 Waste Generated

- Description: The total amount of construction-related waste including both landfilled and diverted waste. Typical waste items are removed pavement and structures, scrap metals, excess plastic pipes, clearing and grubbing, and unsuitable (not allowed to be reused on the project) soil excavation (Bamigboye et al., 2021).
- Data source: Greenroads-specific data. Data came from Construction and Demolition Waste Management Plans (CWMP) submitted for the Waste Management Plan (PR-6) project requirement or construction site recycling plans submitted for the Site Recycling Plan (CA-3) credit.
- Calculations: Total tonnage of waste divided by the project's bid price.

4.4.3.6 Local Materials

- Description: The fraction of total material costs sourced within 50 miles of the project. This fraction can be quite high since low-cost, high-volume items like asphalt pavement and cast-in-place concrete are nearly always purchased from a local production plant due to high transportation costs.
- Data source: Greenroads-specific data collection. Materials data came from required reporting forms associated with the Regional Materials credit (MR-5).
- Calculation: The sum of prices for items sourced within 50 miles of the project divided by the total bid price of all physical items (i.e., items that are built or installed on the construction site).

4.4.3.7 Pedestrian Area

- Description: The fraction of a project's total construction area that is ultimately covered with pedestrian facilities such as sidewalks and Americans with Disabilities Act (ADA) compliant ramps.
- Data source: The combination of standard project documents and Greenroads-specific data. Pedestrian areas were identified from transportation master plans, project plans and specifications, pay item lists, and project reports submitted to meet the Pedestrian Access (AE-5) credit requirements.

- Calculation: Pedestrian area divided by the total project area.

4.4.3.8 Bicycle Facilities

- Description: The total lane-mile length of dedicated bicycle lanes (protected or unprotected) and separated multi-purpose pathways.
- Data source: Combination of standard project documents and Greenroads-specific data. Bicycle facilities areas were identified from transportation master plans, project plans and specifications, pay item lists, and project reports submitted to meet the Bicycle Access (AE-6) credit requirements.
- Calculations: Total lane miles of bicycle lanes divided by total project lane miles.

4.4.3.9 Recycled Content

- Description: The fraction of recycled materials by weight used on a project. Greenroads offers four paths to track recycling efforts which consider: 1) pavement asphalt/cement component only (1 project chose this path), 2) hot mix asphalt (HMA) or portland cement concrete (PCC) only (11 projects chose this path), 3) all pavement materials including sublayers (4 projects chose this path), and 4) all project materials (6 projects chose this). These four tracks create a tiered approach to the value of recycled materials with higher values going to those materials that replace virgin materials with a higher environmental burden (e.g., asphalt binder, and cement).
- Data source: Greenroads-specific data. Projects typically submitted data in spreadsheets to meet Recycled Materials (MR-4) credit requirements. Site recycling plan documents (as part of the CA-3 credit) were also used in some instances.
- Calculation: Total recycled materials weight divided by the denominator defined by the track chosen.

4.4.3.10 Pavement Reused

- Description: The fraction of existing pavement that is retained (not removed) within the project boundaries. For Greenroads, reuse is defined as "…a continued use or repurposing of not being transported beyond the project limits at any time during project construction and that it has been minimally processed or changed from its original condition." (Muench et al., 2011) The most common occurrences of pavement reuse are 1) pavement that remains in place and is overlayed by a new pavement layer or covered by a surface treatment, or 2) pavement subject to an in-place reprocessing operation such as hot in-place recycling, cold in-place recycling or full-depth reclamation (Xiao et al., 2018).

- Data source: Combination of standard project documents and Greenroads-specific data. Projects provide a stand-alone document to meet Pavement Reuse (MR-2) credit requirements, or the amount can be estimated from project plans and specifications, and/or pavement design documents.
- Calculation: Total volume of pavement reused divided by the total volume of existing pavement within the project boundaries.

4.4.3.11 Carbon Footprint

- Description: The global warming potential (GWP), expressed in terms of carbon dioxide equivalents (CO_2-eq), attributable to the project's construction based on materials production, transportation, and construction activities associated with the project. We refer to this as a project's carbon footprint.
- Data source: Standard project documents. Pay item lists in contract documents define which common items, described in the specifications, are used for each project and in what quantity.
- Calculation: A life-cycle assessment (LCA), described in **Section 4.4.5** is conducted.

4.4.3.12 Energy Footprint

- Description: The energy consumption in Terajoules (TJ) attributable to the project's construction based on materials production, transportation, and construction activities associated with the project. We refer to this as a project's energy footprint.
- Data source: Same as for carbon footprint.
- Calculation: Same as for carbon footprint.

4.4.4 Data Categorization

This section describes how the pay item data (over 6,200 rows of data from 30 projects – Projects #9, #19, and #25 were excluded) are split into construction and materials categories for analysis.

4.4.4.1 Construction Category Assignment

Thirteen highway construction categories were defined based largely on *NCHRP Report 916* (Muench et al., 2019):

- Administrative and project control: actions necessary to manage and administer the project. Usually not a physical project component.
- Demolition: activities involving the removal, disposal, and salvaging of structures and obstructions.
- Lighting and electrical: electrical systems (software and hardware) used solely for illumination systems such as light poles.
- Pavement, sidewalk, accessibility: constructed horizontal project surfaces used by vehicles, pedestrians, and cyclists.
- Preparation and earthwork: disturbance of land, including removal, replacement, addition, and preparation of base and subgrade materials.
- Signals and traffic control: electrical systems used to control traffic during and after construction including their foundations and structures. Includes intelligent transportation system (ITS) features.
- Signs and markers: road signs and pavement markings.
- Storm drain: stormwater systems including traditional (e.g., pipes, culverts, etc.) and green stormwater infrastructure (e.g., rain gardens, bioswales, etc.).
- Structures: structures not addressed in other categories. Mainly includes walls, bridges, tunnels, and temporary structures used to build them.
- Utilities: electrical, fuel, and communications utilities as well as project amenities not addressed in other categories. Includes utility conflict resolution, benches, bike racks, mailboxes, trash cans, etc.
- Vegetation and landscaping: preparation and establishment of plants and landscape.

- Water and sewer: all project elements (e.g., pipes, bedding materials, etc.) used to convey water and sanitary sewer from residential, commercial, or industrial facilities surrounding the project boundary.
- Workzone and safety: construction workzone traffic control facilities and approaches including road closure plans, scheduling, labor, and installation of temporary traffic control elements like barricades and traffic cones.

Section 8.2.2.2 provides examples of pay items assigned to these construction categories.

Fifty-seven percent of pay items were assigned to a single one of these 13 categories. For the rest, the pay item price was divided up amongst relevant pay item categories (33% amongst two categories, 10% to three categories, and <1% to four categories). For example, a sanitary sewer pipe pay item that includes excavation is assigned to *water and sewer* and *preparation and earthwork* categories.

4.4.4.2 Pay Item Price Allocation

Pay item prices were adjusted to real 2020 USD values using the *Engineering News-Record* (ENR) cost index for the completion year of each project (see **Table 2.3**). For pay items with more than one assigned construction category, the pay item price was first divided by the number of construction categories and then equally allocated to each of the categories. Construction categories were then aggregated by summing up the pay item prices allocated to them. Finally, the total price associated with each construction category was divided by the total bid price of that particular project. This procedure can be expressed for each project as:

$$\%\mathrm{P}_c = 100 \times \sum_{i=1}^{n} \frac{\mathrm{P}_i|_{c\in i}}{N_i} \Big/ \sum_{n=1}^{n} \mathrm{P}_i \qquad \textbf{(4-1)}$$

where,

n	=	Total number of pay items in any given project,
c	=	Any of the thirteen construction categories described above,
N_i	=	Number of construction categories assigned to pay item *i*,
$\%\mathrm{P}_c$	=	Percent of each project's price allocated to construction category *c*,

P_i = Total price of pay item *i* for a total of *n* pay items in project *P* expressed in 2020 USD value, and

$P_i|_{c \in i}$ = Price of pay item *i* that is assigned to N_i construction categories *c*.

4.4.4.3 Material Type Assignment

Six basic material types were identified that describe the main constituent materials used in road construction:

- *Asphalt*: Hot, warm, or cold bituminous mixtures used in pavement applications and asphalt cement used for sealing and coating compounds.
- *Concrete*: Portland cement concrete used in horizontal surfaces (e.g., concrete pavements and sidewalks) and structures (e.g., walls and bridges, pipes, catch basins, etc.).
- *Metals*: All metals used including steel, cast iron, aluminum, copper, and more. Steel, which is most prevalent, is used as a stand-alone structural element (e.g., bridge girders), as rebar in concrete structures, as dowel bars, tie bars, and rebar in concrete pavement, or in other roadside features (e.g., poles, guardrail). Other metals are typically used in roadside features/signs (e.g., aluminum), pipes (e.g., cast iron), and electrical systems (e.g., copper).
- *Plastics*: Polyvinyl chloride (PVC) and high-density polyethylene (HDPE) are used for pipes and geotextiles, polyethylene (PE) for coverings or moisture barriers, thermoplastic paint for pavement markings, and other plastic products such as traffic cones, trash cans, and other appurtenances.
- *Rocks*: Crushed stone, sand, and gravel. Commonly used as fill material, pavement sub-layers, pipe beddings, wall backfills, landscaping, etc. Aggregate as a constituent of concrete is included in the *concrete* category.
- *Wastes*: Materials removed from the construction site for landfilling, recycling offsite, or reuse within the project boundaries. The largest contributors are clearing and grubbing, demolition, and earthwork activities.

4.4.5 Life Cycle Assessment (LCA) Overview

This section overviews the life cycle assessment (LCA) process used to estimate carbon and energy footprints (see **Section 8.2** for details) resulting from the entire road construction process. This dissertation terms it *whole roadway LCA* to differentiate it from more common pavement-only analyses. To conduct our LCA, we developed a customized spreadsheet-based LCA tool that follows standardized procedures outlined in ISO14040 and 14044 and is consistent with several other published reports and journal articles (e.g., (Harvey et al., 2016; Mukherjee et al., 2013; Stripple, 2001)).

The goals of this LCA are to 1) evaluate the energy and carbon footprint of construction materials used to build roadway infrastructure, 2) set carbon footprint and energy consumption benchmarks for future roadway construction projects while helping them provide estimates on their environmental footprints, and 3) investigate the correlation between the economic and environmental footprints of the most common construction materials. The functional unit is defined as d*elivering a roadway construction project that meets specifications.* The system boundary is cradle-to-construction (**Figure 4.4**), which includes raw material extraction and processing, upstream (from materials processing to suppliers) and downstream (from suppliers to construction sites) transportation of materials, on-site construction activities, and electricity and fuel consumption at each of these stages for the entire road construction project. The cut-off criteria are set to exclude pay items that contribute less than 0.1% of each project's bid price.

To allocate the carbon footprint and energy consumption of each pay item to its assigned construction category, an approach similar to **Section 4.4.4.2** was followed. Classification and characterization of environmental impacts include total energy consumption and global warming potential (GWP) measured in metric tons of CO_2 equivalent. The majority of life cycle inventory (LCI) data are collected from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET 2020) (Wang et al., 2020), the United States Environmental Protection Agency (EPA) AP-42 report (RTI International, 2004), Asphalt Institute (Wildnauer et al., 2019), and EPA Motor Vehicle Emission Simulator (MOVES) 2014b (US EPA, 2015). **Section 8.2** contains a more detailed description of the LCA framework, LCI and reference flow data sources, LCA characterization factors, and life cycle inventory analysis (LCIA). The following **Equations (4-2)** thru **(4-9)** summarize the inventory problem solutions:

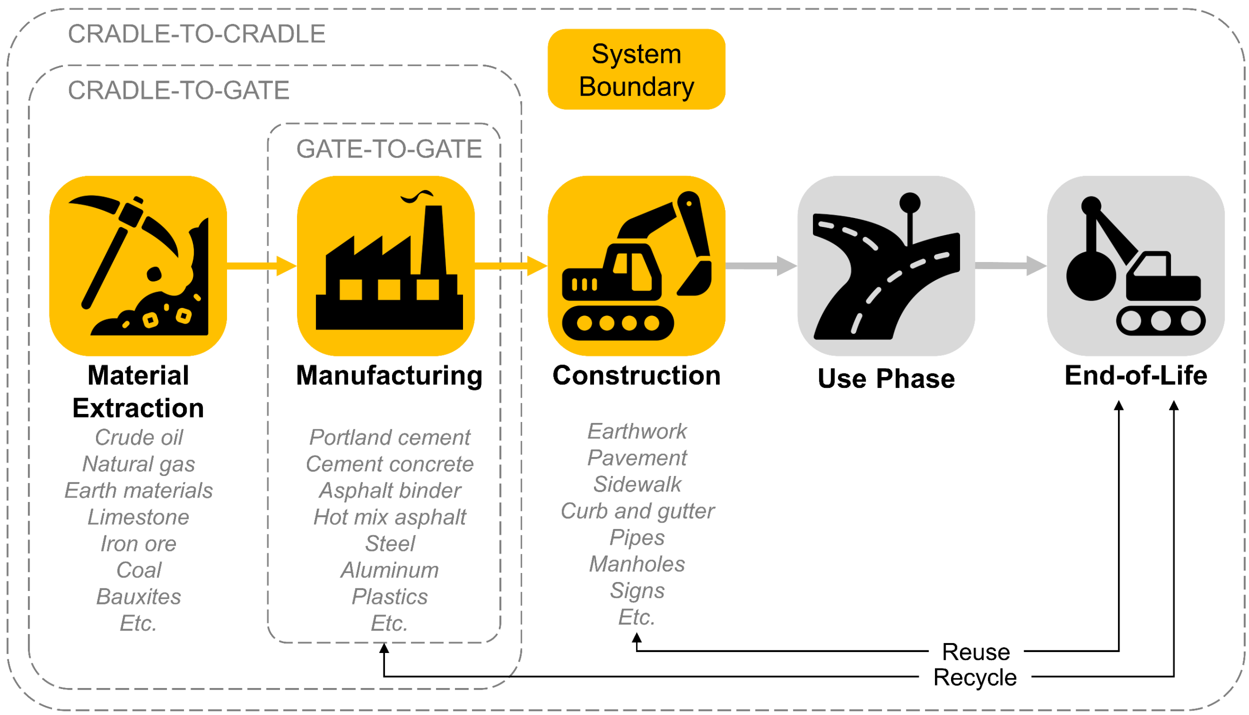

Figure 4.4 The cradle-to-construction system boundary defined in this study. The yellow-shaded life cycle stages (i.e., material extraction, material manufacturing, and construction processes) are included in the system boundary. Material transportations within the system boundary are further indicated with yellow-shaded arrows.

$$GWP_i = GWP_i^{PM} + GWP_i^{TV} + GWP_i^{CE} \quad \text{(4-2)}$$

$$E_i = E_i^{PM} + E_i^{TV} + E_i^{CE} \quad \text{(4-3)}$$

$$GWP_i^{PM} = \sum_j (W_i)(PMP_{i,j})(GWP_j^{PM}) \quad \text{(4-4)}$$

$$E_i^{PM} = \sum_j (W_i)(PMP_{i,j})(E_j^{PM}) \quad \text{(4-5)}$$

$$GWP_i^{TV} = \sum_t (W_i)(D_i)(GWP_t^{TV}) \quad \text{(4-6)}$$

$$E_i^{TV} = \sum_t (W_i)(D_i)(E_t^{TV}) \quad \text{(4-7)}$$

$$GWP_i^{CE} = \sum_e (OH_i)(WE_{i,e})(GWP_e^{CE}) \quad \text{(4-8)}$$

$$E_i^{CE} = \sum_e (OH_i)(WE_{i,e})(E_e^{CE}) \quad \text{(4-9)}$$

where,

GWP_i = Total global warming potential associated with the i^{th} pay item in metric tons of CO_2-eq,

GWP_i^{PM} = Total global warming potential of the primary material production for the i^{th} pay item in metric tons of CO_2-eq,

GWP_i^{TV} = Total global warming potential of transporting the i^{th} pay item in metric tons of CO_2-eq,

GWP_i^{CE} = Total global warming potential of constructing the i^{th} pay item in metric tons of CO_2-eq,

E_i = Total energy consumption associated with the i^{th} pay item in GJ,

E_i^{PM} = Total energy consumption of the primary material production for the i^{th} pay item in GJ,

E_i^{CE} = Total energy consumption of constructing the i^{th} pay item in GJ,

E_i^{TV} = Total energy consumption of transporting the i^{th} pay item in GJ,

W_i = Total weight of the i^{th} pay item in tons, $W_i = (Q_i)(UW_i)/2000$,

Q_i = Quantity of the i^{th} pay item according to the unit of measure,

UW_i = Unit weight of the i^{th} pay item in pounds per unit of measure,

$PMP_{i,j}$ = j^{th} primary material proportion of the i^{th} pay item expressed in percentages,

GWP_j^{PM} = Per unit global warming potential of the j^{th} primary material in metric tons of CO_2-eq /US tons,

E_j^{PM} = Per unit energy consumption of the j^{th} primary material in Giga Joules (GJ)/US tons,

D_i = Transportation distance of the i^{th} pay item in miles,

GWP_t^{TV} = Per unit global warming potential of the t^{th} transportation vehicle in metric tons of CO_2-eq /US ton-miles,

E_t^{TV} = Per unit energy consumption of the t^{th} transportation vehicle in GJ/US ton-miles,

OH_i = Operation hours of the i^{th} pay item, $OH_i = 8\times(Q_i)/(PR_i)$,

PR_i = Production rate of the i^{th} pay item in the unit of measure per day (assuming 8-hour workdays),

$WE_{i,e}$ = Working efficiency of the e^{th} construction equipment to place or install the i^{th} pay item,

GWP_e^{CE} = Per unit global warming potential of the e^{th} construction equipment in metric tons of CO_2-eq /hours of operation, and

E_e^{CE} = Per unit energy consumption of the e^{th} construction equipment in GJ/hours of operation.

4.5 Results and Discussion

4.5.1 Sustainable Performance Benchmarks

Benchmarks are presented as normalized median values (see **Figure 4.5**):

1. *Water use: 32,000 gallons per $1 million (2020 USD) of project bid price.*
2. *Vegetated area: 28% of the total project construction area.*
3. *Total suspended solids (TSS) removal: 85% TSS removal.*
4. *Lighting power: 2.5 kW per lane-mile of the roadway.*
5. *Waste generated: 1,761 tons per $1 million (2020 USD) of project bid price.*
6. *Local materials: 83% sourced within 50 miles of the project.*
7. *Pedestrian area: 17% of the construction area.*
8. *Bicycle facilities: 62% of project lane miles have bicycle facilities.*
9. *Recycled content: 20% of project material by weight is recycled.*
10. *Pavement reused: 86% of the existing pavement is reused.*
11. *Carbon footprint: 221 tons CO_2-eq per $1 million (2020 USD) of project bid price.*
12. *Energy consumption: 2.2 TJ per $1 million (2020 USD) of project bid price.*

4.5.1.1 Discussion

Collectively, these twelve benchmarks represent what road projects achieve when they have a declared general sustainability goal (what we term a *sustainable road project*); in this case, a Greenroads certification. The term *general* is used to differentiate projects that pursue multiple sustainability topics in a holistic manner (e.g., use a rating system) from projects that pursue just a few or one sustainability topic (e.g., just pursue a reduced carbon footprint).

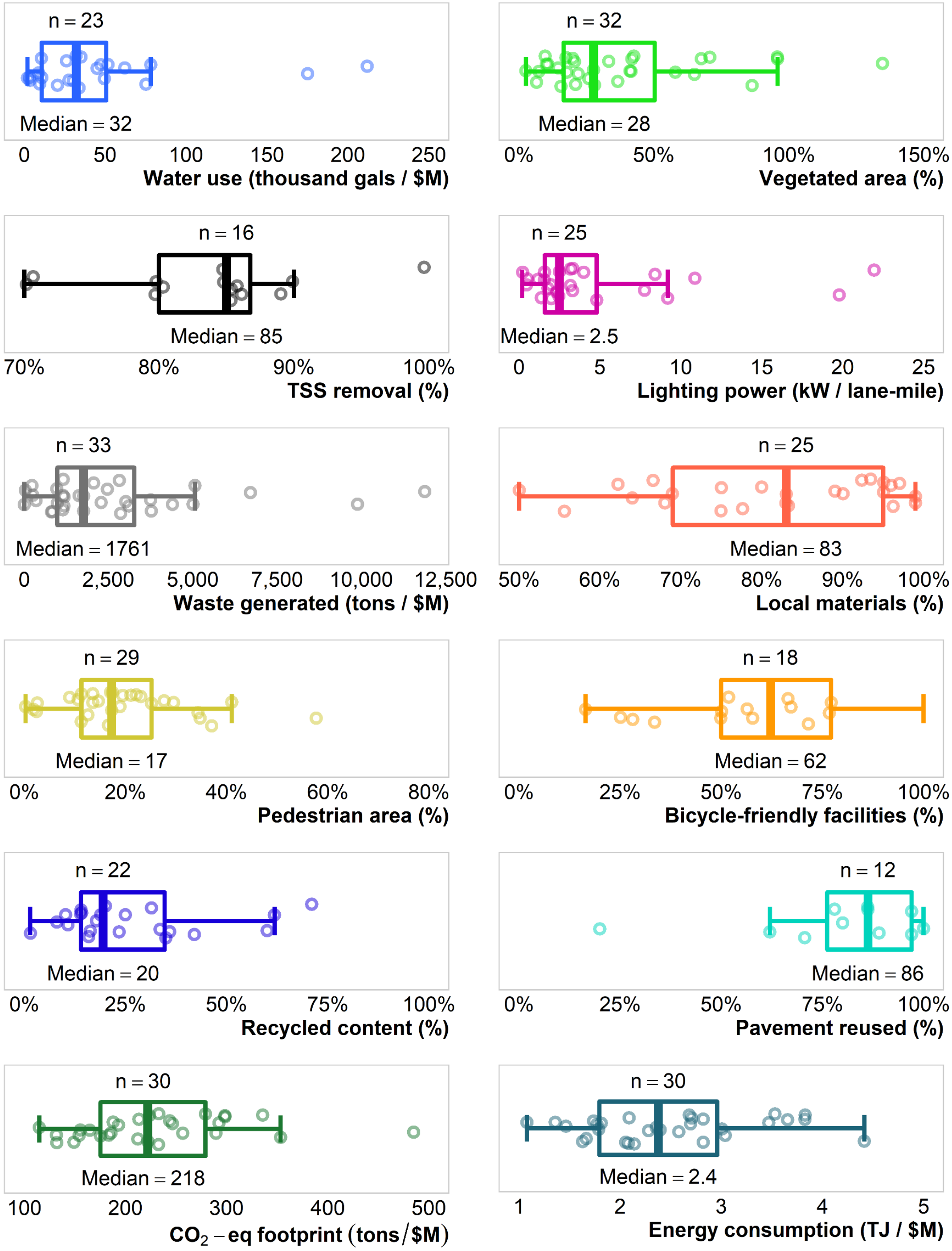

Figure 4.5 Twelve sustainability performance benchmarks established based on construction data. Each panel in this figure includes a box plot illustrating the spread of measured data. All performance benchmarks are normalized to a common project metric (e.g., bid price, area, lane-mile, or unitless fraction). Not all 33 projects provided data for each of the performance metrics (the n value denotes the number of projects included in each graph). Each circle indicates a data point with the thick vertical solid line showing the median value. The width of each box demonstrates the inter-quartile range (IQR). The whiskers on the far left and far right show 1.5 times IQR subtracted from the first quartile and added to the third quartile, respectively.

