THESIS

QUANTIFYING SUSTAINABILITY METRICS FOR TRUNKLINE BRIDGES IN THE MOUNTAIN PLAINS REGION

Submitted by

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ABSTRACT

QUANTIFYING SUSTAINABILITY METRICS FOR TRUNKLINE BRIDGES IN THE MOUNTIAN PLAINS REGION

The use of millions of cubic yards of concrete and steel to support the U.S infrastructure may result in a significant negative impact on the environment. CO_2 released by the construction processes as well as the material production, is taking a toll on the environment. This study is aimed at developing a ranking system to determine the emission of CO_2 for bridges and rank them based on their CO_2 emission. Firstly, in order to accomplish this objective, rating systems for buildings from around the world were analyzed for common attributes applicable to bridges. Secondly, a sample of bridges from the state of Colorado was selected and analyzed for their sustainability by only considering their main materials and a ranking system based on the emission of CO_2 was developed. This served as the first step in developing a rating system for bridges in Colorado where only the CO_2 emission from the production and transport of concrete and steel were considered. This rating system can be further developed to include CO_2 emissions from construction processes, demolition and disposal and other factors that contribute to sustainability, but its current version is intended only to provide an example of an approach for development of a ranking system.

ACKNOWLEDGMENTS

I'd like to thank my family for supporting me all throughout my college career as well as my friends who made every day in college special. I would also like to thank all my professors who supported me with understanding and applying my knowledge in engineering and other disciples. I am especially thankful to my advisers Dr. John Van de Lindt and Dr. Bolivar Senior for guiding me in this research project and supporting me whenever I needed it. My final thank you goes to the Colorado Department of Transportation (CDOT) officials especially Mr. Steven White, who helped me with supplying the structural drawings for bridges whenever I needed and hence making this project better.

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Chapter 1-Introduction

One of the most important aspects of modern civil engineering design is the inclusion of design practices where the environmental impacts are of major concerns. The real world, however, is far from this ideal. There is growing concern about the long-term future, resources of the planet, the environment and high levels of poverty, which are linked with the spread of disease, social unrest, population growth and environmental degradation. According to the U.S Environmental Protection Agency (EPA), electricity production generates the largest share (31%) of greenhouse gas (GHG) emission with the second largest producer of GHG being transportation (27%) (EPA, 2013). But one of the other indirect contributors to the rise in global temperatures and climate change is the increasing population. According to the World Bank (The World Bank, 2013), the world has experienced an unprecedented increase in population growth and it is projected to increase to at least 8 billion by the end of 2050. With the population on the rise, the construction industry is experiencing a higher demand for additions to the physical infrastructure than ever before. This increasing demand is well understood from the increase in civil engineering graduates from all over America. According to Yoder (2011) using data from the American Society for Engineering Education (ASEE), during the 2011-2012 academic year there were 12,309 civil engineering undergraduate students from USA (Yoder, 2011) and still continues to rise.

Even though rise in number of civil engineers and civil engineering products can be seen as a good indicator, it also comes with a cost. Due to a rise in commercial and residential buildings the U.S Green Building Council (USGBC) states that buildings are one of the heaviest consumers of natural resources and account for a significant portion of the GHG gas emissions that affect climate change. In the US, buildings account for 38% of all of CO_2 emissions and 73% of electricity consumption (USGBC, 2015)

Despite such conditions, the civil engineering industry soon recognized the problems and are working towards building and designing buildings that are energy efficient and that have a minimal impact on the environment. It was reported by the USGBC (McGraw-Hill, 2013) that around the world, green building construction is accelerating as they are becoming viewed as a long term opportunity. Majority of the architects, engineers and contractors, owners and consultants participating in the study anticipate that more than 60% of their work will be green by 2015, up from 28% of firms in 2012.

But, commercial and residential buildings are only a portion of the physical infrastructure. Infrastructure systems, and especially transportation systems, within civil engineering, still do not receive adequate attention when it comes to sustainable design/construction practices. According to a study performed by Korkmaz (2012), transportation is a vital part of the economy but also a significant source of GHG emission. It involves a large number of construction activities, which directly or indirectly release GHG, water, and land pollutants. (Korkmaz, 2012).

Before any sustainability standards can be enforced for infrastructure systems, there must be some type of provision to quantify it. One such example of considering criteria for sustainability in infrastructure construction projects is a study performed in the United Kingdom (UK), entitled ‘Quantification of Sustainability Principles in Bridge Projects.’(Spencer et al, 2012). In the study, they provided information on key attributes to be considered while developing a metric for bridges related to the economy, society, environment, resources and climate change. Moreover, the Building Research Establishment Environmental Assessment Methodology (BREEAM) in the UK (which has been described as the world's foremost environmental assessment method and rating systems for buildings (Fowler and Rauch, 2006)) also suggests that while proposing any local requirements for sustainable buildings, planning authorities must be able to demonstrate with clear robust evidence the circumstances that warrant these requirements, focusing on local or site-specific opportunities and constraints (BREEAM 2012).

Based on the recommendation by BREEAM and the study by Spencer et al, a basic metric is used to characterize the sustainability of a bridge in Colorado which can be further developed to include other aspects of bridge sustainability. The metric is applied to a small but representative, group of bridges in Colorado to provide information on bridge sustainability; looking solely at bridge superstructures as described later in this thesis.

Chapter 2- Methodology

Worldwide there are hundreds of building evaluation tools that focus on different areas of sustainable development and are designed for different types of projects such as life cycle assessment, life cycle costing, energy systems design, performance evaluation, productivity analysis etc (Fowler and Rauch, 2006). Many of the systems developed in different countries around the world were created by modifying a single system or integrating multiple systems (Fowler and Rauch, 2006). Examples of such single systems are LEED (Leadership in Energy & Environmental Design), BREEAM Green Building Tool, Green Globe US, Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) (Fowler and Rauch, 2006).

The study presented herein is divided into two sections. First, the study comprised the derivation of standards to quantify sustainability of bridges from different green building rating systems around the world. Secondly, one of the chosen criteria for sustainability of bridges was quantified for a select number of bridges from the Colorado bridge inventory.

Most of the rating systems around the world share a common goal of creating sustainable structures; a number of rating systems available in several different countries around the world were analyzed. Rating systems analyzed were from USA, UK, Australia, Japan, China, France, Germany, India, Malaysia, South Africa, Austria and Canada. Each of the aforementioned countries had one or more rating systems and all those that could be identified were analyzed based on the availability of credible data. Different rating systems had different criteria for awarding a building with a status of sustainability. But only the criteria which were repeated twice or more were considered in the analysis in the present study.

Each system analyzed awarded its certification to a structure based on a pre-established scale to determine sustainability. Furthermore it was common for a rating system to have subdivisions in all of its major criteria as is done by LEED-USA (USGBC, 2009). For achieving and/or including certain features from their predetermined list, it awards points to the building. Based on the number of points achieved by a building it is awarded the platinum, gold, silver or certified, certification with platinum being the highest achievable certification and certified being the lowest achievable (LEED, n.d). In line with this concept, sustainability ratings for bridges are believed to be positive and can also be awarded a ‘rank’ which makes the understanding of the bridge’s level of sustainability easier.

All rating systems analyzed herein were used only for residential and commercial buildings. Even though some of the rating systems extended to quantify sustainability for renovating structures, only new building construction was taken into consideration for this study. Initially details of the criteria used by each rating system to award sustainability were procured and then each was classified into general categories of similar nature. It is noted that some rating systems had criteria that were not used in other rating systems, so were disregarded with the assumption that it only pertained to the region where that rating system is operated.

Then, the criterion identified was subdivided to develop a better understanding of the conditions met to fulfill the criteria for each rating system. An example of this process is the checklist formulated by LEED-USA to fulfill the criteria related to having sustainability in materials and resources while constructing a new building. Table 2.1 shows the checklist of attributes that should be fulfilled for achieving credits for a LEED sustainability rating (USGBC, 2009):

Table 2.1: Attributes for material sustainability for LEED

Credit #	**Description**	**Required points**
Prerequisite 1	Storage and Collection of Recyclables	Required
Credit 1.1	Building Reuse-Maintain Existing Wall, Floors and Roof	1-3
Credit 1.2	Building Reuse-Maintain Existing Interior Nonstructural Elements	1
Credit 2	Construction Waste Management	1-2
Credit 3	Materials Reuse	1-2
Credit 4	Recycled Content	1-2
Credit 5	Regional Materials	1-2
Credit 6	Rapidly Renewable Materials	1
Credit 7	Certified Wood	1
	Total Possible Points	14

The approach presented in this thesis attempts to parallel building sustainability for basic metrics used for bridge construction. By figuring out the criterion that can be applied to bridges, it is then possible to award points/checks such that they are fulfilled during or after the construction of a new bridge. The flowchart presented in Figure 2.1 summarizes the steps described above:

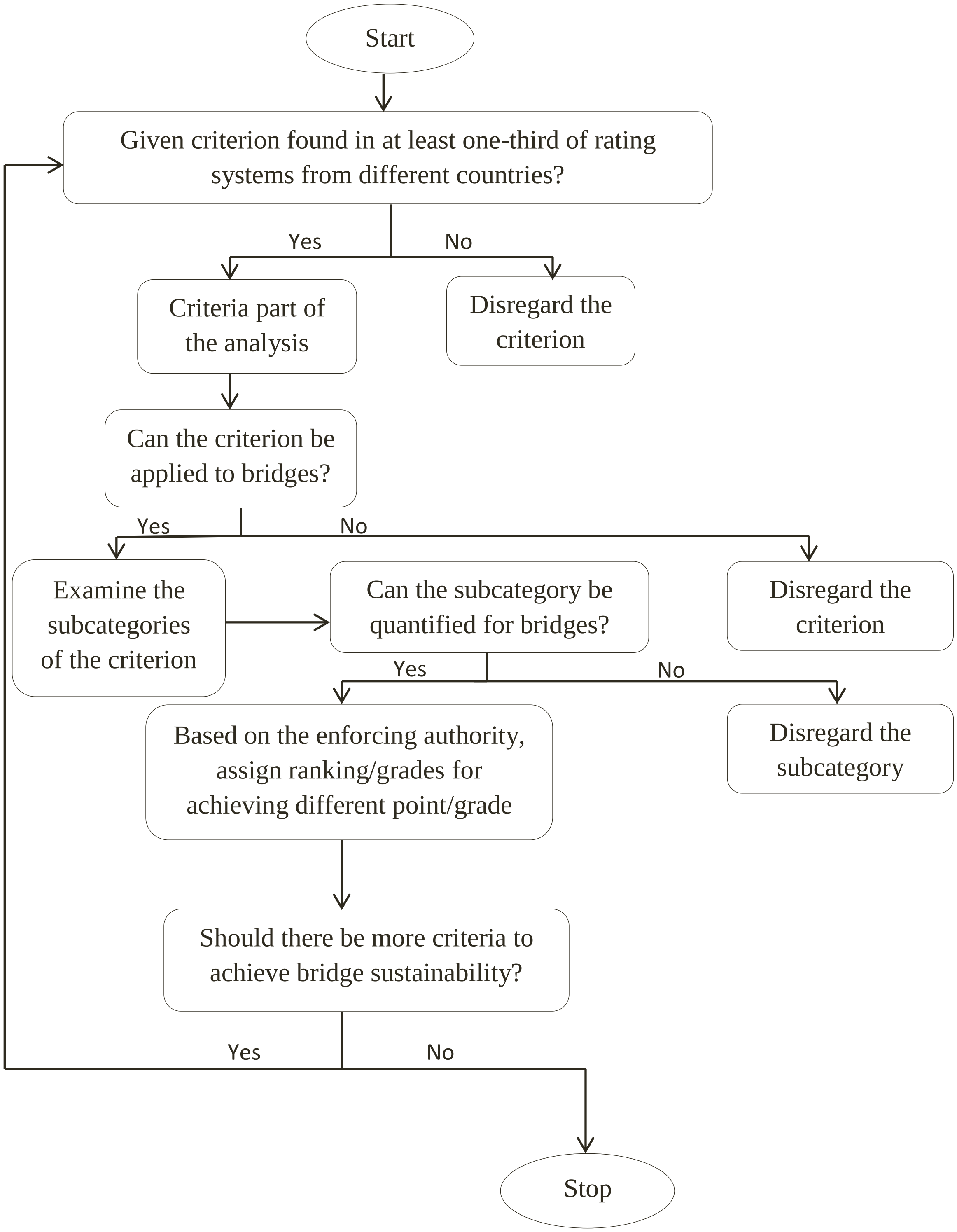

Figure 2.1-Flowcahrt describing stage 1 of the study

After following the process mentioned in stage 1, the criteria with which the sustainability of a bridge can be quantified was identified as five general categories. Such categories include sustainability in materials used for construction, energy (electricity and crude oil products) used during the construction and operation of the bridge, selection of site for bridge construction, air quality, and finally water use for construction and operation of the bridge. Finding such general categories which can be further broken down into sub-categories constitutes the end of stage 1.

For stage 2, one of the criteria, sustainability in materials, was selected herein to serve as a surrogate for sustainability in general. Only one of the criteria was considered because including all the aspects of sustainability in bridges would be beyond the information available at this stage. Also the aforementioned criterion was selected because of the forbearance in acquiring data as well as its direct link to sustainability of a structure. But before starting data collection and analyses, an important assumption made in this study should be described. Each bridge's superstructure carbon footprint was assumed to be representative of its sustainability and the sample size used was assumed to be representative of the bridge population in Colorado. The construction and maintenance of the bridge were not considered in the carbon footprint calculation since it can be built into the rating system with the framework provided in this study.

The reason for choosing the carbon footprint as a sustainability metric is due to its adverse effects on the environment. Climate scientists have observed that carbon dioxide (CO_2) concentrations in the atmosphere have been increasing significantly over the past century, compared to the rather steady level of the pre-industrial era (about 280 parts per million in volume, or ppmv). The 2013 concentration of CO_2 (396 ppmv) was about 40% higher than in the mid-1800s, with an average growth of 2 ppmv/year in the last ten years. Significant increases have also occurred in levels of methane (CH_4) and nitrous oxide (N_2O) (2012 CO_2 Emissions

Overview, (n.d)). Furthermore, the EPA states that cement production is a key source of CO_2 emission, due in part to the significant reliance on coal and petroleum coke to fuel the kilns for clinker production. Globally, CO_2 emissions from cement production were estimated at 829 $MMTCO_2$ in 2000, approximately 3.4% of global CO_2 emission from fossil fuel combustion and cement production (Hanley et al, n.d). Similarly, the steel industry also generates significant amount of CO_2 and other greenhouse GHG's. The GHG emissions in steelmaking are generated as one of the following: (1) process emissions, in which raw materials and combustion both may contribute to CO_2 emissions; (2) emissions from combustion sources alone; and (3) indirect emissions from consumption of electricity (primarily in Electric Arc Furnace (EAF) and in finishing operations such as rolling mills at both Integrated and EAF plants). For EAF steelmaking, the primary sources of GHG emissions include indirect emissions from electricity usage (50 percent), combustion of natural gas in miscellaneous combustion units (40 percent) and steel production in the EAF (10 percent) (Jones, 2012). Such data related to cement and steel production suggests that the main CO_2 contributions from such industries are due to the energy used in them and according to the EPA, the combustion of fossil fuels to generate electricity is the largest single source of CO_2 emissions in the nation, accounting for about 37% of total U.S. CO_2 emissions and 31% of total U.S. GHG emissions in 2013 (EPA, 10/18/15). It is due to such aforementioned reasons, CO_2 content of a bridge was assumed to be the measure of its sustainability.

Initially, a list of bridges fulfilling certain criteria were selected from the complete list of bridges archived by the Colorado Department of Transportation (CDOT). List of bridges selected from the CDOT inventory is shown in appendix A. Since the material aspect of sustainability was to be quantified, only the essential bridge building materials such as concrete and steel were considered and its respective CO_2 emission was assumed to be the CO_2 footprint of the whole bridge. Estimating the CO_2 content of each bridge was based on published data on carbon content as well as existing approaches available in the literature. After quantifying the CO_2 content, it was normalized using several criteria such as the number of lanes, deck area, unit width etc and charts of CO_2 content were developed.

Similar to stage 2, other criterion can be analyzed and quantified accordingly. After quantifying the entire criterion, it can be normalized to provide a rating scale to which ranking/grade can be assigned and hence build a full scale rating system for bridges. Figure 2.2 below shows a flowchart summarizing the procedure described above.