Because this dissertation uses a limited, non-random dataset, generalization of these benchmarks to other road projects is risky. It is believed that these benchmarks are generalizable to road projects in different ways depending on the item measured and associated incentives included in Greenroads. Specifically, there are three categories of generalizability:

- Applicable to all road projects. These items are present on all road projects, and Greenroads offers no specific incentive based on quantities: water use, vegetated area, and waste generated. For instance, the water use benchmark is based on the 23 projects (70%) that reported water use, however, all projects use water, and the Water Tracking (CA-7) credit only incentivizes tracking water use, but does not incentive achieving any specific use quantity.
- Applicable to sustainable road projects. These items are present on all road projects, but quantities are incentivized by Greenroads credits: TSS removal, local materials, recycled content, pavement reused, and carbon and energy footprint (no credit incentivizes a certain level of emissions or energy use, but other Greenroads credits incentivize actions that would reduce these footprints). For instance, all non-greenfield projects can reuse pavement, but this benchmark is based on the 12 projects that pursued the Pavement Reuse (MR-2) credit, which incentivizes higher fractions of pavement reuse.
- Applicable to sustainable road projects that choose to include a specific feature. These items are not included in all road projects, and quantities are incentivized by Greenroads credits: lighting power, pedestrian area, and bicycle facilities. For instance, not all projects include bicycle facilities, and this benchmark is based only on the 18 projects (55%) that pursued the Bicycle Access (AE-6) credit, which incentivizes their inclusion.

4.5.2 Carbon And Energy Footprints of Construction Activities

Figure 4.6 shows the carbon and energy footprints associated with thirteen different construction categories. Understanding these relationships can be useful in directing limited resources to reduce environmental impacts. For instance, **Figure 4.6** suggests pavements warrant close attention given their outsized contributions to a project’s overall price as well as carbon and energy footprints.

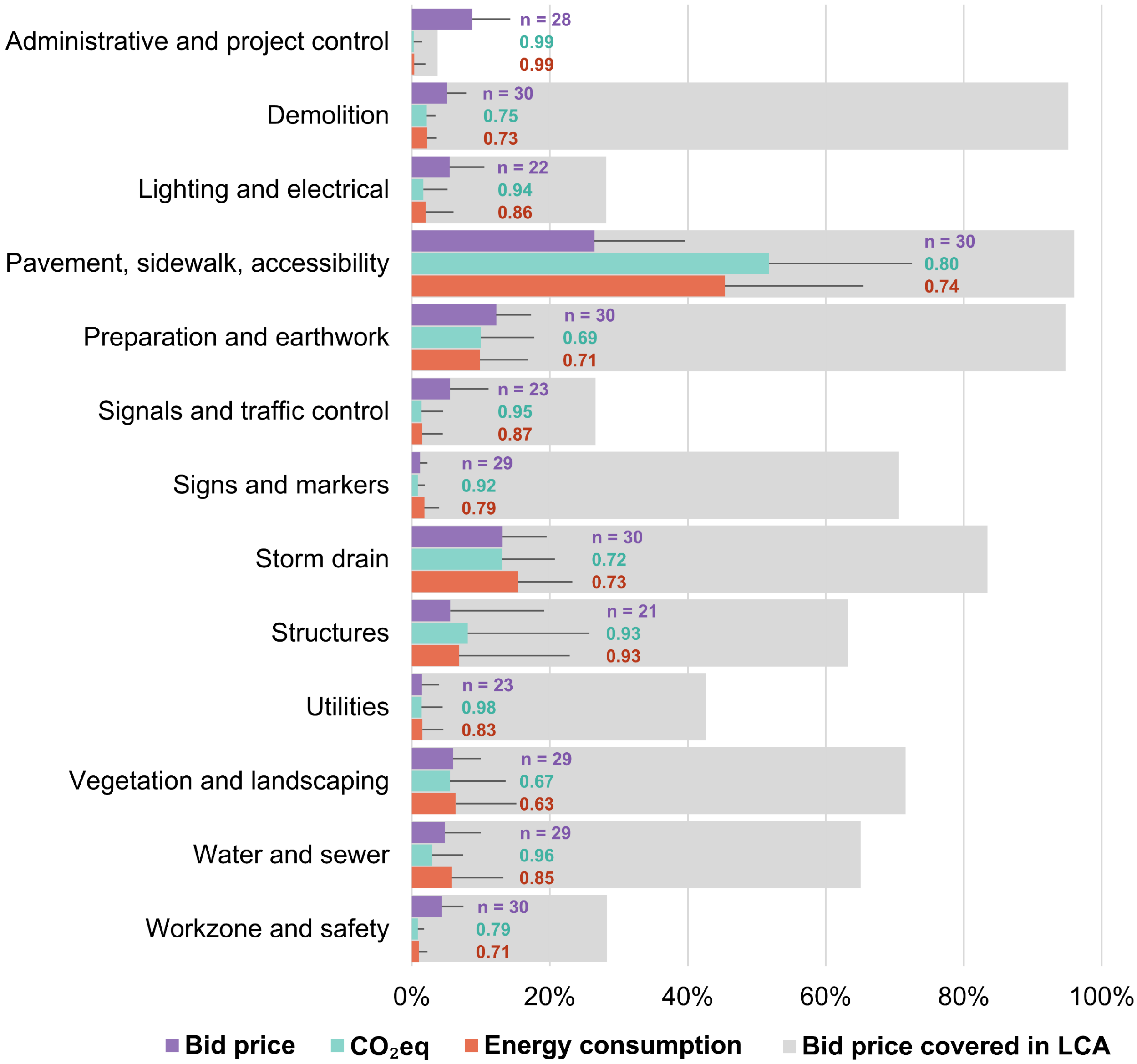

Figure 4.6 The financial, carbon, and energy footprints of roadway construction work categories. We show the fraction of carbon and energy footprint and bid price attributed to 13 common roadway construction work categories from 30 Greenroads-certified projects. The colored bars indicate average values for all projects with the error bars showing the one-way standard deviations. Numbers in front of error bars show Pearson's correlation coefficients between construction category bid prices and carbon (middle numbers) and energy (bottom numbers) footprints. The wide grey bars indicate the fraction of the total bid prices in each category that were accounted for in our LCA. The number of projects included under each construction category is indicated with n.

4.5.2.1 Discussion

It is not possible to include all project items in an LCA. For this dissertation's data, the median fraction of project size (as proxied by pay item prices) included in its LCA is 73%. While almost all pay items associated with demolition, pavement, site preparation, and earthwork are included in **Figure 4.6**, comparatively few of the bid items associated with administration, signals, and workzone safety are included because data sources were either 1) not granular enough to quantify necessary LCA data or, 2) they had negligible carbon and energy footprints. For instance, while demolition and pavement quantities are nearly always quantified in standard unit price contracts, safety and traffic signal items are often bid as lump sum quantities with no detailed material quantities (e.g., metal types and quantities associated with signal wiring) and no record of contractor method choices (e.g., methods, equipment, and materials used for traffic control operations). Furthermore, items describing plans (e.g., stormwater pollution prevention plan) are largely thought processes whose physical manifestation in the project is captured by other items (e.g., the actual pay items associated with stormwater pollution control infrastructure).

Items with conglomerate paving materials (i.e., concrete and asphalt pavements, sidewalks, and other accessibility features) usually dominate a road project's measurable carbon and energy footprint. For this dissertation's data, paving materials are responsible for the largest fraction of measurable carbon and energy footprints at 53% and 48%, respectively. These materials have substantial carbon and energy footprints associated with their production, and they are used in relatively large quantities. This suggests the paving industry's LCA efforts to date (e.g., FHWA, 2021; Harvey et al., 2016; Santero et al., 2011; Van Dam et al., 2015), which focus on pavement alone instead of the full roadway project, may be adequate for decision-making because in most cases conglomerate paving materials are the dominant category. There is an exception when structural elements (i.e., bridges and tunnels) dominate project scopes. Such elements require significant quantities of structural steel or concrete and thus result in high carbon and energy footprints. The high standard deviations for the *structures* category in **Figure 4.6** reflect large differences in structural element scope in our data.

4.5.3 Project Carbon and Energy Footprint Trends based on Project Bid Price

Figure 4.7 relates project carbon and energy footprints to project bid price. As expected, more expensive projects, which invariably use more materials, have larger carbon and energy footprints. The high coefficients of determination (0.924 for carbon and 0.929 for energy) in **Figure 4.7** suggest it is reasonable to predict a project's carbon and energy footprints based solely on its price. For example,

Figure 4.7 predicts that a $10 million project emits about 2,000 tons of CO_2-eq while consuming about 22 TJ of energy.

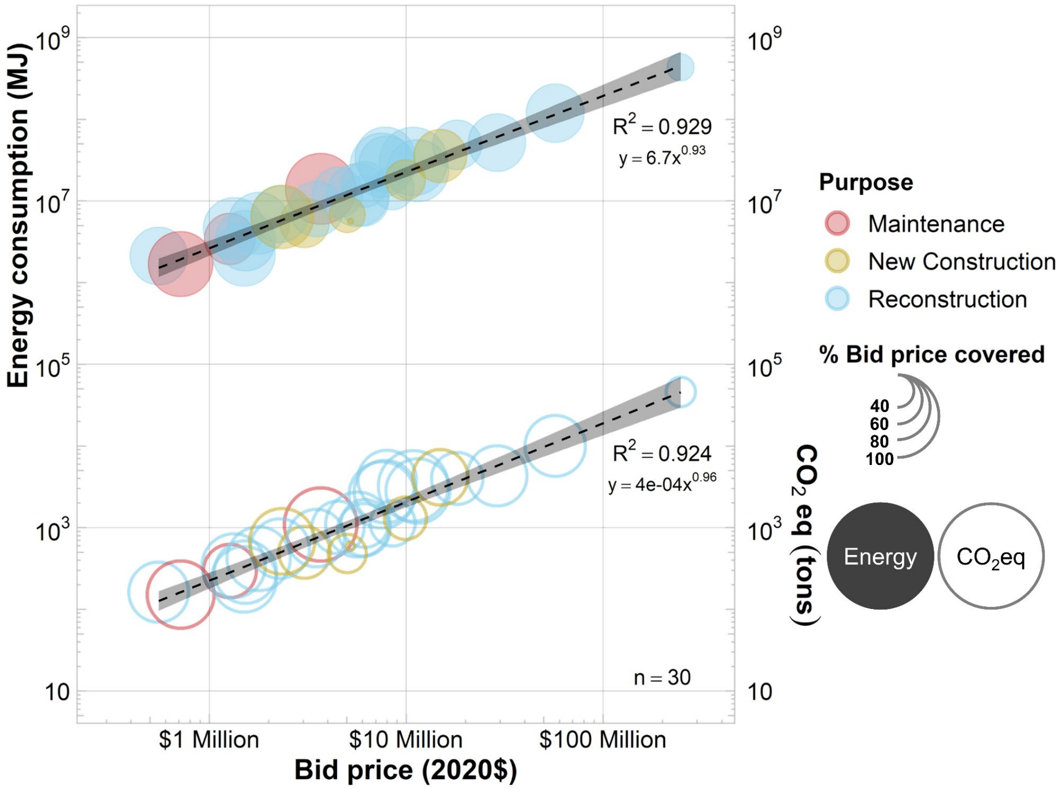

Figure 4.7 Correlations between energy or carbon footprints of projects and their bid price (converted to 2020 USD). The size of each circle is proportional to the fraction of the bid price addressed in the corresponding LCA for each of the 30 Greenroads-certified projects analyzed. There is a strong relationship between carbon and energy footprints and bid prices ($R^2 > 0.9$ in both cases) for analyzed projects. Gray shaded areas represent the regression's 95% confidence interval. Projects are color-coded for construction purposes.

4.5.3.1 Discussion

Although the general increasing trend of the regression lines in **Figure 4.7** seems intuitive, the high coefficients of determination for the regressions might not be. I think there are three reasons for the high coefficients of determination. First, all 30 projects are essentially the same product: a road project dominated by a high-type pavement structure (i.e., asphalt or concrete surfaced, not gravel or unsurfaced) or bridge that meets local and national standards and regulatory minimums for geometry, safety, drainage, and environmental impact. In other words, when deconstructed into a collection of materials, transportation distances, and construction equipment operation as an LCA does, road construction projects are remarkably similar.

Second, the underlying LCA data are essentially the same. Our data contains relatively few Environmental Product Declarations (EPDs) that describe specific constituent materials (e.g., crushed stone, asphalt pavement, concrete, steel, aluminum, plastic, etc.) because they do not exist in great numbers yet. Therefore, the carbon and energy footprints for most constituent materials come from what is generally available: generic material lifecycle inventories (LCIs) that only report industry averages. For instance, data from the Asphalt Institute's LCA study (Wildnauer et al., 2019) and the United States Environmental Protection Agency (EPA) AP-42 report (RTI International, 2004) were used for all asphalt production, and data from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET 2020) (Wang et al., 2020) were used for all portland cement production (**Section 8.2.2** contains a full list of data sources). Therefore, even where manufacturing processes may have been different, the available data lack the fidelity to differentiate between them and therefore effectively treats them as the same.

Lastly, the analysis normalizes LCA results based on price as a project size proxy. It appears fluctuations in carbon and energy footprints based on the number and size of included structures (e.g., bridges, walls), the amount of materials used, material transport distances or other reasons are captured by price in a rather consistent manner. In short, higher prices equate to higher footprints. Therefore, price can be used as a surrogate metric for carbon and energy footprints. However, this is only true for projects that have comparable design lives because this LCA is cradle-to-construction (i.e., its temporal scope begins with materials extraction and ends with project construction), which does not account for design life, maintenance, rehabilitation/reconstruction, or disposal/reuse. In other words, it is not appropriate to compare cheap, short-lived roadways with expensive long-lived roadways because they are not equivalent infrastructure. So long as design life is set by the owner, this should not be an issue.

4.6 Carbon and Energy Footprint Trends based on Material Types

Figure 4.8 relates carbon and energy footprints to bid prices for six common construction material categories (asphalt, concrete, metals, plastics, rocks, and waste). See **Section 4.4.4.3** for a description of material types included under each category. Primary material types are further aggregated by their mass, carbon footprint, and energy consumption for each project and are plotted in **Figure 4.9**. It should be noted that only import materials are included in **Figure 4.9** (i.e., exported materials are mainly those that are excavated or removed from the job site and are not included in this graph).

4.6.1 Discussion

There are few pay items associated with asphalt and many associated with concrete. This is because while asphalt quantities may be quite large, they are usually concentrated in just a few pay items associated with pavements. Conversely, concrete is used in a wide array of applications including pavement, curbs, gutters, manhole structures, inlets, catch basins, foundations, pipes, culverts, sidewalks, walls, bridge girders, etc. **Figure 4.8** shows high coefficients of determination (ranging from 0.802 to 0.951) for the regression of carbon footprint and energy consumption with their bid price. Findings corroborate and expand upon Ozer et al. (2017), who reported a positive correlation between environmental impacts and the cost of pavement materials.

Pavements (all of the asphalt graph and the pavement portion of the concrete graph in **Figure 4.8**) show a noticeably higher carbon and energy footprint per dollar than other materials. It can be argued that there are two reasons for this. First, both asphalt and concrete pavements are relatively low-cost materials for their carbon and energy footprints. This means the higher carbon/energy footprint per dollar is a result of pavements having a low cost per unit weight rather than high carbon/energy footprints per unit weight. Furthermore, asphalt is a lower cost per unit weight than concrete, so it appears even higher in a carbon/energy footprint per dollar metric. For instance, it generally costs less to initially construct an asphalt pavement than a functionally equivalent (one designed to withstand the same amount and type of traffic loading) concrete pavement.

Second, the LCA used for asphalt cement (Wildnauer et al., 2019), the binding material in asphalt pavement that constitutes about one-third to half of its price and carbon/energy footprint, gives higher values than previous sources. For instance, when a similar European LCA (Blomberg et al., 2012) was substituted, the asphalt carbon and energy footprints in **Figure 4.8** decreased by about twenty percent. If nothing else, this demonstrates the potential volatility of LCAs when data sources are changed or updated. Thus, the importance of LCA trends is mainly emphasized here, which tend to hold constant through different/updated data, rather than absolute values, which can vary quite a bit as argued here.

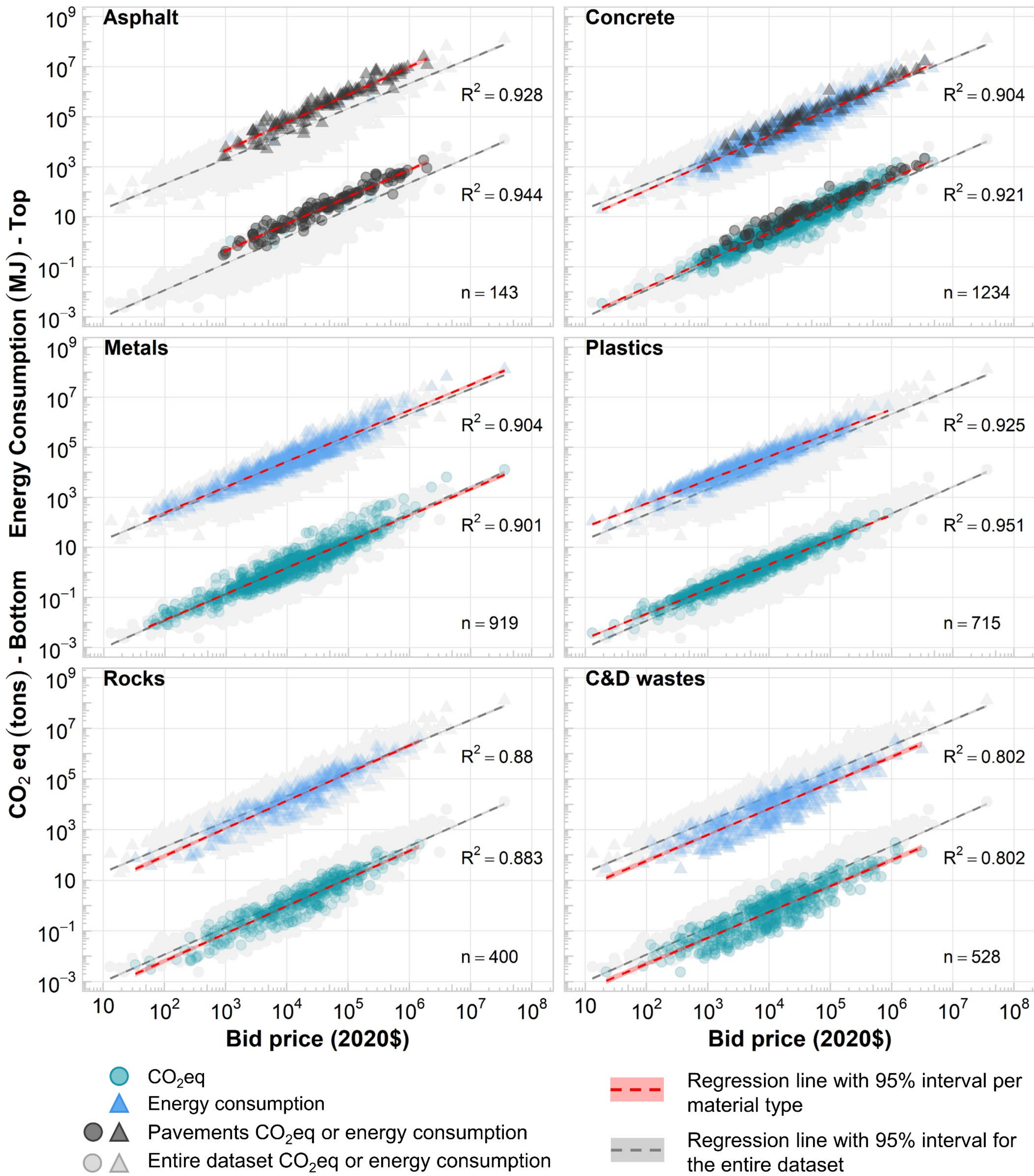

Figure 4.8 Relationship of carbon and energy footprints with pay item prices associated with six common construction material categories. Each pay item and its carbon (bottom) and energy (top) footprint are plotted separately as the grey background point cloud with each plot highlighting one of the six material categories. Regression lines are shown for (1) the entire dataset and (2) each of the six material data subsets with the R^2 values shown for carbon and energy footprints. Black-shaded points further indicate pavement-related pay items.

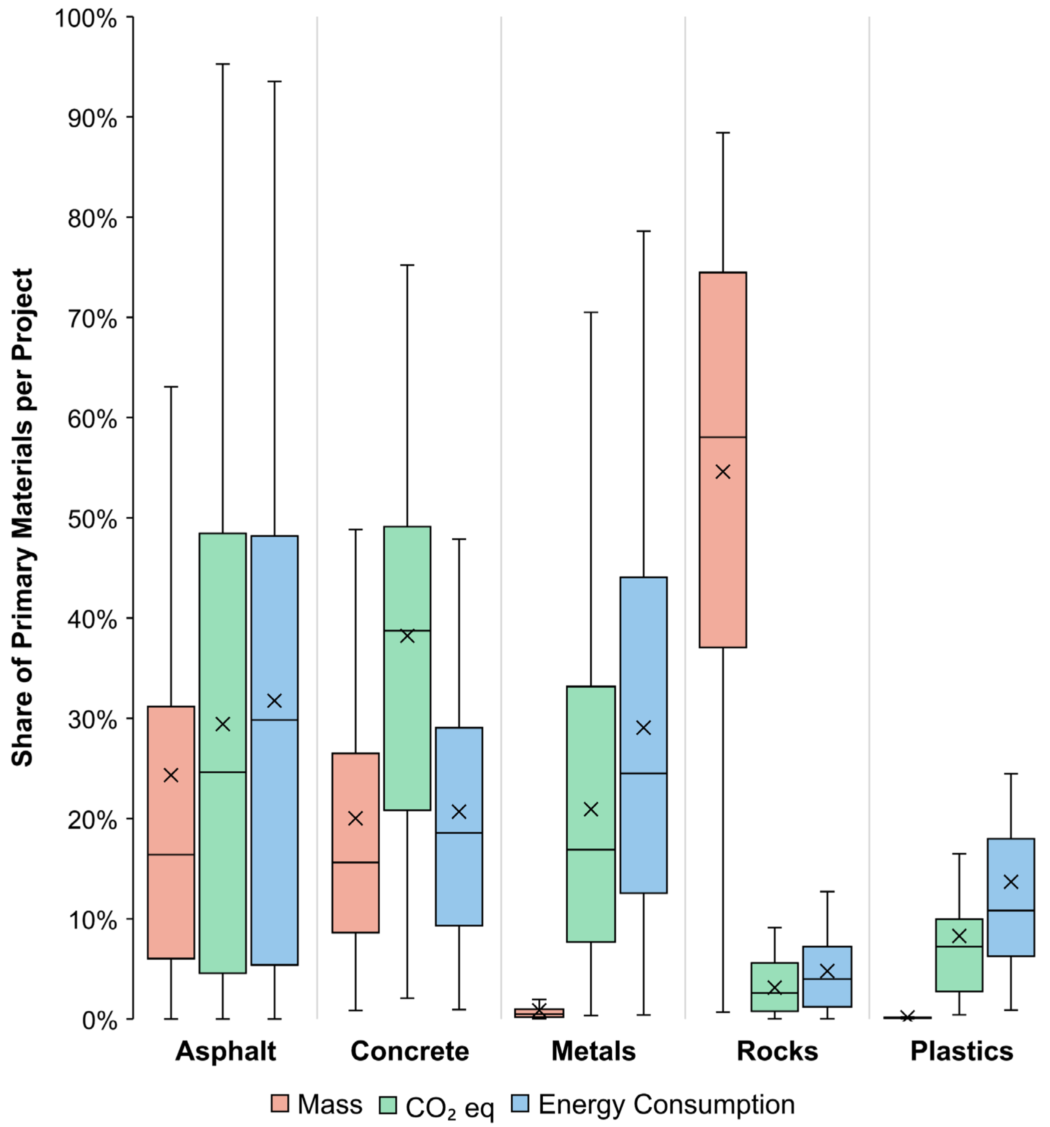

Figure 4.9 The share of each primary material in total mass, carbon footprint, and energy consumption for each project. Each box plot represents data from the 30 projects that are included in the LCA. Note: export materials (i.e., wastes) are excluded from this graph.

Finally, **Figure 4.9** suggests that rocks (i.e., earth materials not included in concrete and asphalt mixes) constitute the highest percentage of material weights for a roadway construction project with a median value of 58.1%. This is followed by asphalt (16.5%), concrete (15.6%), metals (0.5%), and plastics (0.2%). However, this breakdown changes significantly when the share of environmental impacts is of concern. Such that the median share of CO_2-eq per project for rocks, asphalt, concrete, metals, and plastics is 2.6%, 24.6%, 38.7%, 16.9%, and 7.2%, respectively. Similar trends can be observed for the breakdown of energy consumption per material type and per project.

This observation implies the more energy-intensive manufacturing processes for plastics, metals, concrete, and asphalt, in this order. These results imply that sustainable best practices in material manufacturing technologies should mainly focus on the share of emissions from each material which is not necessarily related to how much mass of a certain material is in use. Although metals and plastics are mainly left out of LCA studies on roadways due mainly to mass-based LCA cutoff criteria, this chapter recommends otherwise. Future studies and policies aiming to impose limits on roadway infrastructure materials emissions (e.g., EPD requirements) should also consider metals (mainly steel and iron) and plastics (mainly PVC and HDPE).

4.6.2 LCA Method Limitations

4.6.2.1 Inflation

Inflation must be accounted for, otherwise, it will manifest as a false change in carbon and energy footprints. This chapter's calculations adjusted prices using the ENR Construction Cost Index to broadly account for inflation. This is sufficient, except in the case of high differential inflation between construction materials. For example, the lumber market saw price increases of over 75% between January and August 2021 (ENR, 2021) due to supply chain issues and historic demand. Clearly, such price volatility is indicative of other issues and not underlying carbon or energy footprint increases. More broadly, any metric that relies on surrogate price relationships can be affected by how those relationships change over time.

4.6.2.2 LCA Scope

The LCA used here is cradle-to-construction only, meaning it does not account for carbon emissions and energy use associated with the use, maintenance, and ultimate disposal of these roadways. Most EPDs for construction materials use similar scopes. Functionally, this amounts to a choice in accounting practices. The chosen scope intentionally measures only completed construction actions and does not include future performance predictions, which are typically highly uncertain. This choice in temporal scope is believed to be okay because if this method was repeated as an annual inventory (i.e., by an owner) differences in design life and durability would be captured in future years when less durable designs and materials would require more frequent maintenance and reconstruction.

4.6.2.3 Environmental Product Declarations (EPDs)

More robust use of Environmental Product Declarations (EPDs) may result in more differentiation between projects based on material and design choices. Since the dataset used few EPDs and instead relied on industry average LCAs for constituent materials, comparatively less differentiation was observed. In the future, as EPDs become more ubiquitous, their more precise material details would likely replace some of the generic material datasets we used (Rangelov et al., 2021b), however, the resulting cumulative effect is unknown.

4.6.2.4 Trends Are Most Important

For LCAs, the specific method used and the magnitude of values obtained are less important than the resulting trends (e.g., the regression slope is the most important part of **Figure 4.7** and **Figure 4.8**). Calculated carbon and energy footprints are highly dependent upon LCA scope and data. For instance, Hoxha et al. (2021) showed examples of this in roadway construction LCAs and it has been shown for other LCAs as well (Bhatt et al., 2019; Kirchain et al., 2017). However, so long as different LCA methods produce similar output trends, decisions based on those trends will be reasonably consistent across methods. I expect that as the Bipartisan Infrastructure Law takes hold in the U.S. and more public owners inventory their carbon emissions, it may be difficult to compare emissions between organizations unless they agree on a common set of carbon accounting details (it is not enough to just conform to ISO standards). However, even if they do not, so long as trends are the same, decisions based on those trends will be reasonably consistent from owner to owner.

4.7 Conclusion

This dissertation uses extensive data collected from 33 as-built road construction projects via the Greenroads Rating System certification process to develop 12 performance metrics for sustainable road construction. The results describe what is actually achieved when a road project intentionally tries to be more sustainable. In other words, the state of practice for sustainable road construction. Median achievements in these 12 areas are water use (32,000 gallons per $1 million of project bid price), vegetated area (28% of the total project area), TSS removal (85% removal), lighting power (2.4 kW per lane-mile of roadway), waste generated 1,761 tons per $1 million of project bid price), local materials used (83% of all materials), pedestrian area (17% of the constructed area), bicycle facilities (62% of project lane-miles), recycled content (20% by weight), pavement reused (86% of existing pavement), carbon footprint (221 tons CO_2-eq per $1 million of project bid price), and energy footprint (2.2 TJ per $1 million of project bid price). These values can serve as initial benchmarks for sustainable, and in some cases, regular road construction projects.

The whole roadway LCA process used indicates that project (and individual item) price can be used as a reasonable proxy for carbon and energy footprints based on high correlation. Further examination of LCA results gives the following conclusions:

- It is not possible to include all bid price list items in a whole road LCA. Some items cannot be quantified with typically available project information. A median of 73% of a project's bid price was included in the associated LCA. This dissertation proposes a reasonable standard when using standard project documents should be 50% since it is able to meet that standard on 85% of the projects analyzed. Furthermore, LCAs that claim to be for an entire project should specify what items are not included because it is likely a substantial fraction is not.
- Paving materials are the biggest contributors to a road project's carbon and energy footprints. They tend to be the largest quantity items on road projects that have substantial carbon and energy footprints per unit price and weight.
- Whole roadway projects and individual material carbon and energy footprints can be predicted from project price with good accuracy. Regression analyses in this chapter (**Figure 4.7** and **Figure 4.8**) show coefficients of determination from 0.802 to 0.951 for all relationships. **Figure 4.7** predicts 221 tons of CO_2-eq and 2.2 TJ of energy per $1 million on the project bid price. There are good reasons for this consistency: 1) most road projects are quite similar to one another, 2) material types are quite similar to one another (e.g., curb and gutter are similar, if not identical on most projects), 3) all LCAs draw on the same sets of industry average inventory data, and 4) normalization by bid price accounts for most variations in absolute carbon and energy footprints.

Finally, it can be claimed that the methods followed here could be used to benchmark any amount or type of infrastructure project. For instance, it may be practical for a state Department of Transportation (DOT) to create similar benchmarks using a stratified random sample of its projects (stratified by project size, scope, geography, etc.). This could be an efficient way of estimating sustainability within an entire DOT's construction effort that would not involve specialized data collection beyond bid price (**Chapter 5** provides one example application). Once these benchmarks are known for a particular agency, it could set realistic sustainability goals, measure progress, and manage and improve infrastructure sustainability.

5 Future Direction: Application of Whole Roadway LCA

This chapter serves as a quick peek into the future implications of the findings outlined in this dissertation, particularly from **Chapter 4**. The purpose of this chapter is to showcase how the life cycle assessment (LCA) models developed in this dissertation can be applied to a larger sample population. Based on the whole roadway LCA results presented in **Chapter 4**, this dissertation hypothesizes that the financial costs of roadway construction projects correlate well with their carbon footprint. To investigate the implication of this hypothesis, the whole roadway LCA model can be used to estimate the carbon footprint of a roadway network given financial data. What is presented in this chapter summarizes partial findings from an ongoing research project funded by the Washington State Department of Transportation (WSDOT) in an effort to establish greenhouse gas emission baselines for this agency. This chapter is not intended to defend or describe this research project, rather it is intended to show the potential application of the whole roadway LCA model developed in the previous chapter on a case study. The data and findings presented here are not reviewed by WSDOT and, therefore, should be carefully interpreted.

5.1 Abstract

Recent emphasis on actions to reduce large-scale greenhouse gas emissions has pushed most state departments of transportation (DOTs) to develop carbon accounting practices compatible with their current standard data collection and storage practices. In particular, with the recently passed Buy Clean Acts in California, Colorado, and Oregon and the recently proposed Buy Clean and Buy Fair Washington Act, common construction materials such as Portland cement concrete, steel, and asphalt are now under special attention. Once accurate and reliable accounting of greenhouse gas emissions is established, strategies can be formed that would help mitigate the adverse environmental impacts of a state DOT. This project, in collaboration with the Washington State Department of Transportation (WSDOT), is an attempt to perform life cycle assessment (LCA) on the agency-wide operations that emit greenhouse gases. To date, WSDOT has not conducted comprehensive research on the embodied carbon within its construction material usage (i.e., part of its Scope 3 emissions inventory) with most previous carbon accounting practices being focused on Scope 1 and Scope 2 emissions (i.e., the carbon footprint of direct and indirect energy usage). Although several strategies are now in place to cut Scope 1 and 2 emissions

such as the use of alternative and renewable energy sources, strategies to reduce Scope 3 emissions have neither been fully recognized nor quantified. Therefore, this project uses several data sources from WSDOT in conjunction with life cycle inventory (LCI) data to estimate greenhouse gas emissions from the materials used to build and maintain roadways under WSDOT jurisdiction. Hypothesizing that Scope 3 emissions for WSDOT as an agency is a big contributor to its overall carbon footprint, this project aims at baselining greenhouse gas emissions from WSDOT's roadway material usage between 2017 and 2022 (5 years) and finally providing recommendations to achieve carbon reduction goals in 2030 and 2050.

5.2 Introduction and Background

Over one-third of annual emissions from public sector construction in the United States are attributable to highway and street construction. In addition to carbon-intensive materials like asphalt, the transportation construction sector relies heavily on cement and steel, the largest sources of industrial carbon emissions (Hasanbeigi et al., 2021). These emissions are “hard to abate” due to the energy-intensive methods required to produce these materials. However, readily available, low-cost solutions already exist to reduce the environmental impacts of these construction materials. State Departments of Transportation (DOTs) can heavily influence the uptake and regional availability of these low-carbon solutions while reducing their own emissions footprints because DOTs are reliable customers for high volumes of these materials.

Another aspect to consider is policy. Increasingly, state and federal procurement policies are requiring action from transportation agencies to limit the greenhouse gas emissions of their capital projects. For example, California Transportation Department (CalTrans) projects are required by the Buy Clean California Act (California Public Contracts Code, 2018) to use rebar and structural steel materials that are below certain global warming potential limits, starting in June 2022. Similar bills were passed in Colorado in 2021 (Colorado General Assembly, 2021) and Oregon in 2022 (Oregon Legislative Assembly, 2022) that will require their state DOTs to implement Buy Clean programs to limit emissions from eligible construction materials. Most recently at the federal level, the General Services Administration (GSA) has published its first standard setting thresholds on greenhouse gas emissions for asphalt and concrete materials (GSA, 2022) which further showcases the recent urge toward cutting down emissions from commonly used construction materials.

Legislators in Washington proposed similar bills in 2018, 2020, and 2021, resulting in two buildings-focused pilots of the requirements (Lewis et al., 2021). WSDOT can prepare for these requirements and shape implementation by considering agency policies and practices in advance of newer legislation. Getting ahead on anticipated regulations on construction emissions will ease future decarbonization efforts and allow WSDOT time to identify the most cost-effective route to adopting lower carbon material procurement and construction practices.

The existing literature on a comprehensive agency-wide accounting of embodied carbon for a state DOT is very limited. Oregon DOT has possibly conducted the most thorough research study on its greenhouse gas emissions of asphalt, concrete, and steel consumption. Although ODOT like many other state DOTs typically has unique mechanisms for data collection and storage practices, its overarching approach to quantifying greenhouse gas emissions can be closely replicated. In the report published by ODOT, it was shown that hot mix asphalt and concrete together contribute to the largest chunk of greenhouse gas emissions stemming from the construction and maintenance of roadways in Oregon (Good Company, 2021a, 2021b).

Like other transportation agencies, WSDOT uses large quantities of concrete, steel, and asphalt in its infrastructure projects. However, WSDOT has not yet conducted a systematic assessment of its construction-related greenhouse gas emissions, also known as embodied carbon (arising from manufacturing, transportation, installation, maintenance, and disposal of construction materials). Thus, this project will assess and analyze the greenhouse gas emissions of WSDOT's current material practices, and explore opportunities to drive down these emissions.

Finally, this study would act as a reference for future implications of environmental product declarations (EPDs) in the procurement of roadway construction projects. EPDs are ready to use life cycle assessment results that facilitate data transparency and validity for emission factors to be used by contractors in order to conform with the soon-to-be standardized specifications limiting the embodied carbon of common construction materials (Mukherjee et al., 2020; Rangelov et al., 2021a). Findings would help provide insights into the readiness of WSDOT to incorporate EPD concepts into its currently operating data management systems while also preparing WSDOT to collaborate with the Federal Highway Administration in its recently proposed Climate Challenge.

5.3 Data Analysis Methodology

5.3.1 Life Cycle Assessment (LCA)

The overarching analytical methodology in this project follows a cradle-to-construction life cycle assessment (LCA) of roadway materials. The system boundary denoting this LCA's goal and scope is schematically illustrated in **Figure 4.4** which shows that impacts due to material extraction, manufacturing, transportation to the construction site, and fuel usage by construction equipment are included. This study further limits environmental impacts to global warming potential or greenhouse gas emissions measured using the carbon dioxide equivalent metric (CO_2-eq).

At this stage of the project, life cycle inventory and emissions factor data were obtained from **Chapter 4** findings where LCA on 30 Greenroads-certified roadway construction projects was conducted using publicly available sources such as Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model (GREET, 2020). In particular, LCA models from **Figure 4.7** and **Figure 4.8** were applied to the inventory of WSDOT roadway construction projects to estimate carbon footprints based on projects' bid prices and hot mix asphalt quantities, respectively.

The preliminary LCA of this study relies only on two WSDOT data sources: 1) unit bid analysis data to obtain the total bid price of projects, and 2) Pavement Management System (PMS) data to obtain the total HMA tonnages used in each project. LCA model from **Figure 4.7** is used to estimate the overall carbon footprint of WSDOT construction projects and **Figure 4.8** is used particularly to estimate GHG emissions from hot mix asphalt production. The methodology then takes advantage of Monte Carlo simulations to better capture LCA model uncertainties. It is worth repeating that the temporal coverage of WSDOT projects considered here is from 2017 to 2022.

5.3.2 Monte Carlo Simulations

Due to the uncertainty baked into the LCA models and emission factors to be used for our analysis, a statistical approach is adopted to capture variability. Monte Carlo simulations use statistical distributions to randomly select values from a set of numbers. Assuming that emission factors for entire projects and HMA tonnages are normally distributed, the algorithm follows the steps below:

1. Extract emission factors for entire projects (in units of metric tons CO_2-eq per million dollars) and HMA tonnages (in units of metric tons CO_2-eq per short tons). The sample distribution from the data collected in this dissertation (i.e., Greenroads-certified projects data) can be regarded as the ground truth.
2. Assuming normal distributions for the sampled data, 5000 randomly generated numbers based on the average and standard deviation of sample distributions were constructed.
3. Randomly assign one emission factor from the randomly generated distribution to a project or an HMA item and multiply the project bid price or HMA quantity by emission factors to estimate greenhouse gas emissions.
4. Sum up greenhouse gas emissions for any given year that the contract was awarded and record.
5. Repeat Steps 3 and 4 for 10,000 times and take the average and standard deviation of the result.

Microsoft Excel was used as the main platform for the random generation of numbers. Microsoft Excel VBA space was used to code the Monte Carlo simulations and other quantitative calculations. See the next section for a summary of the results.

5.4 Preliminary Results

Since the main objective of this research is to provide estimates of greenhouse gas emissions produced during the production and placement of construction materials in roadways, this section is attributed to the findings from the LCA methodology explained earlier. In particular, this section summarizes the results from the Monte Carlo simulations described in the previous section to estimate Scope 3 emissions from contracts awarded between 2017 and 2022. Hot mix asphalt as one of the most commonly used materials on roadways is given special attention and its contribution to total Scope 3 emissions is further investigated.

Scope 3 greenhouse gas emissions from WSDOT construction are illustrated in **Figure 5.1**. Although the total annual emissions seem to drop in 2019, this does not necessarily mean that more sustainable materials and practices have been implemented during those times. Rather, this is just reflecting the impact of COVID-19 and shortages in material supplies. Nevertheless, as **Figure 5.1** suggests, the share of HMA on total emissions remained relatively consistent at around 25%. This is an important takeaway from our results which highlights the high contribution of HMA to Scope 3 emissions in a DOT boundary.

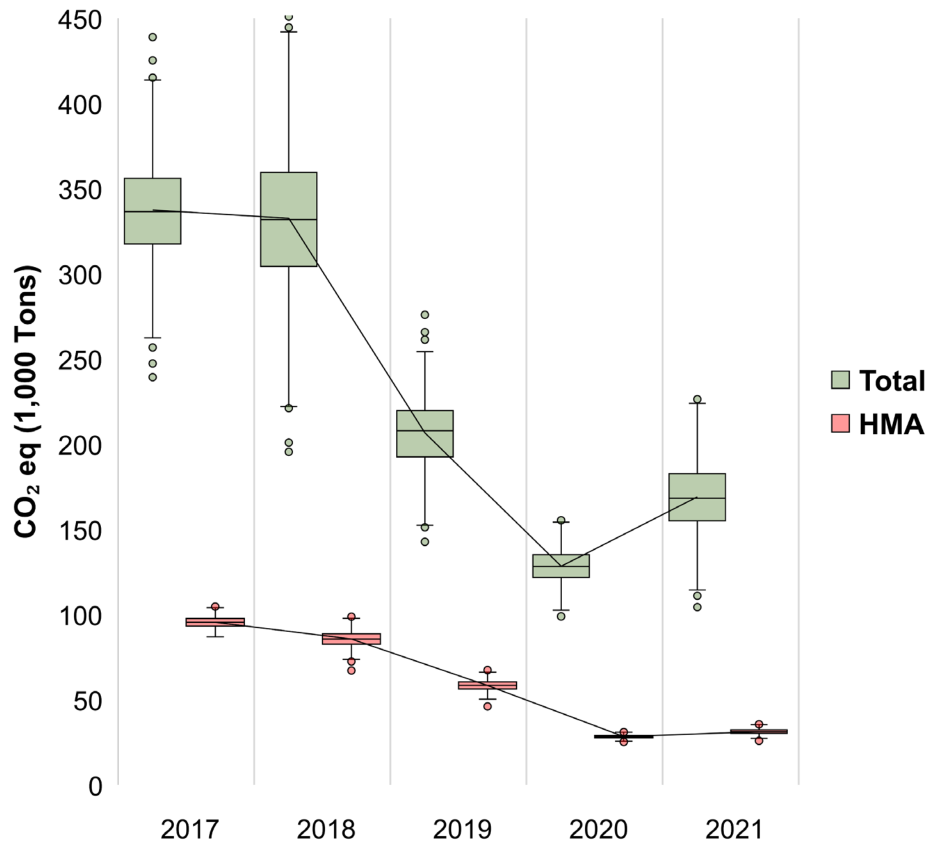

Figure 5.1 Greenhouse gas emissions from WSDOT roadway construction projects between 2017 and 2022. The share of hot mix asphalt (HMA) in total carbon footprint is also illustrated.

Finally, **Figure 5.2** provides a pairwise comparison between Scope 1 and 2 emissions (obtained from WSDOT Facilities Department representing stationary, non-stationary, and mobile energy usage mostly by the Washington State Ferries) and Scope 3 emissions estimated above. It can be argued that findings from **Figure 5.2** are significant because 1) on an average basis, Scope 3 emissions seem to outweigh Scope 1 and 2 emissions, 2) Scope 1 and 2 emissions in WSDOT might be among the highest in retrospect since the Washington ferry system owns the largest vessel fleets in the U.S. and is the biggest contributor to these emissions (Washington State Ferries, 2019), 3) Scope 3 emissions are not well understood and accounted for within DOT environments and findings support the new push towards requiring environmental product declarations (EPDs) for the high impact construction materials, 4) the newly proposed (i.e., Buy Clean and Buy Fair Washington) and passed (California, Colorado, and Oregon Buy Clean Acts) legislations that target reductions in Scope 3 emissions are indeed in place with good intentions.