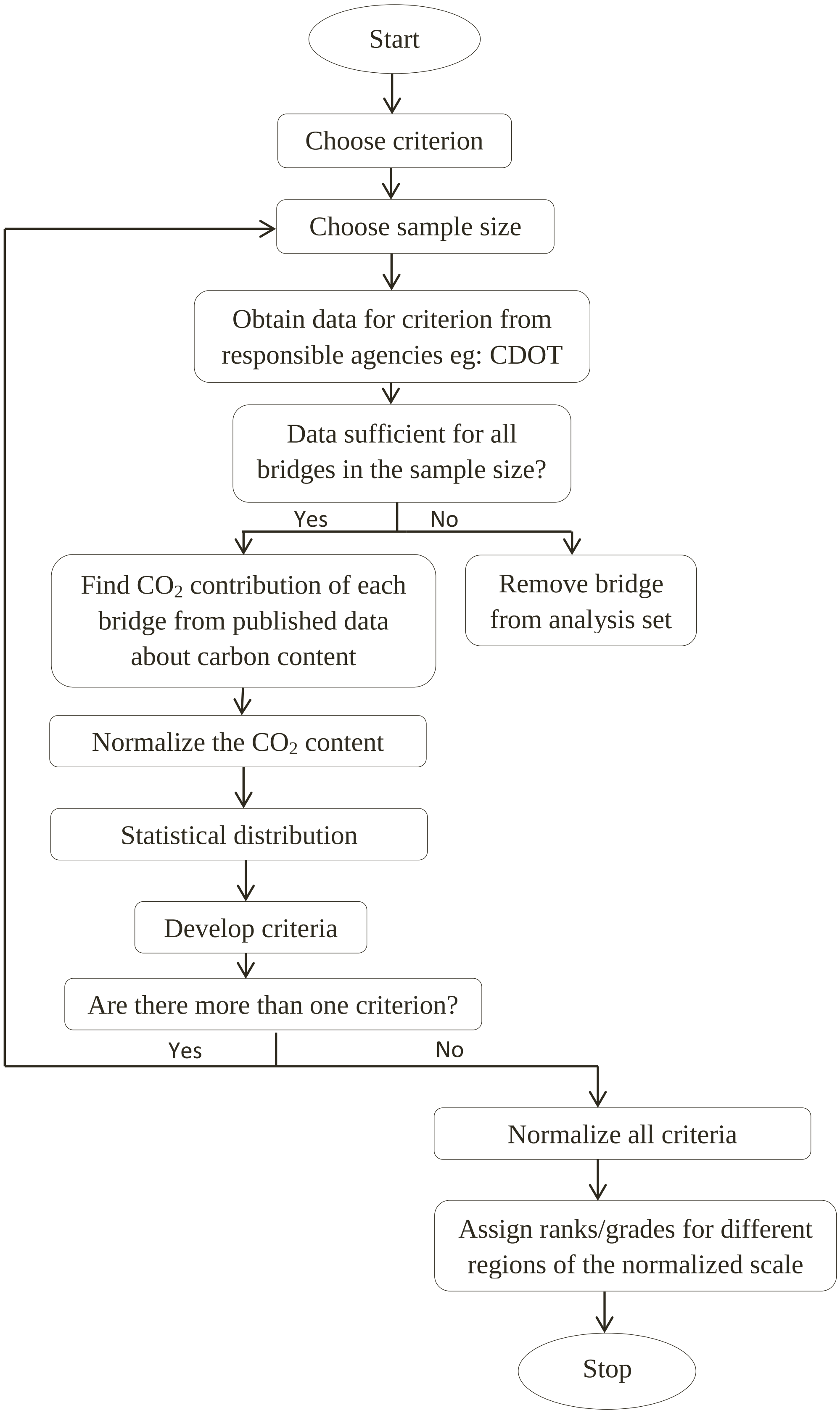

Figure 2.2-Flowchart describing Stage 2 of the study

Chapter 3- Illustrative example

In this chapter an example of the study as mentioned in chapter 2 is presented for Colorado, felt to be representative of the Mountain Plains Region. For this example, due to the vast number of bridges in service in Colorado 36 randomly selected bridges were included in the procedure. All of the bridges selected were constructed after 1990 and had a length of at least 200 feet. Moreover, the bridges chosen had their main structural element to be made of either concrete (prestressed) or steel.

3.1 Assumptions

For each bridge chosen, Table 3.1 shows the assumptions made before quantifying the CO_2 footprint:

Table 3.1: Analysis Assumptions

	Assumption	Variable definition
1	CO_2 content is a representation of the bridge's sustainability	-
2	Area of the bridge	Deck Length (ft) * Deck width (ft)
3	Average days to construct	90 days
4	Service life	75 years
5	Main material	Steel or Concrete
6	Distance travelled by concrete before pouring via road (to and fro)	100 miles
7	Distance travelled by steel before erection via road	560 miles (Plymouth, UT to Denver, CO)
8	Average strength concrete	5 ksi
10	Steel fabrication level	CO2 emissions related to steel fabrication vary greatly depending on the design. Therefore, fabrication level is assumed to be average with the CO_2 emissions related to it assumed to be 0.020 Kg
11	Wind loading	>58 m/s
12	Seismic loading	0.38g to 0.95g

3.2 Procedure:

After making the assumptions for the select bridges, each of their structural drawings was obtained from the Colorado Department of Transportation (CDOT). From the obtained bridge plans, the quantity of concrete and steel used in the construction of the superstructure was quantified for each bridge. This was followed by finding the quantity of structural steel, concrete and rebar per square foot area of the bridge deck to be included in the Environmental Analysis (EA) Tool program created by Skidmore, Owings & Merrill LLP (SOM). The reason for choosing the EA tool was the credibility in their calculation of CO_2 content. All the data regarding the CO_2 in various attributes were derived from various government organization and universities around the globe. Some of those sources include the National Renewable Energy Laboratory (NREL), University of Bath, Inventory of Carbon and Energy, Portland Cement Association (PCA), California Energy Commission, Carnegie Mellon University, South Coast Air Management District.