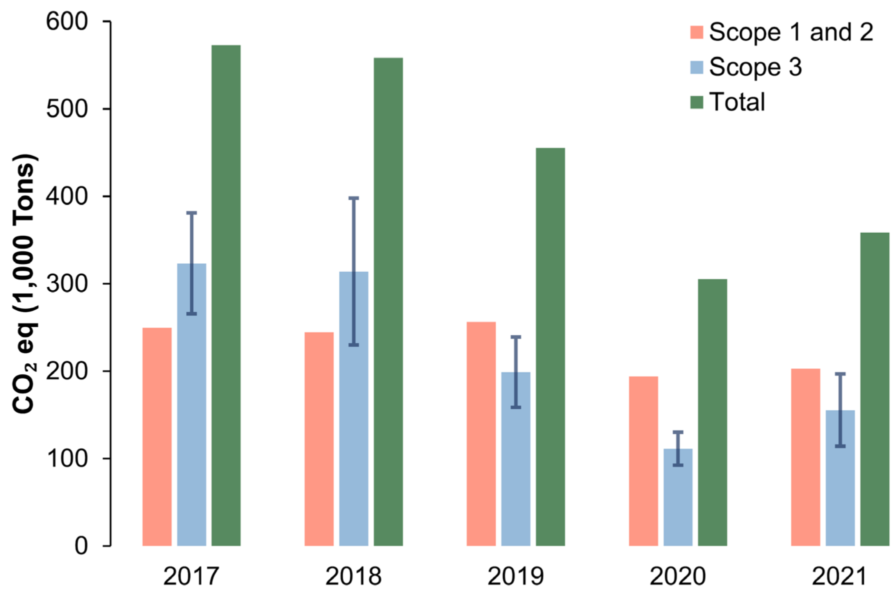

Figure 5.2 Comparison of Scope 1 and 2 greenhouse gas emissions with Scope 3 for WSDOT as an agency from 2017 to 2022. Results suggest a relatively equal share of Scope 3 emissions from roadway construction in total WSDOT greenhouse gas emissions. The error bars in this graph denote standard deviations due to the uncertainty of emission factors used to run LCA on entire projects and HMA line items.

However, as mentioned before, the results of this study are not final, and more investigations are required before findings can be fed into the decision-making process. In particular, material-specific emission factors (or preferably EPDs) need to be developed based on particular material properties (e.g., asphalt and concrete mix design and the type of raw ingredients used in them) to capture a higher resolution picture of the breakdown of Scope 3 emissions. In addition, the analysis was limited to hot mix asphalt materials and it is expected that this research expands its analysis domain to include as a minimum portland cement concrete, structural and reinforcement steel, and crushed or natural aggregates used in several instances within a roadway construction project.

5.5 Conclusions

This chapter outlined the progress made in an effort to estimate the greenhouse gas emissions associated with the production and placement of materials used to build and preserve the Washington

State roadway network owned and operated by WSDOT. Following the goal and scope of this project, the environmental impacts considered in the analysis are limited to global warming potential measured in units of carbon dioxide equivalent or greenhouse gas emissions. Using the LCA models developed in this dissertation, this chapter offered rough estimates of the overall greenhouse gas emissions produced by WSDOT as part of its Scope 3 emissions category during the time period of 2017 to 2022 (5 years' worth of data). For instance, about 300 thousand tons of CO_2-eq was emitted in 2018 due to roadway construction activities and materials.

Lastly, to put our numerical findings into perspective, Scope 1 and 2 greenhouse gas emissions reported to the Washington State Department of Ecology were compared with those from Scope 3 categories estimated in this study. It was concluded that mitigating Scope 3 emissions can play an important role towards a net-zero future as much as cutting Scope 1 and 2 emissions would do. Our results further support the push from several state legislators in the form of the Buy Clean Acts.

6 Discussions and Limitations

So far in this dissertation, the application of the Greenroads Rating System in collecting and measuring sustainability achievements of roadway construction projects using a variety of metrics was explored. Previous chapters presented the analytical methods to analyze the data and partially discussed the findings and limitations of each study. This chapter discusses the overall results and possible shortcomings of this dissertation with a critical eye. The following discussion points do not necessarily belong to a specific chapter and are organized by topic.

6.1 Project Size and Scope

Due to their wider scope, large projects with higher budgets tend to have more opportunities to pursue and implement sustainability best practices (Chang and Tsai, 2015). Despite Greenroads claim that all roadway construction projects regardless of their size have equal opportunities to attain certification, data show that a median Greenroads-certified project has a value of about $6 million. This is mainly because Greenroads treats all projects similarly and passes them through the same screening criteria. However, to earn certification, a minimum number of credits must be pursued and that poses a real challenge for projects with limited scopes. For example, in order for pavement resurfacing projects to become certified, nearly all relevant credits must be pursued and achieved. On the contrary, a project that involves pavement resurfacing, roadside revegetation, and traffic signal upgrades has much wider options to pursue certification.

Nevertheless, data from the 33 Greenroads-certified projects studied in this dissertation show that the highest awarded score for projects with a bid price of over $50 million is 37 (Projects #9, #11, #19, #24, #25.) This is while the average awarded score for all projects considered here is 40. Despite larger projects having more opportunities to pursue a wider array of Greenroads credits, in practice, they were awarded fewer points than average-size projects. It can be argued that the effect of project size outweighs the effect of project scope. Among many possible reasons, the author thinks this is expected because of the following reasons.

First, data collection and documentation of construction practices for large civil projects (those that involve more activities than just pavement construction) is difficult and in some cases can become very complex. CA-7 (water use tracking) and MR-5 (regional materials) credits are very good examples of activities that mainly involve documentation practices. Examining the scorecards suggests that 75% of smaller-size projects earned points for CA-7, as opposed to only 20% of large projects that attempted and scored some points for this credit. For MR-5 credit, the percentages are 80% for small projects and 40% for large projects; still a big difference. This is mainly because documentation and data tracking for larger projects can pose serious challenges. For a small project, there might be a few sources where water and other material types are purchased or sourced, so a rather simple accounting process. For a large project, however, there might be tens of hundreds of material and water sources involved and if no rigorous accounting procedure already exists in the project's agenda, such data will be difficult to obtain.

Second, some credit criteria in Greenroads are proportional to the size of projects expressed as a percentage of area, percentage of weight, percentage of volume, etc. Although normalized to the project size, these credits are more difficult to achieve for large projects. There are some examples to support this claim. PT-2 (permeable pavement) and PT-3 (warm mix asphalt) credits both set requirements based on a 50% criteria (use permeable pavement or WMA on 50% of the project's area and weight, respectively). Scorecard data show that only one large project (Project #9) earned points for PT-2 while 11 lower budget projects earned points for this credit. Another example is the MR-2 (pavement reuse) credit for which no large projects earned points for it. MR-2, however, is more of a context sensitive option for road segments with existing deteriorated pavements and mostly applies to maintenance and rehabilitation (M&R) projects. Therefore, large projects have minimal opportunities to pursue and earn points for pavement reuse credit.

Third, there seems to be only a certain number of credits that larger projects earned points for more frequently than small projects. In all cases though, the achievement of those credits is highly tied with the scope and size of projects. For example, larger projects have a higher chance of satisfying the CA-8 (contractor warranty) and CA-1 (ISO 9001 certified contractor) requirements simply because both depend on the contractor and the fact is that bigger contracting companies have enough power and resources to seek ISO certifications and provide longer-term performance warranties. Other examples are AE-1 (safety audit), AE-2 (intelligent transportation systems), AE-8 (scenic views), and AE-9 (cultural outreach) credits that do not have a criterion that is proportional to project size. A typical paving project has fewer opportunities to provide a scenic view or implement ITS facilities and the scorecards show that the frequency of earning points for these credits is twice as much for larger projects than for smaller ones.

Finally, project teams in most cases assign only one (or in some cases a few) person in charge of the Greenroads certification process (i.e., communicate with Greenroads staff, provide documentation, indicate target credits, etc.). This is not something Greenroads can control; this is how projects do business. One person might be aware of a lot that is going on in a small project, but that one person will have a very hard time digesting all that is going on in a mega project. Therefore, the chances are that a small project would earn points from all possible avenues within the Greenroads Rating System while a large project might miss several potentially possible points due to that one person's lack of knowledge about all aspects of the project.

6.2 Analysis Period

This dissertation by large ignored the performance life of projects. This is a crucial piece to consider when discussing sustainability, as long-life performance typically translates into more environmental and economic benefits. Although most Greenroads-certified projects considered here documented a hypothetical design life (40 years for pavements and up to 75 years for bridges), these numbers cannot be regarded as reliable. Moreover, this dissertation excluded maintenance phases taking place before the projects' end of life. The study of the long-term performance of projects requires longitudinal data collection methods to track deterioration events and maintenance activities over time. Such data is absent from the database of this dissertation and the analysis of long-term performance is postponed to future studies. However, what this dissertation has offered is a methodological way of collecting quantitative performance benchmarks that can be tracked over time and circumvent the assumptions about the analysis period through continuous data collection efforts.

6.3 Data Quality

In a world overwhelmed by massive amounts of information, a rising question is typically about the quality of collected data, mostly regarding accuracy and precision. Data quality assessment in the context of Greenroads is difficult to carry out. It is mostly assumed that individual project teams provided the most accurate and precise information. What matters the most in the database of this dissertation is how consistent the measurements are across different projects that include a wide range of scopes, sizes, and geographic locations. With over 4,300 documents submitted totaling about 13 gigabytes in memory size, the majority of data examined in this dissertation are qualitative in nature.

The most challenging task of a Greenroads assessor, hence, is finding the right information from the right document. There are many instances where the same piece of information can be found under different documents. A good example is the project's disturbed area and boundary for which the environmental impact statements, context sensitive solutions, pavement design documents, pollution prevention plans, as-built project drawings, and water and stormwater management plans are among the submittals that might have included project area measurements. These documents are used by the assessor to validate project claims when the achievement of a Greenroads credit is claimed. The use of official templates provided by Greenroads can act as a solution to solve any ambiguities in calculations, measurements, and documentation involved when applying for a credit.

6.3.1 Data Gaps

Data gathered as part of the Greenroads certification process is not an exhaustive list of all project documents. Greenroads only requires certain information from projects and not all the existing information. The exception to this is the documents provided to meet PR credits. However, there are a limited amount of data that can be obtained from documents submitted for PR credits (they are early-stage documents). Greenroads offers flexibility in the selection of its voluntary credits, so that project teams can pick the most relevant sustainable practices that fit their scope of work. For this reason, a drawback of the data collected here is that they do not represent all there is, rather the dataset is a selection of construction practices identified as sustainable by Greenroads. This can be observed from the data gaps that existed within the dataset of this dissertation. Moreover, it was sometimes the case that projects were not aware of a sustainable practice they had performed while if attempted through Greenroads those could have been qualified for partial or full scores. This was in part illustrated in **Figure 2.4** with green-shaded cells denoting those credits that project teams assumed to earn less than expected, or in some cases no scores for. Sustainability education and increased awareness as one of

Greenroads' missions are partially responsible for envisioning best construction practices and helping bridge such data gaps.

6.3.2 Lifecycle Inventory (LCI)

This dissertation took advantage of the LCA methodology to quantify the environmental impacts of construction projects. While powerful, the robustness of LCA is highly dependent on its input reference flow and inventory data. Greenroads v1.5 used the PR-3 Tool to perform LCA. Although it was argued that a cradle-to-construction LCA according to pay item lists is the best-known method to quantify the environmental impacts of construction projects, there are some issues to be discussed and addressed:

- Lack of high-quality LCI data. PR-3 Tool uses rather outdated emission conversion factors in its inventory that make its use questionable. To address this issue, the method took advantage of the pay item lists and the most recent LCI (including EPDs) to tackle data quality issues. However, there is still much room for improvement, especially in the realm of using EPDs.
- Reference flows and material breakdowns. Pay items in a bid tab list almost always indicate a lump of materials or processes. Performing LCA, thus, requires these pay items to be broken down into smaller pieces. This in turn involves more digging into project documents to make input data digestible to any LCA platform. This dissertation found out that records of materials (ROMs) are the best source of such information projects can offer. For example, irrigation systems are typically lump summed as a single item while constituting a variety of components such as valves, sleeves, conduits, adapters, pumps, etc., and therefore need multiple entries into LCA tools.
- Material weights. The most challenging information to collect and estimate in the LCA framework introduced in this dissertation is about material weights and weight breakdowns. Due to inconsistent reporting of materials in different units of measures, finding the right densities to convert units of measures to mass (or weight) was found difficult. I hypothesize that the sensitivity of LCA results to uncertainties in material weights can have a much bigger impact on conclusions than uncertainties in LCI data.

- Cradle-to-gate LCA. This dissertation scoped LCA down to cradle-to-construction and identified maintenance, end of life, and use phases outside the system boundary. Contractors are usually responsible for the initial construction of projects and future maintenance activities are relegated to another party. That makes the inclusion of the maintenance phase into LCA questionable and reliant on many assumptions. Moreover, pay item lists, as used here, only include initial construction data. Considering the use phase in the LCA boundary further poses several predicaments. Electrical power to operate roadways (e.g., lighting and traffic control systems) and vehicle use are the two major categories to consider in the use phase. Such information or subsequent analysis (e.g., traffic analysis for vehicle use projections) are in most cases absent from standard project documents; and even if available, lack accuracy. A full LCA, hence, calls for several mathematical models to predict the future behavior of a roadway system, which falls beyond the scope of this dissertation.
- Carbon sequestration. Sustainability endeavors are not solely about reducing impacts but can also help mitigate them. It was shown here that nearly all projects had some sort of landscaping plan that either increased green space or replaced the existing vegetation with native plants. Trees and groundcovers are known to absorb carbon dioxide from the atmosphere over their lifetime. Other roadside components such as wetland soils are also known as important carbon sinks. This sequestration of carbon dioxide is rarely considered in LCA studies of roadway systems. Data collected in this dissertation can enable future LCA to include the environmental impact of plantations in the context of roadway construction projects. Another related example is carbon uptake by cement concrete (Xi et al., 2016) which is recently proposed to be a major source of carbon sequestration by concrete. Leaving the use phase out of the system boundary would ignore such long-term impacts and thus makes this dissertation's results less relevant for decision making.
- LCA as a policy driver and decision-making tool. Once fed in with high-quality LCI, the question then becomes whether LCA outcomes can rank higher in the decision-making process when project alternatives are being evaluated. The power of LCA, as opposed to other sustainability indicators, is its quantifiable nature and the fact that it is data-driven and is compatible with pay

item lists. This can revolutionize the bidding process as the lowest bid price, as in the case of the traditional design-bid-build delivery method, does not necessarily drive the lowest environmental impact of a project. This is only feasible using agreed-upon and standardized LCA frameworks to be used widely by the construction industry. Studies like this one encourage such efforts through emission factors as developed in the form of EPDs. Furthermore, recent green public procurement (GPP) initiatives on the use of EPDs, such as the Buy Clean act of California, indicate the legislative push toward low-impact production of commonly used construction materials (Rangelov et al., 2021b).

6.4 Whole Roadway LCA

In this dissertation, a whole roadway LCA framework was proposed and it was argued that a mere focus on pavement LCA might not provide a clear picture of an entire project's environmental footprint. In fact, this is implicitly baked into the Greenroads v1.5 category structure where pavement technologies are only responsible for about 17% of total possible points. This dissertation suggests that pavement LCA only captures an average of about 30% of a project's financial cost (i.e., bid price) while a whole roadway LCA that goes above and beyond pavements can capture an average of about 70%. Nevertheless, it was shown that the carbon and energy footprint of projects are highly correlated with their bid price. In that, trends seem to be more consistent than absolute numbers.

To elaborate, this dissertation used Greenroads PR-3 Tool to perform LCA on pavement sections (see **Chapter 3**) and later developed a whole roadway LCA based on pay item lists (see **Chapter 4**). **Figure 6.1** is a pairwise comparison of the two LCA scopes in one scatterplot. The main takeaways from this graph are consistent with what was previously discussed. Although more than twice as many material prices are included in the whole roadway LCA framework, the trends are relatively similar to the pavement-only LCA. Both LCA models, however, are valuable. One can provide estimates of carbon and energy footprints for the pavement sections and the other does the same for an entire roadway. Depending on the scope, projects can take advantage of either or both.

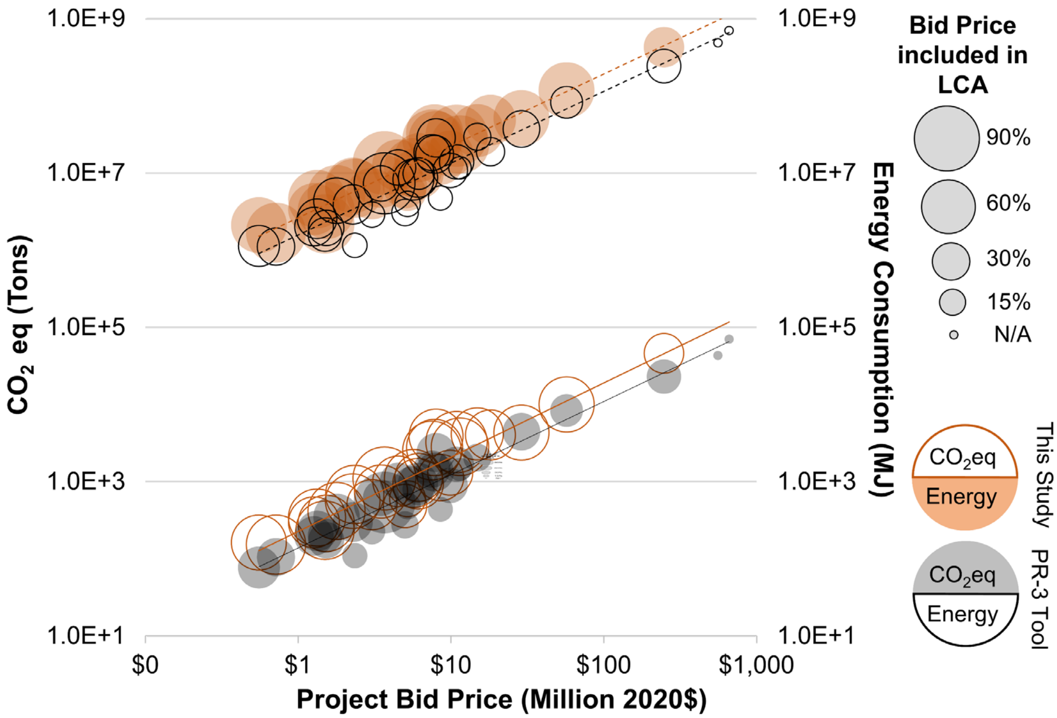

Figure 6.1 A comparison between the correlation of projects' bid price and their carbon and energy footprints using a pavement-only LCA (PR-3 Tool) and a while roadway LCA (this study's LCA). It can be observed that bid price and environmental footprints trend similarly in both cases, despite a whole roadway LCA's ability to capture a higher percentage of a project's bid price.

6.5 Greenroads Network

Not every company or contractor is equally aware of Greenroads existence. Nor do they care much about sustainability if not required by their stakeholders. As a result, the number of contractors and construction firms familiar with Greenroads is limited. Personal and professional connections to the Greenroads team through the board of directors and its CEO act as the main point of contact and recognition. For this reason, most certified and registered projects in Greenroads are local, such that about 60% of them are located in Washington State. This is of no surprise, however, since Greenroads itself was born and based in Washington. Despite critiques about its local popularity and that its structure is developed based on the Washington State standards, Greenroads seems to be nationally and internationally recognized and implementable to a wide variety of standard specifications and requirements. In effect, growing the Greenroads network is of mutual interest, as not only will Greenroads expand its horizons to encompass more comprehensive sustainability approaches suitable to a global context, but this can also help more companies become aware of sustainability best practices as offered and assessed by Greenroads.

7 Summary and Conclusions

To answer the research question: *what is the state of practice in sustainable roadway construction?* this dissertation highlighted the application of the Greenroads Rating System as a data collection and sustainability assessment tool. This dissertation then took a data-driven approach to explore the state of practice in sustainable roadway construction using Greenroads scorecards (**Chapter 2**), used Greenroads' life cycle assessment (LCA) submittals to estimate the carbon and energy footprint of pavement construction and materials (**Chapter 3**), introduced twelve data-driven sustainable performance benchmarks based on project documents and outlined a whole roadway LCA framework to capture an entire roadways environmental footprints (**Chapter 4**), and finally showcased the implications of the whole roadway LCA models constructed in **Chapter 4** on a larger scale of roadway projects within the state of Washington (**Chapter 5**). The following bullet points collectively provide some recommendations for future research and also conclude this dissertation.

7.1 Summary of Findings

Chapter 2 summaries about the Greenroads Rating System and its value in measuring and understanding the state of practice are listed below:

- <u>Projects tend to perform what is considered common practice</u>. 50% of all Greenroads points achieved by all projects came from only 8 credits. This suggests that projects typically report what they have done and do not adjust their scope of work solely because of becoming more sustainable, or equivalently, obtain sustainability certification through Greenroads. However, Greenroads is capable of rating the performance quality of common practices and would help projects gain recognition for their sustainability efforts whether intentionally or unintended.
- <u>Projects expect to be more sustainable than they actually are</u>. Among various reasons, the unfamiliarity with Greenroads credits, lack of sustainability knowledge, and unawareness of sustainability impacts can be mentioned. For example, planting a tree might be conceived as a high-impact practice while it is in fact not as impactful as earthwork balance. This is because Greenroads uses different weighting themes to assign points to activities.

- The key to success, as observed here, is good documentation and accountability. The amount of data produced in a construction project can become overwhelmingly large. However, this dissertation contends that information collection and management is doable with minimal effort given a solid and comprehensive tool such as rating systems. To promote, encourage, and spread awareness of sustainable construction practices, project teams and organizations need to establish structurally sound ways of documenting their practices. Advocating the use of rating systems, this dissertation believes that such systems are powerful in hardwiring systematic documentation and data collection schemes into project deliveries.

Summaries from **Chapters 3** and **4** regarding the use of LCA (either pavement LCA or whole roadway LCA) in measuring and establishing performance benchmarks based on the carbon and energy footprints are:

- Life cycle assessment normalization based on bid price results in more consistent conclusions. The majority of existing LCA studies on pavements or other roadway elements report environmental impacts normalized by an aspect of project size (e.g., project area, length, material volume, etc.) This dissertation, by leveraging financial information of projects in the form of pay item lists, introduced bid price as a better proxy to project size and used it as the normalization reference to report more consistent LCA results. Doing so would circumvent challenges associated with the context and scope sensitivity of roadway projects and the fact that roadway functionality is not necessarily depicted by its geometric or volumetric properties.
- The carbon energy footprints of roadway projects can be estimated based on price. A direct implication of the previous bullet point is that projects can use the LCA models developed in this study to estimate their carbon and energy footprints simply by knowing their bid price. It was found that bid price and quantitative environmental impacts are highly correlated and this would suggest using this model can produce acceptable first-hand estimates. I admit this will not produce the highest resolution or most accurate results; however, this provides the quickest way possible to have an idea about the expected order of magnitudes.

- Roadways are more than just pavements. This dissertation allocated financial costs, carbon footprint, and energy consumption outcomes to different roadway construction categories. It was found that pavement structures (including sidewalks, driveways, and their sublayers) are only responsible for less than 30% of the average bid price and less than 50% of the average accountable carbon and energy footprints. Thus, a mere emphasis on pavement sustainability might not draw an accurate picture of all sustainability potentials of a roadway project.
- Whole roadway LCA frameworks need to be considered. Akin to how the building industry introduced the whole building LCA (WBLCA) concept, roadways should consider following that trend. This dissertation showed that a traditional pavement LCA framework can capture an average of 30% of a project's bid price, while a whole roadway LCA scope would increase that percentage to 70%. This is a significant finding suggesting that the major shortcoming of existing LCA studies on roadways is about reference flows (i.e., what type of materials are used in a process and by how much). A data-driven LCA approach using real construction data can help bridge this wide gap.
- Six primary material types dominate roadway projects. Asphalt, concrete, metals (mainly reinforcing and structural steel and to some extent aluminum), earth materials (i.e., crushed rocks in different sizes), plastics (mainly PVC, HDPE, and pavement markings), and waste materials (as a result of roadway demolition and structural removals) are the six material types that constitute more than 99% of a roadway project's material weights. However, some are more energy-intensive than others to produce and, therefore, LCA cut-off criteria are recommended not to be mass-based.
- 100% material recycling/reuse should be the goal. Incorporation of 20% recycled content, as it is currently common practice in asphalt pavements and the use of supplementary cementitious materials like fly ash, or using warm mix asphalt technologies would not alone make a big difference in total greenhouse gas emissions from roadway construction projects. We need more aggressive recycling practices to make a real difference. The sky is not really the limit here. The limit should be 100% recycled or reused material contents as in the case of cold in-place

recycling and full depth reclamation for asphalt pavements and crack and seat option for existing concrete pavements.

Chapter 4 also explored data-driven performance measures and the value of actual roadway construction data in establishing sustainable performance benchmarks. The following bullet points summarize this topic:

- Sustainable performance benchmarks should be data-driven and based on real construction data. This dissertation introduced twelve data-driven performance benchmarks that roadway construction projects regardless of size and scope can be assessed upon. The value of such data-driven metrics is the fact that they are less subjective to interpretations and are based on actual performance and transparent arithmetics. This is in contrast to a rating system scheme that uses unitless hollow numbers to assess practices based on several hypothetical impact themes.
- Sustainability rating systems should use data-driven criteria. A follow-up on the previous bullet point is the recommendation to adjust the Greenroads Rating System to award scores based on data-driven criteria. For example, the pedestrian facility benchmark introduced in this dissertation can act as a better criterion for the existing Greenroads criteria. This would require Greenroads to produce simple-to-use templates for project teams to report on specific performance benchmarks.
- Data transparency. To help make the methodology followed in this dissertation reproducible and repeatable, key datasets used for data analysis are published in a public data repository (see **Chapter 9**) and are intended for publication in the *Data in Brief* journal. Advocating transparency and open access to data, this dissertation contends that the value of data collection efforts like this one is in spreading the ready-to-use products. This will create room for improvement and enables future research to address the shortcomings of previous research.
- Construction data collection needs to be automated and digitized. In this dissertation, several thousand hours were spent on data collection and cleaning since the vast majority of construction data are not still digitized. The point was made clear by Yamaura (2018) that the civil construction industry needs to leverage mobile data collection technologies to facilitate subsequent data analysis similar to this dissertation. Relevant to sustainability, this dissertation provided examples

of what type of data and in what format need to be collected to make sustainability assessment of roadway projects entirely data-driven. Such efforts would eventually make the sustainability evaluation, or the soon to enacted green procurement initiatives and policies, a fair process.

7.2 Overarching Conclusions

Although the development of transportation infrastructure rating systems including roadways dates back to more than a decade ago, the study of the application of data collected during the certification process of these systems is ongoing research. The main contribution of this dissertation, therefore, is beyond the development of new sustainability indicators or even rating systems. Rather, it is in exploring the value of a rating system, Greenroads in this case, as a data collection and categorization tool to help establish data-driven performance measures for the state of practice in sustainable roadway construction. Collectively, the chapters presented in this dissertation yield the following overarching conclusions:

- The core effort in sustainable roadway construction is confined by a small set of practices. The analysis of Greenroads scorecards in **Chapter 2** showed that 8 practices comprise 50% of total awarded Greenroads credits. Projects tend to achieve many of these core credits and then a few more based on context. In many cases, Greenroads credits and their associated practices were outside the scope of projects and pursuing those would have caused an extra financial burden on projects. In other instances, the sustainable practices were simply not applicable to a project given its unique characteristics (e.g., pavement credits do not apply to a landscaping project). And finally, misunderstanding credit requirements may hinder project teams from even considering a practice that could have otherwise applied to the project scope (e.g., water treatment quality).
- Overoptimism in sustainability achievement is common among projects. The comparative analysis between expected and awarded Greenroads scores in **Chapter 2** suggests that project teams typically expect to be more sustainable than they actually are. Although such human behavior is natural (i.e., setting the goals high), it also indicates the importance of sustainability measurement systems and third-party verifications in evaluating general project claims.

- Sustainable performance of roadway projects can be assessed using 12 benchmarks. **Chapter 4** introduced 12 performance measures and used project data to establish the state of practice benchmarks for those. Such performance benchmarks never existed before and they are believed to act as sustainability standards once validated with more real construction data. Road owners with sustainability agendas in place can leverage this set of 12 performance benchmarks for alternative selection and decision making. Moreover, rating systems can take advantage of these benchmarks both as a sustainability indicator (i.e., performance measure) and sustainability criterion (i.e., performance benchmark).
- Financial costs are highly correlated with carbon and energy footprint of projects and materials. This dissertation used an existing pavement LCA tool (**Chapter 3**) and later developed a whole roadway LCA framework (**Chapter 4**). In both cases, the bid price of projects or constituent materials showed a high correlation with LCA results. There are two possible justifications for this. First, projects directly or indirectly pay for the energy; therefore, more energy-intensive materials and processes incur more costs and emissions. Second, life cycle inventory data used in many industry-wide LCA models are either based on economic models or use economic factors to allocate emissions and energy to different unit processes. This correlation is likely to persist until the use of more product-specific EPDs for primary construction materials becomes widespread.
- Economic-based LCA models can provide quick estimates of carbon and energy footprints for roadway projects. These LCA models with high correlation coefficients can be used to quickly predict owner Scope 3 emissions. Most agencies keep good track of financial records, and this will feed the right amount of information into the LCA models developed in this dissertation. This was further demonstrated as a case study for the Washington State Department of Transportation on their collection of roadway projects in a 5-year span (**Chapter 5**). Admittedly, the use of such simple models comes with several limitations and using those for decision making does not seem prudent at this point.
- A data-driven approach to measuring and benchmarking sustainable performance is key to success. Most sustainable practices are those that attempt to go above and beyond common practice. Without a robust benchmarking mechanism based on real construction data (i.e., state

of practice) to act as a baseline, progress beyond common practice cannot be recognized or measured. Once measured based on real data, valid comparisons can be made on the level of sustainability achievement. Furthermore, this dissertation advocates the use of rating systems as a data collection tool that facilitates the data acquisition process to become more structured, categorized, and consistent.

8 Appendix A: Supplemental Greenroads, Data Collection, and Life Cycle Assessment Information

This Appendix provides more detailed information on 1) the Greenroads Rating System and its certification process, our data source, 2) data collection, cleaning, and manipulation, and 3) the whole roadway life cycle assessment (LCA) method.

8.1 Greenroads Rating System

The Greenroads Rating System is a collection of sustainable roadway construction best practices (called credits) grouped into several categories based on sustainability theme areas. To date, Greenroads has released several versions each differing from the previous in credit details, requirements, and topics. 28 projects reviewed in this dissertation were certified using Greenroads Version 1.5 (v1.5), with the remaining 5 certified using Version 2. This dissertation uses v1.5 as the primary rating system form and converts project scores from version 2 using a standard algorithm (**Section 8.1.2**).

8.1.1 Greenroads v1.5 Credits Structure

Greenroads v1.5 consists of 11 project requirements, 37 voluntary credits (subdivided into 7 categories), and 13 custom credits (credits added after the initial version release based on project input) (Muench et al., 2011). Project Requirements are not worth any points, and voluntary credits are worth 1-5 points based on sustainability impact. Specifically, Greenroads v1.5 uses seven themes to allocate credit weights (from 1 to 5) to each credit based on their impact: 1) ecology, 2) equity, 3) life cycle assessment (LCA)-based weighting, 4) incentive-based weighting, 5) developed area weighting, 6) durability weighting, and 7) aesthetics weighting.

To obtain Greenroads certification, projects must achieve all Project Requirements and may choose to pursue as many voluntary credits (called Core Credits in Greenroads) as they wish with certification levels corresponding to the number of voluntary credit points achieved: Bronze (32 to 42 points), Silver (43 to 53 points), Gold (54 to 63 points), and Evergreen (64 points and above). **Table 1.1** summarizes Greenroads v1.5 credits.

8.1.2 Greenroads v2 Credit Structure and Conversion to v1.5 Credits

Greenroads v2, which entered into service in 2015, was used to rate projects 26 and 30 through 33. For these projects Greenroads v2 credits were translated into v1.5 credits using equivalencies listed in **Table 8.1**. This translation is important in assigning data to different construction categories described in **Section 4.4.4.1**.

Table 8.1 Greenroads v2.0 list of credits and conversion to v1.5.

Greenroads v2.0 Credits		**Equivalent Greenroads v1.5 Credit(s)**
Number and Title	**Score**	
Project Requirements (PR)	**All**	
PR-1 Ecological Impact Analysis	Req	PR1
PR-2 Energy & Carbon Footprint	Req	PR3
PR-3 Low Impact Development	Req	PR8
PR-4 Social Impact Analysis	Req	NEW
PR-5 Community Engagement	Req	NEW; PR-11
PR-6 Lifecycle Cost Analysis	Req	PR2
PR-7 Quality Control	Req	PR-4
PR-8 Pollution Prevention	Req	PR-7
PR-9 Waste Management	Req	PR-6
PR-10 Noise & Glare Control	Req	PR-5
PR-11 Utility Conflict Analysis	Req	NEW
PR-12 Asset Management Systems	Req	NEW; PR10; PR9
Environment and Water (EW)	**30**	
EW-1 Preferred Alignment	3	NEW
EW-2 Ecological Connectivity	3	EW7
EW-3 Habitat Conservation	3	EW6
EW-4 Land Use Enhancements	3	PT-2
EW-5 Vegetation Quality	3	EW-5; CC-4
EW-6 Soil Management	3	MR-3
EW-7 Water Conservation	3	NEW; EW-5
EW-8 Runoff Flow Control	3	EW-2
EW-9 Enhanced Treatment: Metals	3	EW-3
EW-10 Oil & Contaminant Treatment	3	EW-3
Construction Activities (CA)	**20**	
CA-1 Environmental Excellence	3	EW-1; CA-2; CA-3
CA-2 Workzone Health & Safety	2	CC-2
CA-3 Quality Process	3	CA-1; CA8; CC3
CA-4 Equipment Fuel Efficiency	1	CA4; PT-3
CA-5 Workzone Air Emissions	1	CA5; CA6; PT-3
CA-6 Workzone Water Use	3	CA7
CA-7 Accelerated Construction	2	NEW
CA-8 Procurement Integrity	1	NEW
CA-9 Communications & Outreach	1	NEW
CA-10 Fair & Skilled Labor	2	NEW

CA-11 Local Economic Development	1	NEW
Materials and Design (MD)	**24**	
MD1 Preservation & Reuse	5	MR-2
MD2 Recycled & Recovered Content	5	MR-4
MD3 Environmental Product Declarations	2	MR1
MD4 Health Product Declarations	2	MR1
MD5 Local Materials	5	MR-5
MD6 Long-Life Design	5	PT-1
Utilities and Control (UC)	**20**	
UC-1 Utility Upgrades	2	NEW
UC-2 Maintenance & Emergency Access	1	NEW
UC-3 Electric Vehicle Infrastructure	3	CC5
UC-4 Energy Efficiency	3	MR-6
UC-5 Alternative Energy	3	CC6
UC-6 Lighting & Controls	3	EW-8
UC-7 Traffic Emissions Reduction	3	AE4
UC-8 Travel Time Reduction	2	AE4
Access and Livability (AL)	**21**	
AL-1 Safety Audit	2	AE-1
AL-2 Safety Enhancements	2	NEW
AL-3 Multimodal Connectivity	2	AE-3; AE-5; AE-6; AE-7; CC7
AL-4 Equity & Accessibility	2	NEW; AE-3
AL-5 Active Transportation	2	AE-5; AE-6
AL-6 Health Impact Analysis	2	NEW
AL-7 Noise & Glare Reduction	3	PT5
AL-8 Culture & Recreation	2	AE-8; AE-9
AL-9 Archaeology & History	2	AE-8; AE-9
AL-10 Scenery & Aesthetics	2	AE-8; AE-9
Creativity and Effort (CE)	**15**	
CE-1 Educated Team	2	CC1
CE-2 Innovative Ideas	5	CC10
CE-3 Enhanced Performance	5	NEW
CE-4 Local Values	3	NEW
Certification Levels		
Bronze	40	
Silver	50	
Gold	60	
Evergreen	80	
Total Possible Scores	**130**	

8.1.3 Project Boundaries

Project boundaries as defined by Greenroads are a continuous perimeter around the construction project. They must be defined before certification begins, and they must be consistently used for all credits pursued. When project boundaries encompass more than one non-continuous construction area

Greenroads disaggregates the project into multiple different certifiable segments and calls the collection of segments a Program. All individual segments undergo their own certification process. A Greenroads Program is certified when all its individual segments are certified. This dissertation treats programs as a single project.

8.2 Life Cycle Assessment Method

This research uses an internally-developed LCA method that follows standardized procedures outlined in ISO14040 and 14044 and adheres to other conventions seen in several other published reports or journal articles (for example, Chen and Wang, 2018; Harvey et al., 2016; Jiang and Wu, 2019; Liu et al., 2017; Mukherjee et al., 2013).

Our choice to include the entire roadway construction scope of work (i.e., all items on the price list) necessitated a new, internally developed LCA tool. Existing vetted roadway LCA tools are typically limited to pavement structure only or were not based on editable pay item lists. While Greenroads does require projects to submit a pavement structure life cycle inventory, this scope was not adequate for our *whole road LCA* purposes. The following describes our whole road LCA framework and its execution.

8.2.1 Goal And Scope Definition

The goals of our whole road LCA are to 1) evaluate the carbon and energy footprints of an entire road construction project as defined by its contract documents, 2) investigate the correlation between LCA results and construction price, 3) establish benchmarks for future roadway construction projects, and 4) provide a method, if possible, for others to estimate carbon and energy footprints based on construction price alone.

8.2.1.1 Functional Unit

Our function unit is "constructing a road project that meets specifications". We normalize results by project bid price because this allows for projects of different types (e.g., bridge projects, pavement overlays, intersections, highways, rural roads, etc.) to be compared. More traditional pavement function units (based on lane-miles and/or area, and structural design requirements) would not allow for this comparison. Notably, our function unit does not include a design life. The 30 analyzed projects have design lives that vary from 25 to 75 years.

8.2.1.2 System Boundary

Our LCA is cradle-to-construction meaning that it includes 1) raw material extraction and processing, 2) electricity and fuel consumption at each stage, 3) upstream (from plants to suppliers) and downstream (from suppliers to construction sites) transportation of materials, and 4) on-site construction activities. The cut-off criteria are set to exclude pay items that contribute less than 0.1% of each project's bid price. Additionally, items bid as lump sums (e.g., lump sum traffic control), electrical and mechanical systems (e.g., signals, traffic control cabinets, irrigation systems), and equipment mobilization are excluded because our data do not contain enough information to meaningfully include them.

8.2.1.3 Allocation Procedure

An open-loop approach is implemented where recycled materials are in use. In that, it is assumed that the by-products are available through the [local] plants/suppliers as a raw material. To close the loop, unit processes (i.e., "the smallest element considered in the life cycle inventory analysis for which input and output data are quantified" (ISO 14040)) have been considered for removal/demolition, processing, and transportation of the by-products. For example, reclaimed asphalt pavement (RAP) is assumed to be a "free" material to obtain for the project in use of it. However, the environmental burden of obtaining RAP when a project undergoes pavement milling operations is considered a project-related burden. In addition, asphalt plant adjustments to include RAP in the mix (additional heat to dry RAP particles, RAP crushing and processing, etc.) are also considered within our system boundary and as a burden on projects.

8.2.1.4 Impact Categories

Our LCA considers two impact categories: global warming potential (GWP) and energy consumption. The majority of input data are collected from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET 2020) (Wang et al., 2020), United States Environmental Protection Agency (EPA) AP-42 report (RTI International, 2004), and EPA Motor Vehicle Emission Simulator (MOVES) 2014b (US EPA, 2015). This LCA uses environmental impact characterization factors from the individualistic perspective (20-year GWP) according to ReCiPe (Huijbregts et al., 2017).

8.2.2 Lifecycle Inventory Analysis (LCIA)

The data sources are divided into two groups. First, reference flow data contains information about the weight, type, and composition of materials produced, transportation mode used, hauling distance for those materials, and the construction activities required to install/place them. Second, lifecycle inventory data are information that pertain to the environmental impacts of items described in the reference flows.

8.2.2.1 Reference Flow Data Sources

The following sources are used for reference flow data:

- Pay item lists. All design-bid-build contracts have comprehensive lists that describe each construction item for which the owner will pay, its quantity, and the bid price submitted for that item by the winning contractor. In most cases, pay item lists can be cross-referenced with plans and specifications to determine details (e.g., quantity, constituent materials, dimensions, etc.).
- Plans and specifications. Used with pay item lists to determine constituent materials and their quantities, dimensions, and installation requirements. Example uses are to determine reinforcement details for concrete structures (manholes, catch basins, walls, culverts), pavement materials and thicknesses, bridge super- and sub-structure details, type and size of traffic signs, tree grates, mast arms, luminaires, pipes, etc.
- Pavement design reports and mix designs. Used to determine constituent materials in pavements and layer thicknesses. Examples include portland cement, fly ash, slag, asphalt, additive content; dowel bar, tie bar, and reinforcement weight used in concrete pavements; and reclaimed asphalt pavement (RAP) fraction or warm mix asphalt (WMA) use in asphalt pavements.
- Greenroads-specific documents. Projects pursuing Lifecycle Inventory (PR-3),, Waste Management (PR-6), Site Recycling Plan (CA-3), Reused Content (MR-2), Recycled Content (MR-4), and Regional Materials (MR-5) project requirements and credits submitted documents describing material weights, sources, and transportation distances/modes.
- Record of materials (ROM). The ROM is an owner document that lists major construction items that require materials testing and the requirements for that testing, other inspections or certification of compliance, and shop drawings.

- Online sources. Publicly available online sources were used to gather information about products. They were used to investigate items with identified manufacturers (e.g., sole source items) or to generally determine standard sizes and unit weights.
- Production rates. Used to estimate types of equipment and operating hours for a variety of activities. Major sources are Washington State DOT's *Plans Preparation Manual* (WSDOT, 2020) and Florida DOT's *Construction Project Administration Manual* (FDOT, 2017).

8.2.2.2 Pay Item Categorization

Table 8.2 provides examples of how we attribute each pay item to one or more of the 13 construction categories used in the analysis. Also shown in this table are the relevant Greenroads v1.5 credits to each of the construction categories.

Table 8.2 Pay item assignments to construction categories and relevant Greenroads v1.5 credits.