According to the software, it measures the equivalent carbon dioxide (CO_2e) emission for a structure. In doing so it accounts for all the GHG's besides CO_2 that contribute towards a 100 year global warming potential (GWP) for the structure. To sum up the contribution from each of these gases to the total GWP, factors are assigned to each gas based on molecular weight using CO_2 as the benchmark. These factors are summarized in Table 3.2:

Table 3.2: GWP factor for each GHG gas (EA Tool, 2013)

GHG	GWP Factor (equivalent CO2)
Carbon dioxide	1
Dinitrogen monoxide	310
Methane	21

Methane, HCC-30	9
Nitrogen oxides	Negligible
Nonmethane VOCs	Negligible
Carbon Monoxide	Negligible

After determining the equivalent CO_2, the developers then applied it to the equivalent CO_2 contribution by materials production. All the data shown in Tables 3.3-3.7 are derived from the EA Tool user manual. Since procuring building materials utilize energy sources for production, transportation and installation, the equivalent CO_2 emission for using energy is quantified as shown in the Table 3.3 below:

Table 3.3: CO_2 equivalent for 1 MJ production of energy (EA Tool, 2013)

For 1.0 MJ of energy	Emission	Unit	Factor	Emission	Unit
Embodied carbon dioxide	0.194061	kg	1	0.194061	kg CO2e
Other GHG's:					
Dinitrogen monoxide	0.000001	kg	310	0.000169	kg CO2e
Methane	0.000002	kg	21	0.000041	kg CO2e
Methane, HCC-30	0	kg	9	0	kg CO2e
Nitrogen oxides	0.000473	kg	0	0	kg CO2e
Nonmethane VOCs	0.000005	kg	0	0	kg CO2e
Carbon monoxide	0.000038	kg	0	0	kg CO2e
Total Equivalent Embodied Carbon dioxide:				0.194272	kg CO2e

Similarly, the equivalent amounts of CO_2 emission for production of all steel components and its fabrication as well as concrete products are shown below. Tables 3.4, 3.5 and 3.6 below take into account the CO_2 contribution of energy usage as well as raw materials used in the production:

Table 3.4: Equivalent CO_2 content for 1 kg production of steel components (EA Tool, 2013)

For 1.0 kg of steel	Emission	Unit	Factor	Emission	Unit
Embodied carbon dioxide	2.27118	kg	1	2.27118	kg CO_2e
Other GHG's:					
Dinitrogen monoxide	3E-06	kg	310	0.00081	kg CO_2e

Methane	0.00113	kg	21	0.02371	kg CO_2e
Methane, HCC-30	0	kg	9	0	kg CO_2e
Nitrogen oxides	0.00282	kg	0	0	kg CO_2e
Nonmethane VOCs	0.00107	kg	0	0	kg CO_2e
Carbon monoxide	0.02491	kg	0	0	kg CO_2e
Total Equivalent Embodied Carbon dioxide:				2.2957	kg CO2e

Since uniform data for the fabrication process for steel shapes is not readily available the following quantities in Table 3.5 (SOM, 2013) are assumed for all the bridges. Fabrication for other steel components such as nuts, bolts, rebars etc are not considered since majority of them are manufactured without the need for any further fabrication.

Table 3.5: Equivalent CO_2 emission for rolled shapes fabrication (EA Tool, 2013)

Material (1 kg)	**Low-level Type Fabrication**	**Average-level Type Fabrication**	**High-level Type Fabrication**
Structural Steel – Rolled Shapes	0.010 kg CO_2e	0.020 kg CO_2e	0.030 kg CO_2e

Table 3.6 shows the equivalent CO_2 contribution by different concrete strength types. Further details required for calculating the equivalent CO_2 shown in Table 3.6 can be found in Appendix B. It provides information on the equivalent CO_2 emission due to the production of cement and transportation of other cemenetitious materials to the concrete mix plant. Furthermore, details on equivalent CO_2 emission for different concrete mixes have also been included in Appendix B.

Table 3.6: Equivalent CO_2 emission for varying concrete strengths (EA Tool, 2013)

Strength Type (1 kg)	**Mix Ratio by Weight – Cement: Sand: Coarse Agg.**	**kg CO_2 (equivalent)**
Low-strength	1:02:04	0.092
Average-strength	01:05.5	0.128
High-strength	1:01:02	0.19

After calculating the CO_2 equivalent contribution by the main materials used in the bridge, the equivalent CO_2 contribution by transportation of those materials are shown in Table 3.7.

Table 3.7: Equivalent CO_2 emission due to a heavy truck (EA Tool, 2013)

For 1.0 km of transport by heavy-heavy duty truck	Emission	Unit	Factor	Emission	Unit
Embodied carbon dioxide	1.186926	kg	1	1.187	kg CO_2e
Other GHG's:					
Dinitrogen monoxide	0	kg	310	0	kg CO_2e
Methane	0.00004	kg	21	0.000841	kg CO_2e
Methane, HCC-30	0	kg	9	0	kg CO_2e
Nitrogen oxides	0.010773	kg	0	0	kg CO_2e
Nonmethane VOCs	0	kg	0	0	kg CO_2e
Carbon monoxide	0.003369	kg	0	0	kg CO_2e
Total Equivalent Embodied Carbon dioxide:				1.187767	kg CO_2e

With all the equivalent CO_2 content calculated for production and transportation of materials, SOM then incorporated it into the EA Tool. But before running the analyses, the material consumption in each bridge was quantified in accordance with the EA Tool program. Figure 3.1 to 3.7 below shows the inputs required by the program from each bridge in the analysis for this thesis. As an example, the data from a prestressed bridge (C-20-AS) is included as the data input.