Construction Category	Pay Items and Related Greenoards Credit(s)
Administrative and Project Control	Heritage management (AE-9); Reporting and meeting (AE-9); Layout/staking/surveying/unexpected changes/drawings (NONE); Mobilization (MOB); Greenroads (GR); Quality control plan (PR-4); Environmental awareness training plan (CA-2); Inspection / Quality control (CA-1, PR-4, [EW-2, EW-3], [NONE]); Permits/office buildings (NONE); Progress schedule (NONE); Force account (NONE); Public outreach / information (PR-11, AE-9); Critical path schedules / Sequencing plan (NONE); Safety and health plan (CA-2)
Demolition	Removals (CA-3, [PR-6], MR-3); [Structural] Excavation / shoring (MR-3, CA-3, MR-5 [including haul]); Removal of structure and obstruction (CA-3, MR-3 [if relevant, e.g., are pipes and when some amount of soil is moved]); Sawing / cutting (CA-3, MR-3); Soil contamination mitigation/disposal/removal (CA-3, PR-6, MR-3, [MR-5]); Hazardous material handling (CA-3, PR-6, [MR-5]); Demolition and waste (material) management plan (PR-6); Concrete/cement washout (CA-3); Removal and replacement of unsuitable material / contaminated soil (CA-3, MR-3, MR-5, MR-4 [when replaced]); Contaminated materials handling (CA-3, PR-6); Abandoning piles/valves/utilities/etc. (CA-3, MR-3 [if relevant, e.g., are pipes and when some amount of soil is moved]); Excavations (CA-3, MR-3, MR-5 [when including haul]); Material exports (CA-3, MR-5); Street cleaning (PR-7)
Lighting and Electrical	Conduits for lighting poles (EW-8, MR-6, MR-4, MR-5); Poles (if for lighting) (EW-8, [MR-6], MR-4, MR-5); Luminaires (illumination system) (EW-8, MR-6, MR-5, MR-4); Light pole foundation (EW-8, MR-3, MR-4, MR-5, MR-6); Vault [if for electrical systems/signals] (AE-2, EW-8, MR-4, MR-5); LED Tiles (EW-8, MR-6, AE-9, MR-5, AE-5)
Pavement Sidewalk Accessibility	Curb ramps [concrete] (AE-5, AE-6, MR-4, MR-5, PT-4 [if concrete], MR-3 [if base material included]); Pavement milling (planing) asphalt (CA-3, MR-4, MR-2, PT-1, MR-3); Pavement base/subbase/subgrade (PT-1, [MR-2], MR-4, MR-5, MR-3, EW-2 [if permeable]); Tack/Prime coat (asphalt) (PT-1, MR-5); Asphalt pavement (PT-1, MR-2 [if reused], MR-4, MR-5, CA6 [if attempted]); Concrete pavement (PT-1, PT-4, MR-2 [if reused], MR-4, MR-5); Traffic island (concrete) (AE-5, AE-6, AE-7, PT-4, MR-4, MR-5); Pavers / ADA (AE-5, MR-4, MR-5, PT-4 [if concrete], AE-6, AE-9 [if

	patterned]); Pavers (vehicular rated) (PT-1, MR-4, MR-5); Hand rail (AE-5, MR-4, MR-5); Truncated domes / detectable warning surface (AE-5, MR-4, MR-5); Concrete sidewalk / concrete band (AE-5, PT-4, MR-4, MR-5, AE-6); Cold in-place recycling (PT-1, CA-3, MR-2, MR-4, MR-3); Asphalt rubblize / pulverize (PT-1, MR-2, MR-3); Chip/slurry seal (PT-1, MR-4, MR-5); Removing/striping pavement marking/paint (CA-3); Warm mix asphalt (WMA) (PT-3, MR-4, MR-5, CA6 [if attempted]); Driveway entrance (PT-1, PT-4 [if concrete], AE-5, MR-4, MR-5, AE-6); Concrete island/median (AE-5, AE-7, MR-4, MR-5, [AE-9], [CC-2]); Porous/pervious pavement (PT-2, MR-4, MR-5, [PT-4] if concrete, AE-5 and AE-6 [if sidewalk], EW-2); Crushed surfacing top/base course (PT-1, MR-3, MR-4, MR-5, [MR-2], EW-2[if choker]); Ash urn / Mutt Mitt station (AE-5, MR-4, MR-5); Bus shelter (with footing) (AE-7, AE-5, MR-4, MR-5); Pedestrian barrier and protection (AE-5, MR-4, MR-5, CC-2 [if temporary], AE-7 [if for traffic]); Seat wall (AE-5, EW-5, MR-4, MR-5)
Preparation and Earthwork	Clearing and grubbing / roadside cleanup / street cleaning (EW-5, MR-3, CC-4 [when roadside/street cleaning]); Embankments (MR-3, MR-2 [when in place], MR-5 [if imported]); Compaction (MR-3, PT-1 [if subgrade/subbase/base layers]); Geotextile (EW-2 / PT-1, EW-3 / PT-4, MR-3, MR-4, MR-5, [EW-5]); Pipe bedding (gravel) (MR-3, MR-4, MR-5, EW-2 [drainage], EW-3 [drainage], NONE [sanitary]); Gravel borrow (MR-3, MR-4, MR-5 [including haul]); Trench safety system / shoring (MR-3, CC-2, MR-5, MR-2); [Controlled] Density fill (MR-3, MR-4, MR-5); Backfill (usually gravel) (MR-3, MR-4, MR-5, [EW-2, if drainage], [EW-3, if drainage]); Low density cellular concrete (MR-3, MR-4, MR-5); Property restoration (EW-5, CC-4); Base/subbase treatment [with lime] ([PT-1/2/4], MR-2, MR-3); Dewatering (EW-2, EW-3, MR-3); Soil sampling and testing (MR-3); Subgrade stabilization (MR-3, MR-4, MR-5, PT-1 [if for pavements])
Signals and Traffic Control	Conduits/wires for mast arm and signal poles (AE-2, MR-4, MR-5); Pedestrian signal / push button (AE-5, AE-2, MR-5); ITS (signal related and others) (AE-2, [MR-5], [MR-4]); Guardrail (AE-5, AE-6, AE-7, MR-4, MR-5); Foundation for poles (mast arm) (AE-5 [if pedestrian], MR-3, MR-4, MR-5, AE-2 [if signal/mast arm], EW-8 [if light]); Signal system (AE-2, MR-4, MR-5); Mast arm (and pole) (AE-2, MR-4, MR-5); CCTV camera (AE-2, PR-4/CA-1 [if for inspection])
Signs and Markers	Pavement markings / paints / bar / legends ([AE-5], AE-6, AE-7, MR-4, MR-5); Signs (AE-5, AE-6, AE-7, MR-4, MR-5); Traveler information (AE-9, AE-8, PR-11, AE-5 [if for pedestrian]); Business access sign (AE-5, AE-6, AE-7, MR-5, MR-4); Crosswalks (AE-5, MR-4, MR-5); Plaques (AE-9, MR-5, AE-5 [if pedestrian related]); Sign support structure (AE-5, AE-6, AE-7, MR-4, MR-5)
Storm Drain	Erosion control (EW-2, EW-3 [if includes pollution], PR-7 [if plan]); Catch basins / Manholes (EW-2, EW-3, MR-4, MR-5, NONE [if sanitary/waterline]); Adjust catch basins / manholes (EW-2, EW-3, MR-3, MR-5, PT-1, MR-2); Curb and gutter (EW-2, EW-3, MR-4, MR-5, PT-1, AE-5); Conduits for drainage and storm (EW-2, EW-3, MR-4, MR-5); Junction box (EW-2, EW-3, MR-4, MR-5); Storm/Sewer pipes (EW-2, EW-3, MR-4, MR-5); ESC lead (EW-2, EW-3, CA-2, PR-7); Quarry spalls (EW-2, EW-3, MR-5, MR-4, MR-3); Check dams (PR-7, EW-3, MR-4, MR-5, MR-3); Rain garden (EW-2, EW-3, EW-5, MR-4, MR-5); Pollution prevention plan (PR-7); Storm sewer by open cut (EW-2, EW-3, MR-3, MR-5, MR-4); Spill prevention, control, and countermeasure (SPCC) (PR-7, CA-2); Concrete inlet (EW-2, EW-3, MR-4, MR-5); Inlet protection (PR-7, EW-2, EW-3, MR-2, MR-4, MR-5); Bioretention media (Filterra) ([EW-2], EW-3, MR-4, MR-5); Pipe anchors (EW-2 [if water/sewer], EW-3 [if water/sewer], MR-2, MR-4, MR-5); Wattles (EW-2, EW-3, MR-4, MR-5); Geomembrane liner / Geogrid (EW-3, PR-7, MR-2, MR-4, MR-5, MR-3); Monitoring Well (EW-2, EW-3, PR-7, MR-3); Steel casing pipe (encasement) (MR-3, MR-4, MR-5, [EW-2], [EW-3], [NONE]); Bridge drains (EW-2, EW-3, MR-4, MR-5, NONE); Connection to drainage structure (EW-2, EW-3, MR-4, MR-5); Culverts (EW-2, EW-3, MR-4, MR-5); Grate inlet (EW-2, EW-3, MR-4, MR-5); Paver grate (EW-2, EW-3, MR-4, MR-5); Rock weir (EW-2, EW-3, EW-5 [when applicable], MR-4, MR-5);

	Plants for rain garden (EW-2, EW-3, EW-5, MR-5); Ponds (EW-2, EW-3, EW-5); Riprap basins (EW-2, EW-3, MR-4, MR-5); Tire wash (EW-3, PR-7); Trash rack (EW-3, MR-2, MR-5); Extruded curb (EW-2, EW-3, MR-4, MR-5, PT-1, AE-5); Riprap (EW-2, EW-3, MR-4, MR-5, EW-5)
Structures	Surface finishes (architectural treatments) (AE-9); Kiosk (AE-5, AE-8, AE-9, MR-4, MR-5, PR-11); Articulated walls/benches/etc. and other decorative features (AE-9); Sound walls (PR-5, MR-4, MR-5); Structural Earth Wall (MR-3, MR-4, MR-5); Wall cap (concrete) (MR-5, EW-5, MR-4); Retaining walls / MSE ([NONE], MR-3, MR-4, MR-5, [EW-5]); Concrete parapet (NONE, AE-5, AE-6, MR-4, MR-5); CSL Tests (NONE, PR-4, [MR-2; MR-5 for tubes]); Fascia (AE-9, MR-4, MR-5, NONE); Bridge approaches (PT-1/PT-4, MR-4, MR-5); Bridge related devices (e.g., bent, spandrels, etc.) (NONE); Deck concrete / Girders / Reinforcements / Moment slabs (NONE, MR-4, MR-5); Scour monitoring system (NONE); Drilled shaft concrete (NONE, MR-3, MR-4, MR-5); Lagging (MR-3, MR-4, MR-5); Modular walls (AE-9, MR-4, MR-5)
Utilities	Pull box / Junction box [concrete and steel] for electrical (EW-8, AE-2, MR-4, MR-5); Potholing (MR-3, MR-2, NONE, MR-5); Trash receptable (AE-5, MR-5, MR-4); Bench (AE-5, MR-5, MR-4); Bike rack (AE-6, MR-4, MR-5); Mailbox support (MR-4, MR-5, NONE); Bollard (AE-5, AE-6, MR-4, MR-5); Adjust/Install franchise utilities (CA-3, MR-3, MR-5, MR-4, NONE); Monument (case, cover, pipe) (MR-4, MR-5, NONE); Gate, wooden or other, including post or not (AE-5, MR-4, MR-5, MR-2 [if reused], EW-5 [when for landscaping purposes], AE-9); Utility resolutions (NONE); Handholes (NONE, AE-2, EW-8, MR-4, MR-5); Conduits/wires except for signals, lighting, water/sewer, storm/drain (NONE, MR-4, MR-5); Plumbing and HVAC (NONE, MR-4, MR-5); Utility casting (except for water/sewer) (NONE, MR-4, MR-5); Utility protection (NONE, MR-4, MR-5); Utility support system (NONE, CC-2); Utility vaults (NONE, MR-4, MR-5)
Vegetation and Landscaping	Top soil (EW-5, MR-4, MR-5, MR-3); Mulching (EW-5, MR-4, MR-5, [PR-7 if temporary], [EW-2, EW-3]); Soil amendment (EW-5, MR-4, MR-5, [MR-3]); Chain link fence / screen fences (EW-5, AE-5, MR-4, MR-2 [if reused], MR-5 [if not reused], CA-3 [if removed and reused]); Seeded lawn / Sod / seeding (EW-2, EW-3, MR-4, MR-5, EW-5, CC-4); Ground cover (EW-5, CC-4, MR-5, [AE-9]); Silt fence (PR-7, MR-4, MR-5, EW-5, MR-2); Trees/grass/plants/vegetations (EW-5, MR-5, CC-4); Compost (EW-5, MR-4, MR-5); Tree grate (EW-5, MR-5, MR-4, AE-5); Irrigation systems (EW-5, MR-4, MR-5, MR-2 [if temporary]); Root barrier / tree guard / root path (EW-5, MR-4, MR-5, CC-4); [Raised] planter (EW-5, CC-4, MR-4, MR-5, [AE-9], [EW-2, EW-3]); Amended soil (EW-5, MR-4, MR-5, MR-3); Tree watering bag systems (EW-5, CC-4, MR-4, MR-5); Weed control (EW-5, PR10)
Water and Sewer	Thrust anchors (NONE [if sanitary sewer/waterline], EW-2 [if drainage], EW-3 [if drainage], MR-4, MR-5, MR-3); Conduits for water and sewer (MR-4, MR-5, NONE); Waterline/sanitary sewer pipes and cleanout / fire hydrants / valves and others (MR-4, MR-5, NONE); Adjust water meter box / manholes / valve boxes (MR-4, MR-5, PT-1, MR-2, NONE, MR-3); Sanitary sewer / water line by open cut (NONE, MR-3, MR-4, MR-5); Air release / gate valve (for water line) (MR-4, MR-5, NONE); Gate valve / valve box / tapping sleeve [unless for landscaping purposes] (NONE, MR-4, MR-5, EW-5 [when for landscaping purposes]); Cured in place pipe (CIPP) (NONE, MR-4, MR-5); Trenchless method sewage diversion / sewer pipe lining (NONE, MR-4, MR-5)
Workzone and Safety	Workzone related (CC-2); Temporary signals (AE-2, CC-2, MR-2, MR-5); Workzone traffic control plan and implementation (CC-2); High visibility fence (CC-2, MR-4, MR-5, EW-5); Portable message sign (CC-2, MR-2, MR-5, AE-2); Traffic control / flaggers / police officer (CC-2, [AE-5 if pedestrian]); Construction site sign (CC-2, MR-2, MR-5); Impact Attenuator (CC-2 [if truck mounted], MR-2 [if material]); [Stabilized] Construction entrance (PR-7); Barricades (CC-2, MR-2, MR-5); Channelizing lines (CC-2, MR-4, MR-5); Construction traffic sign (CC-2, MR-2, MR-5); Temporary pavement (PT-1, MR-4, CC-2, MR-5)

8.2.2.3 Lifecycle Inventory (LCI) Data Sources

Electricity mix by U.S. state comes from GREET 2020, while data for Canada and New Zealand come from Canada Energy Regulator and New Zealand's Ministry of Business, Innovation & Employment websites, respectively. **Table 8.3** shows average emissions and energy conversion factors and their sources used for materials, **Table 8.4** does the same for transportation, and **Table 8.5** for construction equipment. Since the electric grid mix was chosen for each project based on the year of completion, **Figure 8.1** and **Figure 8.2** show the range for each of the values for **Table 8.3**.

Table 8.3 Average CO_2-eq emission and energy conversion factors for primary materials.

Material Type	CO_2-eq (kg / US ton)	Energy (MJ / US ton)	Source
Aggregate Base	2.6	46	(McEwen, 2017)
Aluminum	7,259.5	136,066	(GREET, 2020)
Average Plastic	4,336.9	80,189	(GREET, 2020)
Bedding	2.1	26	(McEwen, 2017)
Bitumen	668.1	4,798	(Wildnauer et al., 2019)
Bitumen + Ground Tire Rubber (GTR)	649.9	4,491	(Wildnauer et al., 2019)
Bitumen + Styrene-Butadiene-Styrene (SBS)	800.6	5,096	(Wildnauer et al., 2019)
Coarse Aggregate in Asphalt	3.4	62	(McEwen, 2017)
Coarse Aggregate in Concrete	2.7	49	(McEwen, 2017)
Cement	964.1	5,235	(GREET, 2020)
Cold Steel	3,004.9	31,231	(GREET, 2020)
Copper	3,044.2	40,900	(GREET, 2020)
Fine Aggregate for Asphalt	3.6	66	(McEwen, 2017)
Fine Aggregate for Concrete	2.8	50	(McEwen, 2017)
Galvanized Steel	3,224.1	34,195	(GREET, 2020)
High-density polyethylene (HDPE)	3,778.5	74,041	(GREET, 2020)
Hot Mix Asphalt (HMA)	30.1	577	Energy: IVL; Emission: EPA AP-42 Table 11-1.3&7&8, Table 4-19,20 AP-42 fabric filter, natural gas.
Hot Steel	2,606.5	26,580	(GREET, 2020)
Iron	814.6	29,412	(GREET, 2020)
Lime	1,200.7	4,554	(GREET, 2020)
Polyethylene	3,798.9	73,854	(GREET, 2020)
Polypropylene	3,350.6	71,654	(GREET, 2020)

Polyvinyl chloride (PVC)	3,130.8	53,610	(GREET, 2020)
Reclaimed Asphalt Pavement (RAP)	1.6	18	(Mukherjee and Dylla, 2017), (Miliutenko et al., 2013), (Yang et al., 2014). Assume RAP processing uses Misc equipment from MOVES2014.
Recycled Aluminum	1,575.9	28,090	(GREET, 2020)
Recycled Steel	1,423.9	19,827	(GREET, 2020)
Riprap	1.6	37	(McEwen, 2017)
Rocks	2.2	38	(McEwen, 2017)
Soil	1.4	23	(McEwen, 2017)
Stainless Steel	1,959.6	27,223	(GREET, 2020)
Pavement Marking	1,018,0	29,420	DOW Coating Materials Presentation
Wall Backfill	2.1	38	(McEwen, 2017)
Warm Mix Asphalt (WMA)	28.6	548	Assume 5% less Carbon/Energy than HMA

Table 8.4 Average CO_2-eq emission and energy conversion factors for the most common transportation vehicles.

Vehicle Type	Abbreviation	Image	Load Capacity (tons)	CO_2-eq (grams / US ton-miles)	Energy (kJ / US ton-miles)	Source
Diesel Heavy-Duty Pick-Up Truck	DHDPUT		0.9	65.0	703	(GREET, 2020)
Light Heavy-Duty Vocational Vehicle	LHDVV		2.1	57.7	658	(GREET, 2020)
Medium Heavy-Duty Vocational Vehicle	MHDVV		4.1	35.0	399	(GREET, 2020)
Heavy Heavy-Duty Vocational Vehicle	HHDVV		12.7	9.1	104	(GREET, 2020)
Combination Short-Haul Truck	CSHT		14.7	10.4	113	(GREET, 2020)
Combination Long-Haul Truck	CLHT		18.6	10.2	116	(GREET, 2020)
Barge	Barge		>1000	4.1	45	(GREET, 2020)
Diesel Rail	DR		>1000	2.6	30	(GREET, 2020)
Electric Rail	ER		>1000	0.9	30	(GREET, 2020)
Ocean Tanker	OT		>1000	1.0	11	(GREET, 2020)

Table 8.5 Average CO_2-eq emission and energy conversion factors for the most common construction equipment. Source: MOVES 2014b.

Equipment	Default Engine Power (HP)	CO_2-eq (kg/hr)	Energy Consumption (MJ/hr)
Backhoe	300	26.3	315
Bore/Drill Rigs	300	54.6	654
Cement & Mortar Mixers	40	8.3	99
Chain Saws < 6 HP (Gasoline)	3	1.8	16
Chippers/Stump Grinders (Diesel)	50	12.0	143
Chippers/Stump Grinders (Gasoline)	25	17.3	171
Cranes	300	54.3	651
Crawler Tractor/Dozers	300	74.6	894
Crushing equipment	300	55.1	660
Dumpers/Tenders	50	7.1	84
Excavator	300	73.9	886
Grader	175	44.6	535
Industrial / Concrete Saw	50	15.2	182
Loader	175	43.2	517
Milling Machine	600	156.1	1869
Miscellaneous Equipment	11~1200	29.7	355
Material Transfer Vehicle (MTV)	300	73.0	874
Off-Highway Tractors	1000	287.6	3445
Off-highway Trucks	2000	566.4	6785
Other Lawn & Garden Equipment (Diesel)	50	12.0	143
Other Lawn & Garden Equipment (Gasoline)	25	13.9	133
Paver	175	42.7	511
Plate Compactor	11	2.2	26
Roller	175	41.9	502
Rough Terrain Forklifts	50	15.9	190
Scrapers	300	78.3	937
Shredders < 6 HP (Gasoline)	6	5.1	50
Signal Boards/Light Plants	40	7.7	92
Skid Steer Loaders	16	2.3	27
Sweepers/Scrubbers	40	8.9	106
Trenchers	300	79.4	951

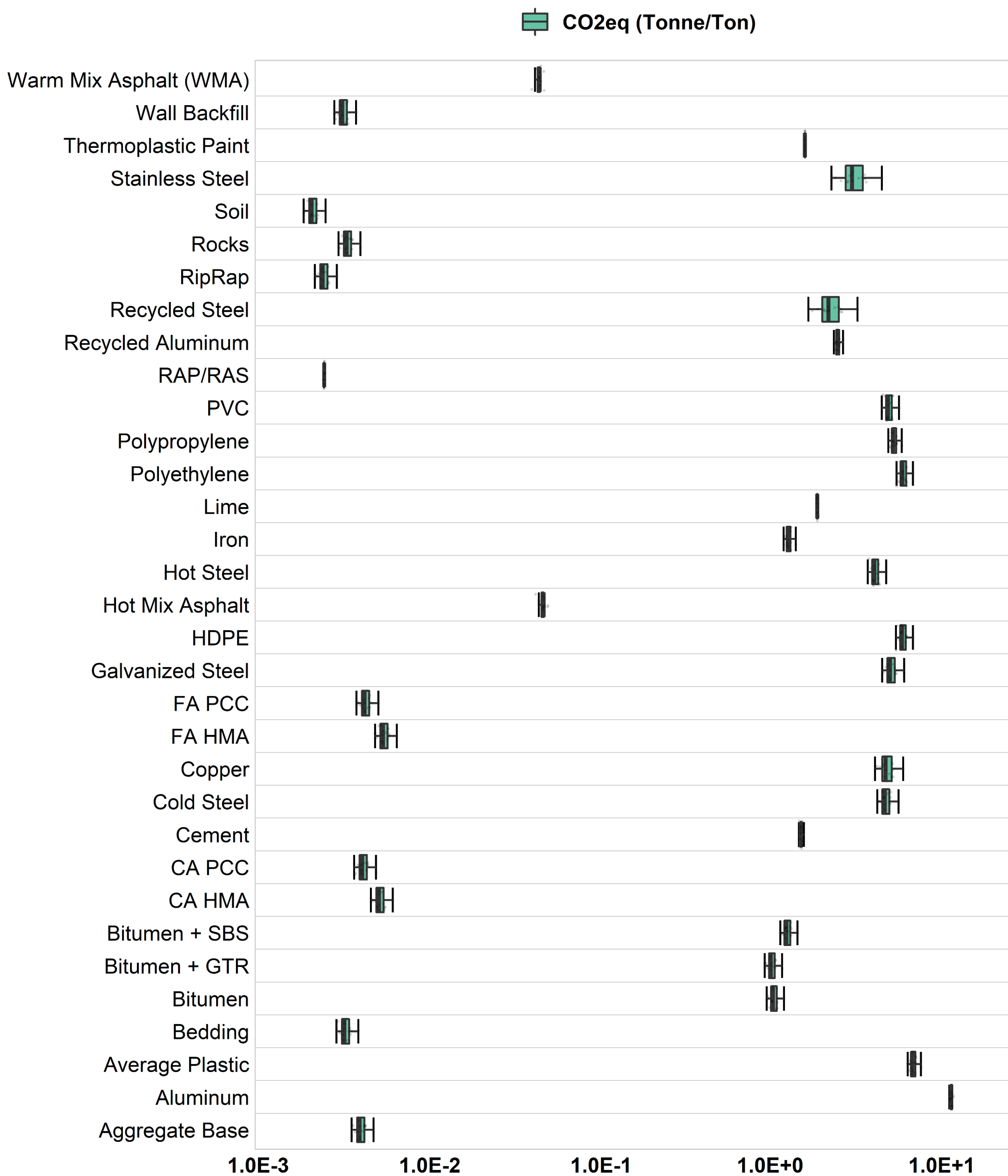

Figure 8.1 CO_2-eq emissions per U.S. ton for the primary construction materials used in this dissertation.

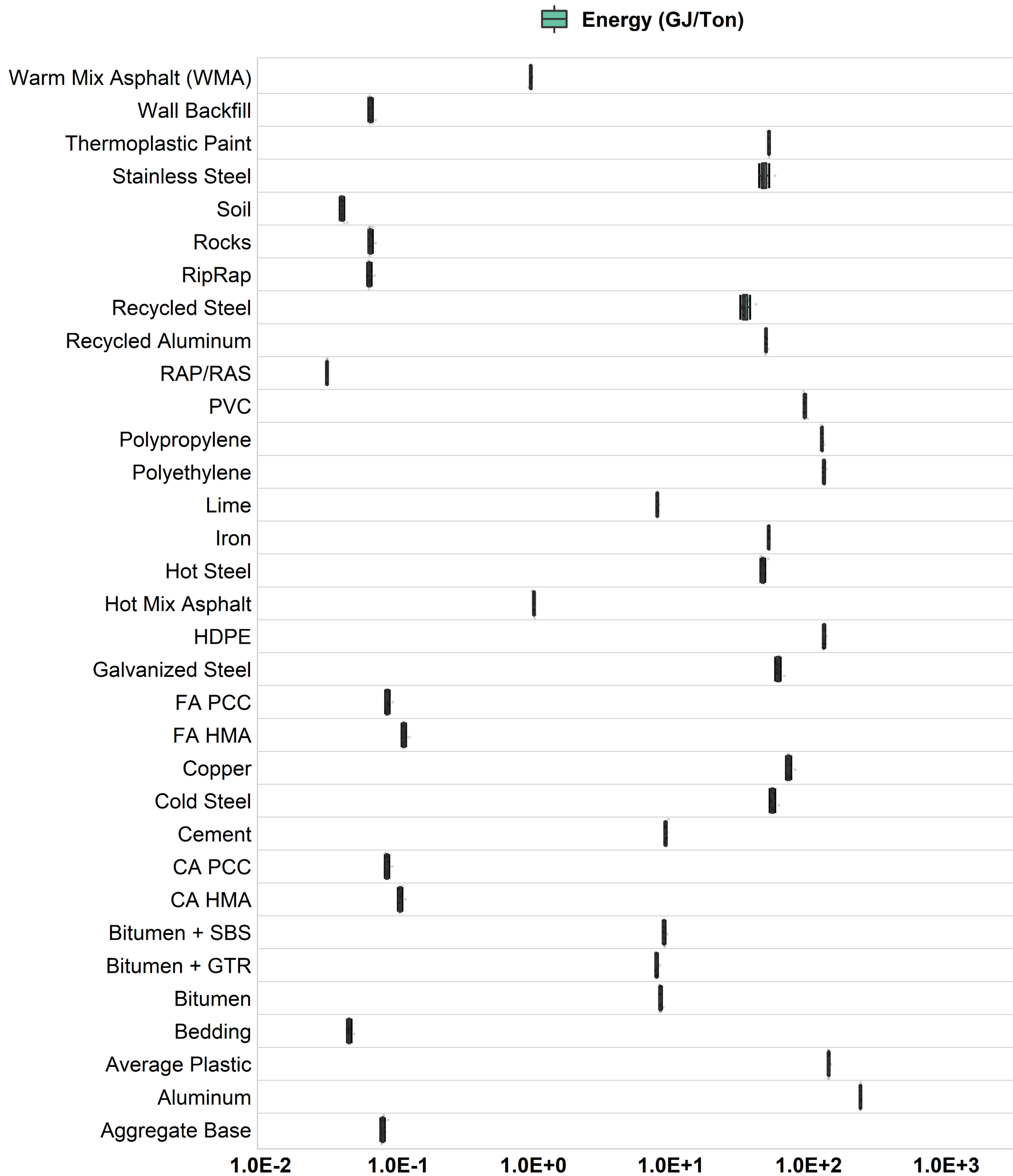

Figure 8.2 Life cycle energy consumption for the primary construction materials used in this dissertation.

8.2.2.3.1 Data Quality Assessment

The LCA follows the methodology proposed by Cooper & Kahn (2012) to assess LCI data quality. In this method, seven data quality categories are selected based on ISO 14044 recommendations as 1) reliability and reproducibility, 2) flow data completeness, 3) temporal coverage, 4) geographical coverage, 5) technological coverage, 6) uncertainty, and 7) precision. Each category is then evaluated with scores of A or B, with A being the higher quality data. **Table 8.6** shows a summary of data quality assessment for the primary materials considered here. Of note, the highest quality data are the ones collected directly from the GREET 2020 database.

Table 8.6 LCI data quality assessment following Cooper and Kahn's (2012) criteria (Cooper and Kahn, 2012).

Material Type	Reliability and Reproducibility	Flow Data Completeness	Temporal Coverage	Technological Coverage	Geographical Coverage	Uncertainty	Precision
Aggregate Base	A	B	B	B	B	B	B
Aluminum	B	A	A	A	A	B	B
Average Plastic	B	A	A	B	B	B	B
Bedding	A	B	B	A	B	B	B
Bitumen	A	B	B	A	B	A	B
Bitumen + Ground Tire Rubber (GTR)	A	B	B	A	B	A	B
Bitumen + Styrene-Butadiene-Styrene (SBS)	A	B	B	A	B	A	B
Coarse Aggregate in Asphalt	A	B	B	A	B	A	B
Coarse Aggregate in Concrete	A	B	B	A	B	A	B
Cement	A	A	A	A	A	A	B
Cold Steel	B	A	A	A	A	B	B
Copper	B	A	A	A	A	B	B
Fine Aggregate for Asphalt	A	B	B	A	B	A	B
Fine Aggregate for Concrete	A	B	B	A	B	A	B
Galvanized Steel	B	A	A	A	A	B	B
High-density polyethylene (HDPE)	B	A	A	B	A	B	B
Hot Mix Asphalt (HMA)	A	B	B	B	B	A	B
Hot Steel	B	A	A	A	A	B	B

Iron	B	A	A	A	A	B	B
Lime	A	A	A	B	A	B	B
Polyethylene	B	A	A	B	A	B	B
Polypropylene	B	A	A	B	A	B	B
Polyvinyl chloride (PVC)	B	A	A	A	A	B	B
Reclaimed Asphalt Pavement (RAP)	A	B	B	B	B	A	B
Recycled Aluminum	B	A	A	B	A	B	B
Recycled Steel	B	A	A	B	A	B	B
Riprap	A	B	B	A	B	B	B
Rocks	A	B	B	A	B	B	B
Soil	B	B	B	B	B	B	B
Stainless Steel	B	A	A	A	A	B	B
Thermoplastic Paint	B	B	B	B	B	B	B
Wall Backfill	A	B	B	A	B	B	B
Warm Mix Asphalt (WMA)	B	B	B	B	B	A	B
Construction Equipment	B	B	A	B	B	B	B
Transportation Vehicles	B	B	A	A	A	B	B

8.2.3 Pay Item List Database Structure

The reference flow data are organized for the LCA in the following sequence:

- Bid tabulation data processing. This includes unit conversions, arrangement in an Excel tabular format, and merging pay item lists from all projects into one master list. Each pay item is identified by an assigned unique numeric identifier (ID), Greenroads project identification, construction year, and description.
- Inclusion in LCA. A binary variable is assigned to each pay item to indicate whether or not it could be included in the LCA. Pay items that were not materials-related, were lump sums, or were a sum of several other items that were not able to be differentiated into measurable pieces were excluded from the LCA.
- Unit and total prices. ENR construction cost indices are used to convert pay item unit prices and total prices to 2020 USD values based on the project's construction completion year.
- Unit of measure and quantity. Each pay item is measured in a specific unit. The most common units of measures are lump sum (LS), ton (TN), pound (LB), cubic yard (CY), square foot (SF),

square yard (SY), acre (AC), linear foot (LF), and the number of items (EA). The quantity of each pay item based on the unit of measure is also expressed in the bid item list.

- Material weights and unit weights. All pay item material quantities are converted to weights (many materials are expressed in units of volume or area on pay item lists). Unit weights for conversion can be found in the Local Materials (MR-5) submitted document, and, in many instances were researched using other data sources.
- Material type assignment. Each pay item is assigned to one or more primary material types (**Table 8.3**) and a secondary material purpose. Material types used are aggregate, aluminum, asphalt, concrete, copper, steel, high-density polyethylene (HDPE), lime, iron, polyethylene, polypropylene, polyvinyl chloride (PVC), thermoplastic paint, and non-materials. Material purpose defines its application. Some commonly used material purposes are pipes, signs, poles, curbs, conduits, signals, manholes, catch basins, walls, culverts, foundations, cables, geotextiles, sidewalks, fences, pavers, etc. For cases where a pay item was only a construction activity, they were assigned to the material type category *operation*. When a pay item addressed removal and excavation of in-situ materials, the material type was categorized as *waste/salvage*.
- Primary material contents. For each pay item, the composition of primary material types is assigned by the fraction of weight each represents. For example, hot mix asphalt has four typical ingredients of coarse aggregate, fine aggregate, asphalt binder, and RAP. The mix design would be used to assign the fraction, by weight, assigned to each.
- Transportation distances. When available, Local Materials (MR-5) credit documents were used to find transportation distances. For some pay items, the average transportation distance of similar material types is used in place of missing distances. For example, the average hauling distance of hot mix asphalt for projects located in Washington State was found to be 15 miles. Therefore, missing hot mix asphalt transportation distances in Washington State were assigned a 15-mile distance. For other pay items, transportation distances cited in the literature are used. For example, transportation of waste and recyclable materials (such as RAP, recycled concrete, and recycled aggregate) was limited to 25 to 50 miles, as suggested by several studies (Anastasiou et

al., 2015; Ashtiani and Muench, 2020; Li et al., 2019; Mladenovič et al., 2015; Rosado et al., 2017).

- Transportation mode. Transportation vehicles were selected based on hauling distance and material weight. Smaller vehicles were picked for short trips and lightweight materials, while larger vehicles were selected for long distances and heavier weights. **Table 8.4** shows a list of all vehicles used to transport materials from suppliers to construction sites.
- Construction equipment. Construction equipment are selected from **Table 8.5**. In our model, up to four different pieces of construction equipment can be selected for a pay item. Engine power (in horsepower) can be selected piece of equipment, or a default value is assigned.
- Operating hours. Construction equipment working hours are found based on total material quantities divided by production rates described previously.
- Construction equipment running time. Since construction equipment may not operate continuously (e.g., downtime, operator breakers, etc.) construction equipment working time are expressed as a percentage of total operating hours. In our accounting, fractions higher than 100% imply that more than one piece of equipment was active at a given time (for example, two breakdown rollers operating concurrently during asphalt paving). Numbers lower than 100% denote equipment with downtime (for example, cranes may have significant downtimes between operations over the course of a construction workday).
- LCI. Emission and energy conversion factors are merged into the reference flow dataset based on the project ID, which creates pay item attributes of carbon footprint and energy footprint for materials, transportation vehicles, and construction equipment.
- Combined pay item list dataset. The attributes described here are combined with construction categories (**Table 8.2**).

9 Appendix B: Roadway Construction Data in Support of Sustainability and Environmental Impact Assessment

Materials in this chapter are intended for publication in *Data in Brief* journal.

Primary data in use of this dissertation were collected during two summer internships in 2018 and 2019 at Greenroads International (now Sustainable Transport Council). Greenroads is a sustainability rating system thru which construction projects can request third-party evaluation and later certification for their level of sustainability achievement. This dataset contains several pieces of information pertaining to 33 Greenroads-certified construction projects with a total value of over USD 2 billion and built between 2011 and 2018. The two primary data sources are 1) Greenroads online platform and its assessment results, and 2) construction documents and data uploaded by project teams into the Greenroads cloud storage.

Greenroads online platform provides two major data. First, scorecard spreadsheets that indicate the result of Greenroads sustainability assessment in the form of numeric values awarded to each credit that a project pursued scores for. Second, project teams provide general qualitative and quantitative information according to Greenroads requirements during the registration stage to describe the project. We call this dataset the project portfolios.

Construction documents were first used to collect data on 12 sustainable performance benchmarks explained in the dataset. Sustainable performance benchmarks are established using median values of quantitatively measurable project practices. These benchmarks are defined in such a way that any roadway construction project regardless of size or scope may use them as sustainability achievement goals. In that, these performance benchmarks are somehow normalized to an aspect of the project's size such as its monetary value, length, or area. Except for the source documents used to produce sustainable performance benchmarks, the dataset contains numeric values obtained from digesting several digitally formatted documents or spreadsheets submitted by project teams.

The other major construction document included in this dataset is the pay item list from 30 of the Greenroads-certified projects (three projects did not provide this data). Pay item lists contain all the items used in the bidding process of a project and include a short description of each item, a unit of measure, the unit price, and the total price. Several other construction documents were employed to reinforce projects' pay item lists with enough information for environmental impact assessment. These include but are not limited to material's unit weights, breakdown of material constituents (e.g., how much cement is in a concrete item), transportation distances, etc. Finally, life cycle inventory (LCI) data for the primary construction materials were collected from publicly available sources and were embedded into the pay item list data for life cycle assessment (LCA) of materials. We analyzed the resultant dataset to estimate the greenhouse gas emissions and energy consumption of projects.

We believe such a dataset is nonexistent within the literature. First, our data reflects several thousand hours of work to certify and collect data for actual construction projects. Second, our analyses only explore the big picture of sustainability achievement by projects while opportunities exist to expand the analyses to produce higher resolution environmental impact assessments based on different material types and applications. Third, future construction projects or those researching sustainability aspects of roadway infrastructure can immediately take advantage of this dataset to set reasonable sustainability goals for their own. Finally, life cycle inventories undergo frequent updates to capture the most recent technology advancements. Our dataset is capable of reflecting those updates to maintain reasonable temporal coverage.

The published dataset can be accessed from the following source:

Repository name: Mendeley Data

Data identification number: doi: 10.17632/ds243x9mbs.1

Direct URL to data: https://data.mendeley.com/datasets/ds243x9mbs/1

9.1 Value of the Data

The data is useful because it provides quantitative measures of sustainability achievement in roadway infrastructure construction. Such quantifiable sustainability measures that act as performance benchmarks are scarce in the literature. Our data is comprehensive and draws a more complete picture of the state of the practice since it comes from real projects. In particular, our data provides baseline values for typical greenhouse gas emissions from roadway construction.

Our data can benefit both sustainability researchers and practitioners. Researchers in several disciplines of civil and construction engineering may use this data to specify sustainable design parameters or compare existing efforts against the state of the practice. Practitioners may leverage this data to set project-or-agency-level sustainability goals and investigate means to accomplish those. In short, our data helps measure and then mitigate adverse environmental impacts of roadways.

The large amount of non-digitized information generated and documented in roadway construction projects makes valuable data undiscovered. Our data provide insights into the specific type of information needed to be collected to quantitatively evaluate the level of sustainability in roadway construction. The usefulness of such data can extend beyond its sample population and to a much broader global market; especially to help developing countries build sustainable roads.

Further, we provide life cycle assessment data that can be updated with soon-to-be-available environmental product declarations or other future life cycle inventory data. With the new surge of statewide and federal-level regulations to limit greenhouse gas emissions from the infrastructure sector (for example, the Buy Clean Acts and Infrastructure Investment and Jobs Act), the usefulness of our data is even more pronounced.

Finally, we need meaningful measures of sustainable practices in order to manage, modify, and later improve those actions. Our data helps measure what was mainly considered proprietary information. Our data helps build more transparent datasets in the horizontal construction industry. Our data also sheds light on what information can and need to be digitized and further practiced for the more stringent environmental policies to be enacted in the future.

9.2 Data Description

The following provides a summary of the data shared in the repository:

9.2.1 Performance Benchmarks and Project Properties

This dataset entails information about the 33 Greenroads-certified projects such as location, length, area, etc. Also included are the twelve sustainability performance benchmarks and their underlying metrics introduced in the accompanying article of this study. **Table 9.1** summarizes the 41 data fields used to create this dataset with a short description of each.

9.2.2 Pay Item Lists For LCA

This dataset contains pay item lists from 30 Greenroads-certified projects. Pay item lists (aka, bid tabulations) are a product of design-bid-build projects to be used for bidding and procurement purposes. Pay items typically include a limited number of data fields including a description, unit of measure, unit cost, and total cost. To enable this dataset for further analysis (in particular, for life cycle assessment – LCA), several other data fields were added to the pay item lists collected and merged into a single dataset. The metadata for this dataset can be found in **Table 9.2** which describes each of the 286 data fields in this dataset. Also included in this dataset are life cycle inventory data for construction materials, transportation vehicles, and construction equipment. These latter datasets are supplementary to performing a life cycle assessment for each pay item.

9.2.3 Construction Materials LCA

This dataset is a subset of the “pay item lists for LCA” dataset. It is formatted differently to make it suitable for quick data analysis. In particular, this dataset only contains those pay items that are of materialistic nature which can, as a result, be included in LCA. **Table 9.3** lists all 53 data fields in this dataset.

9.2.4 Materials LCI

This dataset summarizes life cycle inventory (LCI) data for the 37 generic material types used to perform LCA. The data is formatted as a list for quick data visualization. **Figure 8.1** and **Figure 8.2** are directly constructed based on this dataset. A similar version of this data, albeit being structured as a table, exists in the “pay item lists for LCA” dataset.

9.2.5 Landscape Plans

Landscaping plans from 32 of the Greenroads-certified projects were coalesced into a single dataset. This dataset was particularly used for calculating vegetated areas (one of the twelve sustainability performance benchmarks introduced in this study) from tree canopy areas. Also included in this dataset are the botanical and common names of the plants, their size (height, caliper, spread, or volume), the number of each plant species used in a project, and the calculated canopy area of trees and shrubs assuming a circular growth pattern. Landscape plans for each project are also separately included in this dataset.

Table 9.1 General project information and the metrics used to establish the twelve sustainability performance benchmarks. Green-shaded rows indicate the twelve sustainability performance benchmarks.

Attribute	Description
ProjectNo	An arbitrary number assigned to each project that acts as a unique identifier.
ProjectTitle	An abstract project name to better search project information within the Greenroads website.
Certification	Certification level based on Greenroads evaluation.
V1.5EqScore	Greenroads scores converted to version 1.5 rating system.
City	The city where the project is located.
State	The US state / province (outside the US) where the project is located.
Latitude	The latitude in decimal degrees where the project is located.
Longitude	The longitude in decimal degrees where the project is located.
CompletionYear	The year in which the project finished construction.
BidPriceMillionDollar	Total bid price in million USD converted to 2020 value.
CertificationArea	The construction area of the project in acres.
LaneMiles	Total lane miles of the project.
AADT	Average Annual Daily Traffic of the project.
PercentTSSRemoval	Percent of total suspended solids removed due to the project's implementation of best management practices.
PercentGreenArea	The proportion of project area covered with green space.
kWperLaneMile	Electric power in kW used in a project per lane miles.
PercentPedestrianArea	Portion of the project's area covered with pedestrian friendly facilities like sidewalks and ADA friendly ramps.
BikeLaneMiles	Total lane miles of bicycle friendly facilities (shared or dedicated lanes).
WaterUseGallon	The total amount of water used for different purposes during the construction of project in gallons.
WasteTons	Total amount of waste generated by the project construction in US tons.
PercentCost50Miles	Percent of material costs originated within a 50-mile radius.
PercentRecycled	Percent of recycled materials used in the project.
PercentPavementReused	Percent of existing pavement sections used in place.

WastePerBidPriceTonsPerMillionDollar	Normalized waste generated during construction by the total project's bid price in million USD and in 2020.
BikePerLane	Portion of the project's area covered with bicycle friendly facilities.
PercentCostCoveredinLCA	Percent of the total bid price that was covered in the LCA.
EnergyMJ	Total energy consumption of a project expressed in MJ.
CO2Tons	Total CO2-eq emissions of a project expressed in Metric tons.
EnergyTJperMillionPrice	Total energy consumption of a project normalized to its bid price in TJ per Million USD in 2020.
CO2TonsperMillionPrice	Total CO2-eq emissions of a project normalized to its bid price in Metric tons per Million USD in 2020.
LCAWeightTons	Total material weights considered in each project to perform lifecycle assessment in U.S. tons.
WaterGalperMillionDollar	Normalized water used during construction by the total project's bid price in million USD in 2020.
PercentLED	Percent of project lightings that used LED.
AnnualNightHours	Total night hours in a year where the project is located.
Lanes	Number of average lanes that the project occupies.
Contract	Type of contract used to deliver the project: DBB = Design-Bid-Build; CMGC = Construction Management General Contractor; PPP = Public-Private-Partnership.
Purpose	The main purpose of constructing the project.
Motivation	The main motivation of construction the project.
Location	The location type of the construction project.
Functional Class	The functional class of the road that the project is built.
Zoning	The neighborhood zoning where the project is built (CBD = Central Business District).

Table 9.2 Metadata for the "Pay item lists for LCA" dataset. This table lists all the data fields in this dataset.

Attribute	Description
ID	A numeric unique identifier assigned to each row of data.
Item ID	A unique identifier that contains Project ID information and the order the pay items appeared in the bid tab for each project.
Project ID	Each of the 30 projects are identified with a Project ID in the Greenroads database. This ID contains information about the construction year (first two digits), country where the project is located, state or province where the project is located, and a three-digit ID that distinguishes projects with the same location and construction year.
Year	The year in which the construction finished
Version	Greenroads version used to certify projects.