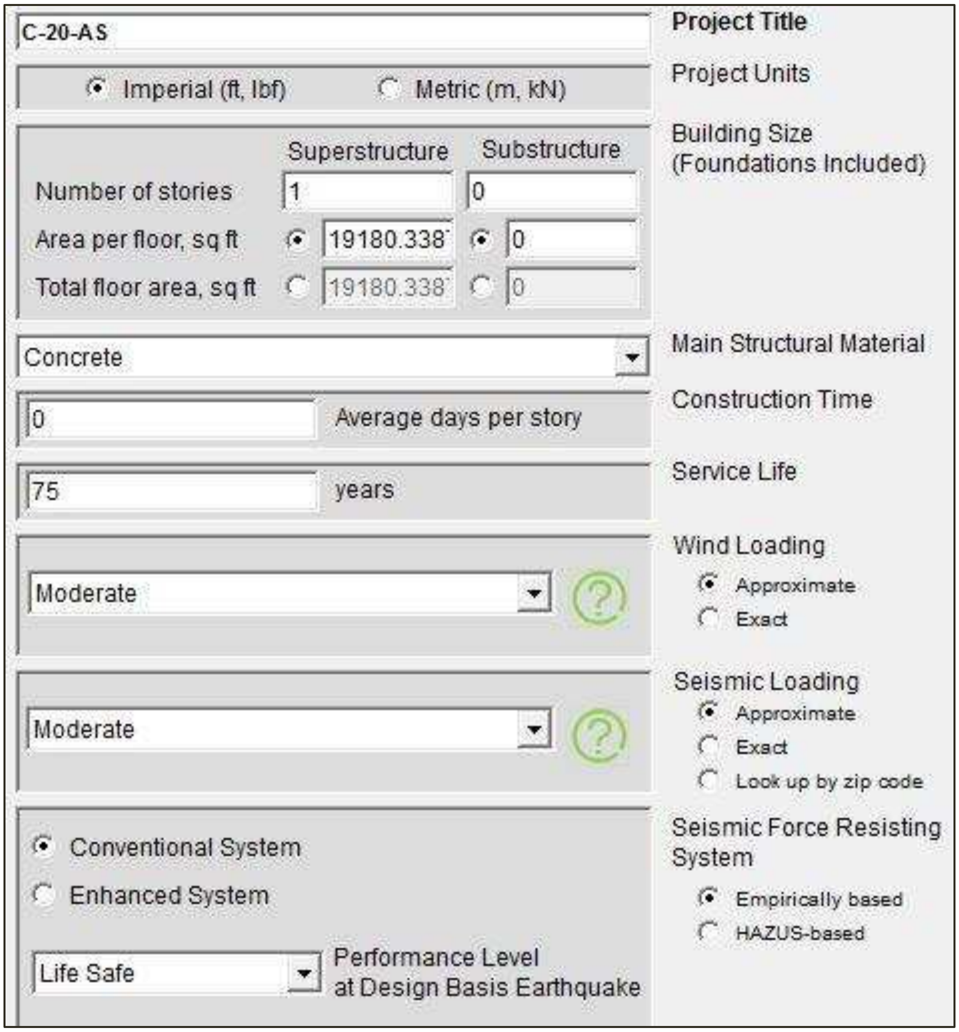

Figure 3.1: Data input section for preliminary data about bridge (EA Tool, 2013)

All the seismic and wind loading is in accordance with International Building Codes (IBC), 2006. For moderate wind loading, it is defined as forces exerted by winds of speed 45 to 58 m/s and for moderate seismic loading; it has a value of 0.38g to 0.95g for the spectral response acceleration (S_s). It can be noticed that the number of days for construction is stated to be zero. It is so because this thesis is limited to examination of the equivalent CO_2 contribution from the material production and transportation alone in the analyses.

Figure 3.2 shows the input section for materials used in the construction of the bridge. It should be noted that, in order to include the quantities of steel and concrete, it had to be separated into units of pounds of structural steel per square foot, cubic feet of concrete per square foot and pounds of rebar per square foot. Such data was collected from bridge plans provided by CDOT. Only concrete and steel present in the superstructure (slabs and girders) of the bridge were considered in this section of the input.