Description	General description of the pay item as it appears in the as built bid tabulation of the projects. Minimal modifications are made to this attribute.
Include in LCA (1,2,3=Yes, 0=No)	Indicates whether a pay item is included in the LCA analysis of this study. Integers 1, 2, and 3 show if the pay item is included and integer 0 indicates exclusion from the LCA.
Unit of Measure	The unit in which the pay item is measured with the most commonly used acronyms as follows: ACRE: Unit of measuring area (1 acre = 4840 square yard); BARREL: Unit of measuring volume (1 barrel ~5.6 cubic feet); CD: Continuous Days; CY: Cubic Yard; DAY: Number of days; EA: Each item; EST: Estimated; FA: Force Account: is a payment method for construction work where there is no existing agreement on cost; HR: Number of hours; HUND: One hundred of the unit; IN-FT: Inch - foot; LB: Pounds; LF: Linear foot; LS: Lump Sum: a single payment made at a particular time, as opposed to a number of smaller payments or instalments.; MGAL: Million Gallon; SF: Square foot; SY: Square Yard; TN: Short Ton (US ton; don't get confused with metric ton)
Quantity	The quantity of pay items per the unit of measure.
Unit Cost	The unit cost of pay items per the unit of measure expressed in USD value in the Year of construction.
Unit Cost (2020 $)	The unit cost of pay items per the unit of measure expressed in USD value in 2020 (based on the ENR cost index).
Total Cost	The total cost of pay items in USD value in the Year of construction.
Total Cost (2020 $)	The total cost of pay items in USD value in 2020 (based on the ENR cost index).
Total Project Value (2020 $)	Total project price converted to USD in 2020 using the ENR cost indices.
ENR Construction Cost Index (based on 2020)	Engineering News-Records cost indices to convert prices in the construction year to 2020 USD values.
% of total cost	The ratio of total cost of the pay item to the total cost of the project both expressed in USD value in 2020.
Unit Weight (lb)	The unit weight of the pay item in pounds. This attribute is only applicable to pay items with a materialistic nature. Several sources of information are used to find unit weights.
Weight (ton)	The total weight of the pay item in US tons. This attribute is only applicable to pay items with a unit weight.
Origin	Information about the material supplier which can include the physical address where the material is sourced or the name of the supplier.
Distance (mi)	Distance in miles from the supplier location to the project site. This piece of information is mainly extracted from the MR-5 credit in Greenroads (Regional or Local Materials).
Vehicle Type	The assumed mode of transportation (based on distance and weight and type of materials) to deliver products to project sites. See the Transportation LCI worksheet for abbreviations used to describe each vehicle in addition to a picture of a typical vehicle.
Comp Strength (psi)	The 28-day compressive strength of pay items that had Portland cement concrete.

Note	Any additional notes about the pay item is expressed here.
Production Rate (unit/day)	Indicates the amount of Unit of Measure that a piece of construction equipment can deliver in a given day.
Operation Hours (assume 8-hour days)	Total operating hours for each construction equipment given the Quantity of pay items.
Construction Equipment Type 1 *thru 4*	The construction equipment types used to deliver a pay item. This spreadsheet can include up to 4 general construction equipment listed under the Construction LCI worksheet.
Construction Equipment 1 *thru 4* % work	This attribute accounts for the downtime of each construction equipment type (1 thru 4). 100% working time means no down time. Numbers higher than 100% imply the use of more than one piece of the same equipment.
Construction Equipment 1 *thru 4* HP	The horsepower (HP) of each construction equipment 1 thru 4. Default values are used if none indicated.
Related Greenroads Credit 1 *thru 6*	Each pay item is assigned to up to 6 related Greenroads version 1.5 credits.
Related Greenroads Credit ALL	All related Greenroads categories are merged into one cell to facilitate data browsing.
Highway Construction Category1 *thru 4*	Each pay item is assigned to up to 4 highway construction categories. 27 Construction categories are used in the first place and then grouped into 14 categories in the Construction Cat by Proj worksheet.
Highway Construction Category ALL	All related highway construction categories are merged into one cell to facilitate data browsing.
Material Type1 *thru 5*	Each pay item is described by up to 5 general material categories. Several material categories depending on the type of material (e.g., concrete) and their functionality (e.g., culvert, pipe, pavement, etc) are considered. The list of materials are further grouped into only 6 *primary material* categories for data analysis.
Material Type All	All related material types grouped into one cell to facilitate data browsing.
Aggregate Base (%)	Rocks used as base and subbase layers in a pavement structure.
Lime (%)	Hydrated lime used mostly in base treatment.
Soil (%)	Any imported soil to the project site which is mostly used as subgrade layers.
Wall Backfill (%)	Rocks used to support retaining walls and mechanically stabilized earth (MSE).
RipRap (%)	Pieces of rock used mostly for landscaping purposes.
Bedding (%)	Rocks used as pipe beddings for both sanitary and sewer.
Rocks (%)	Rocks in general used for aesthetics purposes or river beddings.
Cement (%)	Portland cement used mostly in concrete manufacturing.
CA PCC (%)	Coarse aggregate (larger than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.

FA PCC (%)	Fine aggregate (smaller than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.
Fly Ash (%)	Fly ash (a byproduct of coal plants) used as a supplementary cementitious material in Portland cement concrete manufacturing.
RCA (%)	Recycled concrete aggregates which are crushed out-of-service Portland cement concrete pieces used to manufacture concrete.
Bitumen (%)	Bitumen (or asphalt binder) used in hot or cold mix asphalt production.
Bitumen + SBS (%)	Bitumen (or asphalt binder) modified with Styrene-Butadiene-Styrene (SBS) used in hot or cold mix asphalt production.
Bitumen + GTR (%)	Bitumen (or asphalt binder) modified with ground tire rubber (GTR) used in hot or cold mix asphalt production.
CA HMA (%)	Coarse aggregate (larger than 3/8" in nominal maximum aggregate size - typically angular aggregates for asphalt) used in asphalt mixtures.
FA HMA (%)	Fine aggregate (smaller than 3/8" in nominal maximum aggregate size - typically angular aggregates for asphalt) used in asphalt mixtures.
RAP/RAS (%)	Reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS) used in asphalt pavement recycling.
HMA (%)	Hot mix asphalt.
WMA (%)	Warm mix asphalt, which is a technology used to decrease mixing temperature of hot mix asphalt and is also used as a compaction aid.
PVC (%)	Polyvinyl chloride (PVC).
Iron (%)	Iron.
Hot Steel (%)	Hot-rolled steel.
Cold Steel (%)	Cold-rolled steel.
Galvanized Steel (%)	Galvanized steel.
Recycled Steel (%)	Steel with recycled contents.
Stainless Steel (%)	Stainless steel.
Copper (%)	Copper.
Aluminium (%)	Aluminium.
Recycled Aluminium (%)	Aluminium with recycled contents.
Wood (%)	Engineering wood products.
HDPE (%)	High Density Polyethylene (HDPE).
Thermoplastic Paint (%)	Thermoplastic paint used as pavement markings.
Water Paint (%)	Water-based paint used as pavement markings.
Polypropylene (%)	Polypropylene.
Average Plastic (%)	Any average plastic product with no accurate description about its type. The term "average plastic" is adopted from GREET.

Polyethylene (%)	Polyethylene.
Aggregate Base (tons), Lime (tons), Soil (tons), Wall Backfill (tons), RipRap (tons), Bedding (tons), Rocks (tons), Cement (tons), CA PCC (tons), FA PCC (tons), Fly Ash (tons), RCA (tons), Bitumen (tons), Bitumen + SBS (tons), Bitumen + GTR (tons), CA HMA (tons), FA HMA (tons), RAP/RAS (tons), HMA (tons), WMA (tons), PVC (tons), Iron (tons), Hot Steel (tons), Cold Steel (tons), Galvanized Steel (tons), Recycled Steel (tons), Stainless Steel (tons), Copper (tons), Aluminum (tons), Recycled Aluminum (tons), Wood (tons), HDPE (tons), Thermoplastic Paint (tons), Water Paint (tons), Polypropylene (tons), Average Plastic (tons), Polyethylene (tons)	These attributes are calculated based on the percent of each material constituent used in each pay item multiplied by the Total Weight.
CO2-eq Aggregate Base (metric ton/us ton), CO2-eq Lime (metric ton/us ton), CO2-eq Soil (metric ton/us ton), CO2-eq Wall Backfill (metric ton/us ton), CO2-eq RipRap (metric ton/us ton), CO2-eq Bedding (metric ton/us ton), CO2-eq Rocks (metric ton/us ton), CO2-eq Cement (metric ton/us ton), CO2-eq CA PCC (metric ton/us ton), CO2-eq FA PCC (metric ton/us ton), CO2-eq Fly Ash (metric ton/us ton), CO2-eq RCA (metric ton/us ton), CO2-eq Bitumen (metric ton/us ton), CO2-eq Bitumen + SBS (metric ton/us ton), CO2-eq Bitumen + GTR (metric ton/us ton), CO2-eq CA HMA (metric ton/us ton), CO2-eq FA HMA (metric ton/us ton), CO2-eq RAP/RAS (metric ton/us ton), CO2-eq HMA (metric ton/us ton), CO2-eq WMA (metric ton/us ton), CO2-eq PVC (metric ton/us ton), CO2-eq Iron (metric ton/us ton), CO2-eq Hot Steel (metric ton/us ton), CO2-eq Cold Steel (metric ton/us ton), CO2-eq Galvanized Steel (metric ton/us ton), CO2-eq Recycled Steel (metric ton/us ton), CO2-eq Stainless Steel (metric ton/us ton), CO2-eq Copper (metric ton/us ton), CO2-eq Aluminum (metric ton/us ton), CO2-eq Recycled Aluminum (metric ton/us ton), CO2-eq Wood (metric ton/us ton), CO2-eq HDPE (metric ton/us ton), CO2-eq Thermoplastic Paint (metric ton/us ton), CO2-eq Water Paint (metric ton/us ton), CO2-eq Polypropylene (metric ton/us ton), CO2-eq Average Plastic (metric ton/us ton), CO2-eq Polyethylene (metric ton/us ton)	CO2-eq emission factors related to each of the generic materials used to describe pay items. The values here are linked to the emission factors listed in the Materials Production LCI worksheet.
CO2-eq Aggregate Base (metric ton), CO2-eq Lime (metric ton), CO2-eq Soil (metric ton), CO2-eq Wall Backfill (metric ton), CO2-eq RipRap (metric ton), CO2-eq Bedding (metric ton), CO2-eq Rocks (metric ton), CO2-eq Cement (metric ton), CO2-eq CA PCC (metric ton), CO2-eq FA PCC (metric ton), CO2-eq Fly Ash (metric ton), CO2-eq RCA (metric ton), CO2-eq Bitumen (metric ton), CO2-eq Bitumen + SBS (metric ton), CO2-eq Bitumen + GTR (metric ton), CO2-eq CA HMA (metric ton), CO2-eq FA HMA (metric ton), CO2-eq RAP/RAS (metric ton), CO2-eq HMA (metric ton), CO2-eq WMA (metric ton), CO2-eq PVC (metric ton), CO2-eq Iron (metric ton), CO2-eq Hot Steel (metric ton), CO2-eq Cold Steel (metric ton), CO2-eq Galvanized Steel (metric ton), CO2-eq Recycled Steel (metric ton), CO2-eq Stainless Steel (metric ton), CO2-eq Copper (metric ton), CO2-eq Aluminum (metric ton), CO2-eq Recycled Aluminum (metric ton), CO2-eq Wood (metric ton), CO2-eq HDPE (metric ton), CO2-eq Thermoplastic Paint (metric ton), CO2-eq Water Paint (metric ton), CO2-eq Polypropylene (metric ton), CO2-eq Average Plastic (metric ton), CO2-eq Polyethylene (metric ton)	Total CO2-eq emissions related to each of the generic materials. This is calculated by multiplication of emission factors by the Total Weight of pay items.
Energy Aggregate Base (GJ/us ton), Energy Lime (GJ/us ton), Energy Soil (GJ/us ton), Energy Wall Backfill (GJ/us ton), Energy RipRap (GJ/us ton), Energy Bedding (GJ/us ton), Energy Rocks (GJ/us ton), Energy Cement (GJ/us ton), Energy CA PCC (GJ/us ton), Energy FA PCC (GJ/us ton), Energy Fly Ash (GJ/us ton), Energy RCA (GJ/us ton), Energy Bitumen (GJ/us ton), Energy Bitumen + SBS (GJ/us ton), Energy Bitumen + GTR (GJ/us ton), Energy CA HMA (GJ/us ton), Energy FA HMA (GJ/us ton), Energy RAP/RAS (GJ/us ton), Energy HMA (GJ/us ton), Energy WMA (GJ/us ton), Energy PVC	Energy consumption factors related to each of the generic materials used to describe pay items. The values here are linked to the emission factors listed in the

(GJ/us ton), Energy Iron (GJ/us ton), Energy Hot Steel (GJ/us ton), Energy Cold Steel (GJ/us ton), Energy Galvanized Steel (GJ/us ton), Energy Recycled Steel (GJ/us ton), Energy Stainless Steel (GJ/us ton), Energy Copper (GJ/us ton), Energy Aluminum (GJ/us ton), Energy Recycled Aluminum (GJ/us ton), Energy Wood (GJ/us ton), Energy HDPE (GJ/us ton), Energy Thermoplastic Paint (GJ/us ton), Energy Water Paint (GJ/us ton), Energy Polypropylene (GJ/us ton), Energy Average Plastic (GJ/us ton), Energy Polyethylene (GJ/us ton)	Materials Production LCI worksheet.
Energy Aggregate Base (GJ), Energy Lime (GJ), Energy Soil (GJ), Energy Wall Backfill (GJ), Energy RipRap (GJ), Energy Bedding (GJ), Energy Rocks (GJ), Energy Cement (GJ), Energy CA PCC (GJ), Energy FA PCC (GJ), Energy Fly Ash (GJ), Energy RCA (GJ), Energy Bitumen (GJ), Energy Bitumen + SBS (GJ), Energy Bitumen + GTR (GJ), Energy CA HMA (GJ), Energy FA HMA (GJ), Energy RAP/RAS (GJ), Energy HMA (GJ), Energy WMA (GJ), Energy PVC (GJ), Energy Iron (GJ), Energy Hot Steel (GJ), Energy Cold Steel (GJ), Energy Galvanized Steel (GJ), Energy Recycled Steel (GJ), Energy Stainless Steel (GJ), Energy Copper (GJ), Energy Aluminum (GJ), Energy Recycled Aluminum (GJ), Energy Wood (GJ), Energy HDPE (GJ), Energy Thermoplastic Paint (GJ), Energy Water Paint (GJ), Energy Polypropylene (GJ), Energy Average Plastic (GJ), Energy Polyethylene (GJ)	Total energy consumption related to each of the generic materials. This is calculated by multiplication of energy consumption factors by the Total Weight of pay items.
CO2eq DHDPUT tons/ton-mile, CO2eq LHDVV tons/ton-mile, CO2eq MHDVV tons/ton-mile, CO2eq HHDVV tons/ton-mile, CO2eq CSHT tons/ton-mile, CO2eq CLHT tons/ton-mile, CO2eq Barge tons/ton-mile, CO2eq DR tons/ton-mile, CO2eq ER tons/ton-mile, CO2eq OT tons/ton-mile	CO2-eq emission factors related to each of the transportation modes. These factors are linked to the Transportation LCI worksheet. For a full description of abbreviations please refer to the Transportation LCI worksheet.
Energy DHDPUT GJ/ton-mile, Energy LHDVV GJ/ton-mile, Energy MHDVV GJ/ton-mile, Energy HHDVV GJ/ton-mile, Energy CSHT GJ/ton-mile, Energy CLHT GJ/ton-mile, Energy Barge GJ/ton-mile, Energy DR GJ/ton-mile, Energy ER GJ/ton-mile, Energy OT GJ/ton-mile	Energy consumption factors related to each of the transportation modes. These factors are linked to the Transportation LCI worksheet.
CO2eq Transportation (metric tons/short ton-mile)	The CO2-eq emission factor to be used for the particular pay item that used a certain Vehicle Type.
Energy Transportation (GJ/short ton-mile)	The energy consumption factor to be used for the particular pay item that used a certain Vehicle Type.
CO2eq Transportation (metric tons)	Total CO2-eq emissions (in metric tons) related to the transportation of materials included in each pay item.
Energy Transportation (GJ)	Total energy consumption related to the transportation of materials included in each pay item.
CO2eq Construction (metric tons)	Total CO2-eq emissions (in metric tons) related to the construction equipment operation to deliver the pay items.
Energy Construction (GJ)	Total energy consumption (in GJ) related to the construction equipment operation to deliver the pay items.

CO2eq Materials Production (metric tons)	Total CO2-eq emissions (in metric tons) related to the transportation of materials included in each pay item.
Energy Material Production (GJ)	Total energy consumption (in GJ) related to the transportation of materials included in each pay item.
TOTAL CO2eq (Metric Tons)	Total CO2-eq emissions (in metric tons) of the pay item.
TOTAL ENERGY (GJ)	Total energy consumption (in GJ) of the pay item.

Table 9.3 Data fields used to create "construction materials LCA" dataset.

Attribute	Description
ID	A numeric unique identifier assigned to each row of data.
Item ID	A unique identifier that contains Project ID information and the order the pay items appeared in the bid tab for each project.
Project ID	Each of the 30 projects are identified with a Project ID in the Greenroads database. This ID contains information about the construction year (first two digits), country where the project is located, state or province where the project is located, and a three-digit ID that distinguishes projects with the same location and construction year.
Description	General description of the pay item as it appears in the as built bid tabulation of the projects. Minimal modifications are made to this attribute.
Include in LCA (1,2,3=Yes, 0=No)	Indicates whether a pay item is included in the LCA analysis of this study. Integers 1, 2, and 3 show if the pay item is included and integer 0 indicates exclusion from the LCA.
TotalBidPriceUSD2020	Total project price converted to USD in 2020 using the ENR cost indices.
Highway Construction Category1 thru 4	Each pay item is assigned to up to 4 highway construction categories. 27 Construction categories are used in the first place and then grouped into 14 categories in the Construction Cat by Proj worksheet.
Highway Construction Category ALL	All related highway construction categories are merged into one cell to facilitate data browsing.
Material Type1 thru 5	Each pay item is described by up to 5 general material categories. Several material categories depending on the type of material (e.g., concrete) and their functionality (e.g., culvert, pipe, pavement, etc) are considered. The list of materials are further grouped into only 6 primary material categories for data analysis.
Material Type All	All related material types grouped into one cell to facilitate data browsing.
Primary Material	We identified each pay item to constitute a primary material from these six categories: asphalt, rock, concrete, steel, waste, plastics
SubPrimaryMaterial	This attribute identifies a subcategory of the primary material. For example, galvanized steel as a subcategory of steel.

Weight (tons)	Total weight of the materials in the pay item expressed in short U.S. tons.

The following attributes indicate the breakdown of materials used in each pay item (when the pay item has a material nature). 37 material types are considered to best describe material constituents of each pay item.
Rocks used as base and subbase layers in a pavement structure.
Hydrated lime used mostly in base treatment.
Any imported soil to the project site which is mostly used as subgrade layers.
Rocks used to support retaining walls and mechanically stabilized earth (MSE).
Pieces of rock used mostly for landscaping purposes.
Rocks used as pipe beddings for both sanitary and sewer.
Rocks in general used for aesthetics purposes or river beddings.
Portland cement used mostly in concrete manufacturing.
Coarse aggregate (larger than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.
Fine aggregate (smaller than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.
Fly ash (a byproduct of coal plants) used as supplementary cementitious material in Portland cement concrete manufacturing.
Recycled concrete aggregates which are crushed out-of-service Portland cement concrete pieces used to manufacture concrete.
Bitumen (or asphalt binder) used in hot or cold mix asphalt production.
Bitumen (or asphalt binder) modified with Styrene-Butadiene-Styrene (SBS) used in hot or cold mix asphalt production.
Bitumen (or asphalt binder) modified with ground tire rubber (GTR) used in hot or cold mix asphalt production.

Aggregate Base (tons)	Rocks used as base and subbase layers in a pavement structure.
Lime (tons)	Hydrated lime used mostly in base treatment.
Soil (tons)	Any imported soil to the project site which is mostly used as subgrade layers.
Wall Backfill (tons)	Rocks used to support retaining walls and mechanically stabilized earth (MSE).
RipRap (tons)	Pieces of rock used mostly for landscaping purposes.
Bedding (tons)	Rocks used as pipe beddings for both sanitary and sewer.
Rocks (tons)	Rocks in general used for aesthetics purposes or river beddings.
Cement (tons)	Portland cement used mostly in concrete manufacturing.
CA PCC (tons)	Coarse aggregate (larger than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.
FA PCC (tons)	Fine aggregate (smaller than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.
Fly Ash (tons)	Fly ash (a byproduct of coal plants) used as a supplementary cementitious material in Portland cement concrete manufacturing.
RCA (tons)	Recycled concrete aggregates which are crushed out-of-service Portland cement concrete pieces used to manufacture concrete.
Bitumen (tons)	Bitumen (or asphalt binder) used in hot or cold mix asphalt production.

Bitumen + SBS (tons)	Bitumen (or asphalt binder) modified with Styrene-Butadiene-Styrene (SBS) used in hot or cold mix asphalt production.
Bitumen + GTR (tons)	Bitumen (or asphalt binder) modified with ground tire rubber (GTR) used in hot or cold mix asphalt production.
CA HMA (tons)	Coarse aggregate (larger than 3/8" in nominal maximum aggregate size - typically angular aggregates for asphalt) used in asphalt mixtures.
FA HMA (tons)	Fine aggregate (smaller than 3/8" in nominal maximum aggregate size - typically angular aggregates for asphalt) used in asphalt mixtures.
RAP/RAS (tons)	Reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS) used in asphalt pavement recycling.
HMA (tons)	Hot mix asphalt.
WMA (tons)	Warm mix asphalt, which is a technology used to decrease mixing temperature of hot mix asphalt and is also used as a compaction aid.
PVC (tons)	Polyvinyl chloride (PVC).
Iron (tons)	Iron.
Hot Steel (tons)	Hot-rolled steel.
Cold Steel (tons)	Cold-rolled steel.
Galvanized Steel (tons)	Galvanized steel.
Recycled Steel (tons)	Steel with recycled contents.
Stainless Steel (tons)	Stainless steel.
Copper (tons)	Copper.
Aluminum (tons)	Aluminum.
Recycled Aluminum (tons)	Aluminum with recycled contents.
Wood (tons)	Engineering wood products.
HDPE (tons)	High Density Polyethylene (HDPE).
Thermoplastic Paint (tons)	Thermoplastic paint used as pavement markings.
Water Paint (tons)	Water-based paint used as pavement markings.
Polypropylene (tons)	Polypropylene.

Average Plastic (tons)	Any average plastic product with no accurate description about its type. The term "average plastic" is adopted from GREET.
Polyethylene (tons)	Polyethylene.
LCAWeight(tons)	Total weight of the materials included in the LCA of the pay item in U.S. short tons.
CO2Tons	Total CO2-eq emissions (in metric tons) of the pay item.
EnergyMJ	Total energy consumption (in MJ) of the pay item.

10 References

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