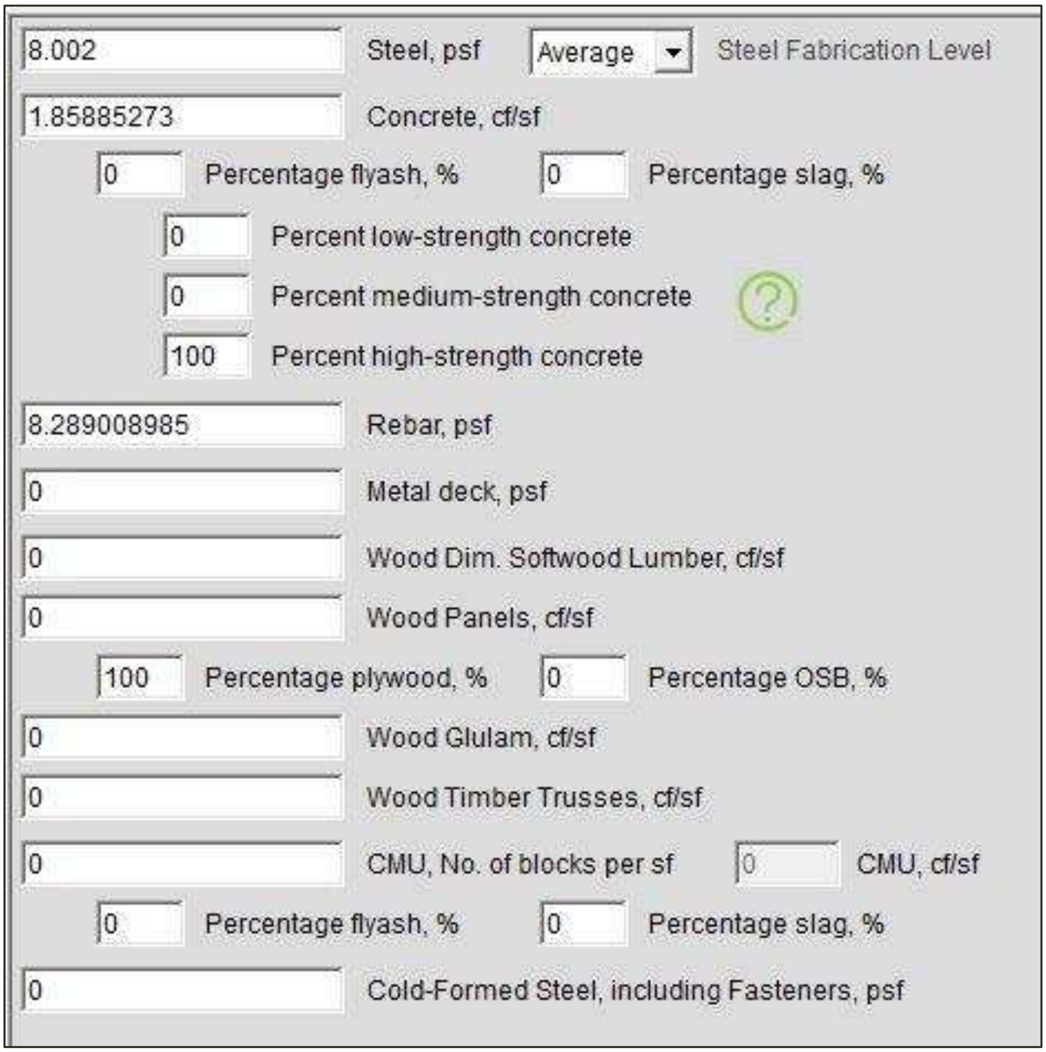

Figure 3.2: Data input section for materials used in superstructure (EA Tool, 2013)

Figure 3.3 shows the input section for data about material transportation. Distance travelled by concrete and steel before reaching the plant/work site is entered as per the assumptions in section 3.1. It can be noticed that the distance travelled by concrete is twice as much as mentioned in the assumption. Reason for doing so is to consider the return trip by the truck to the plant. Whereas for delivery of steel, it is not the same case since the trucks delivering steel typically gets another transport job assigned for their return journey (EA Tool, 2013)

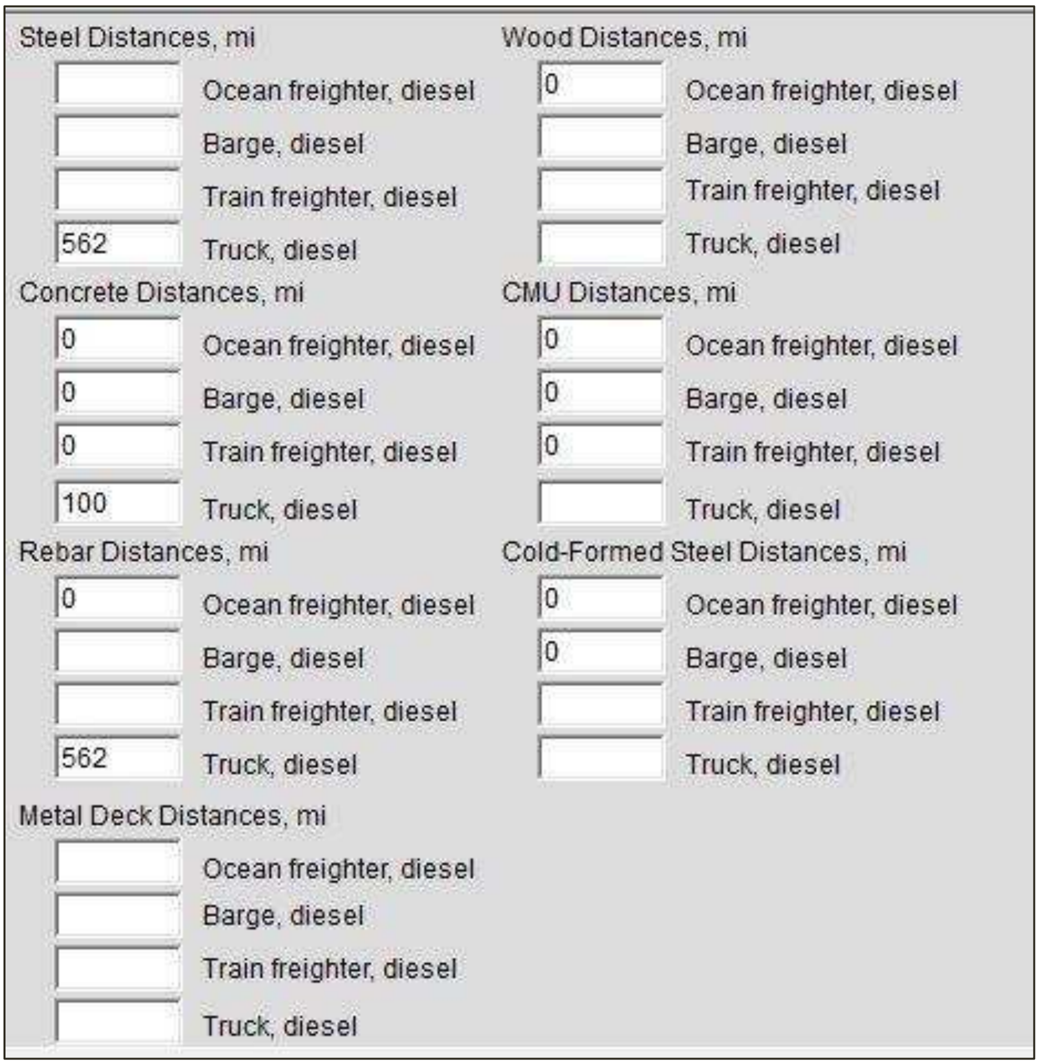

Figure 3.3: Data input section for material transportation (EA Tool, 2013)

It can be seen from Figure 3.4 and 3.5 that there is no consideration of CO_2 emission from equipment to support the construction of the bridge. Since the study focuses on prestressed and steel bridges, the usages of such equipment vary widely for construction of each bridge type and including them in the analyses can skew the results intended to obtain the CO_2 emission solely from material usage. Applying the technique described in this thesis to a specific bridge would require a list of equipment and durations from the contractor which would be relatively easy to obtain.

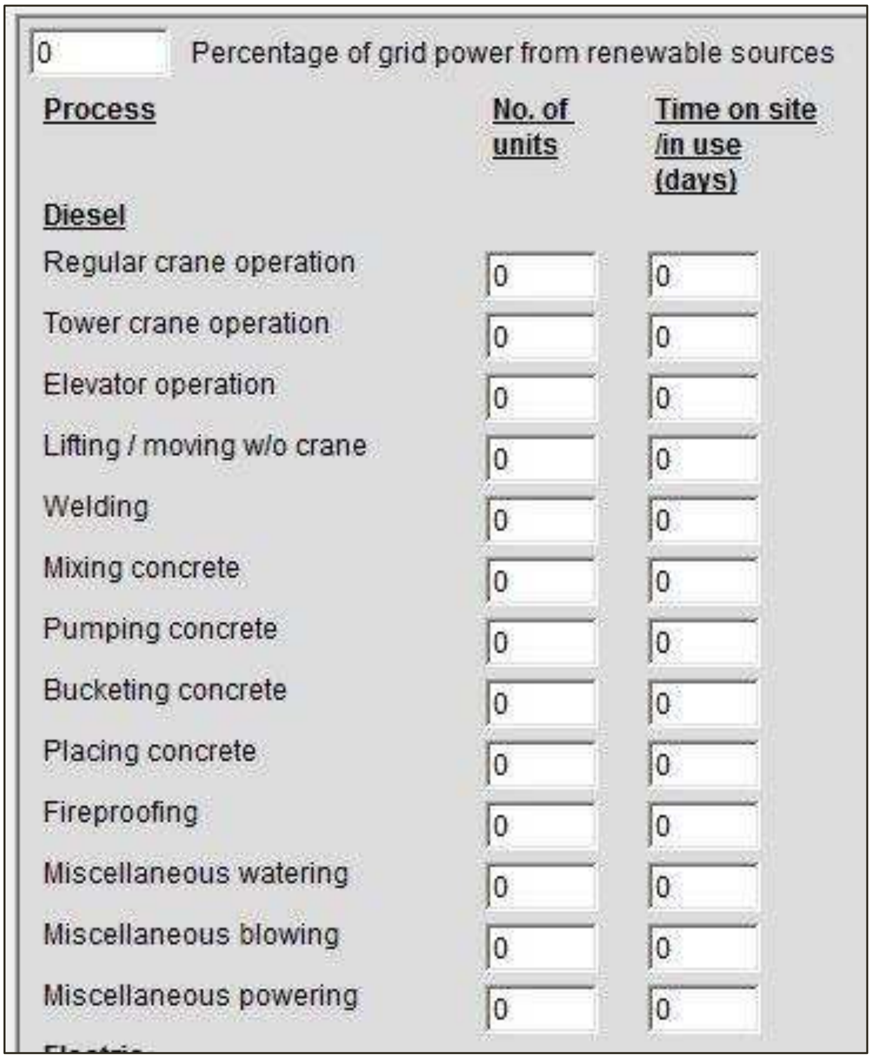

Figure 3.4: Input box for diesel construction equipment (EA Tool, 2013)

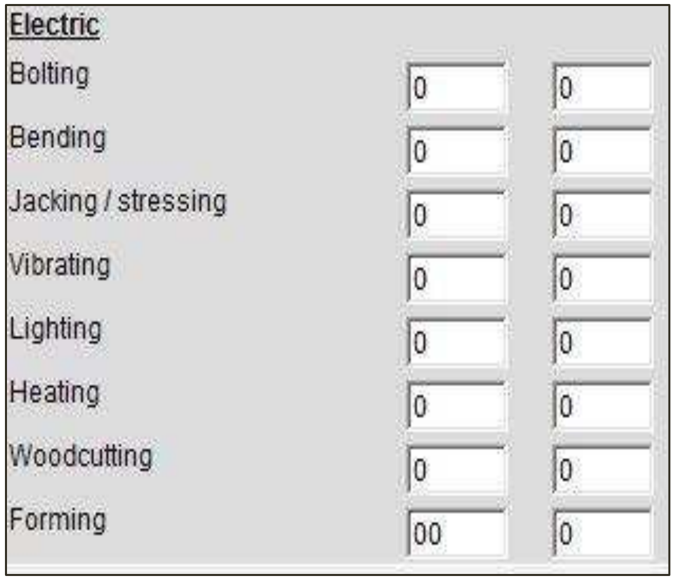

Figure 3.5: Input box for electric construction equipment (EA Tool, 2013)

Figure 3.6 shows the input section to account for probabilistic damage of the structure. This section is left as zero because the bridge is assumed to be functioning with no damage and without the need for any demolition or significant rehabilitation over a realistic analysis time frame.

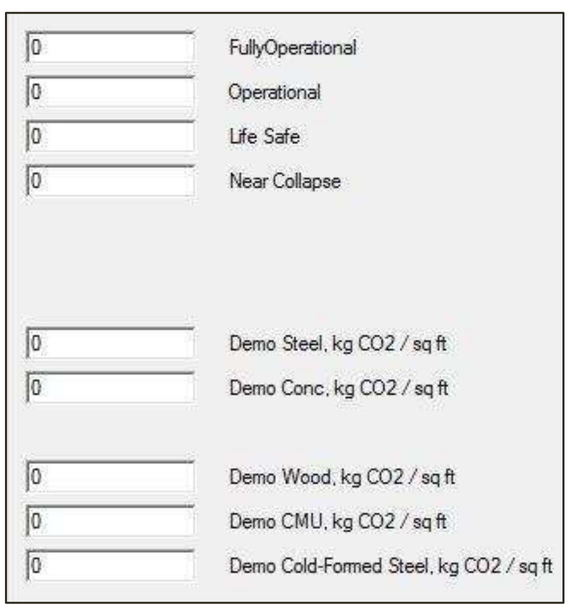

Figure 3.6: Input box for probabilistic damage (EA Tool, 2013)

With the materials in the superstructure quantified as shown in Figure 3.2, materials used in the construction of foundation is quantified as shown in Figure 3.7. Data in Figure 3.7 represents the amount of concrete and steel used in the piers and other support features of a bridge. All the data presented in this example for the bridge C-20-AS is also presented in appendix C for further reference.

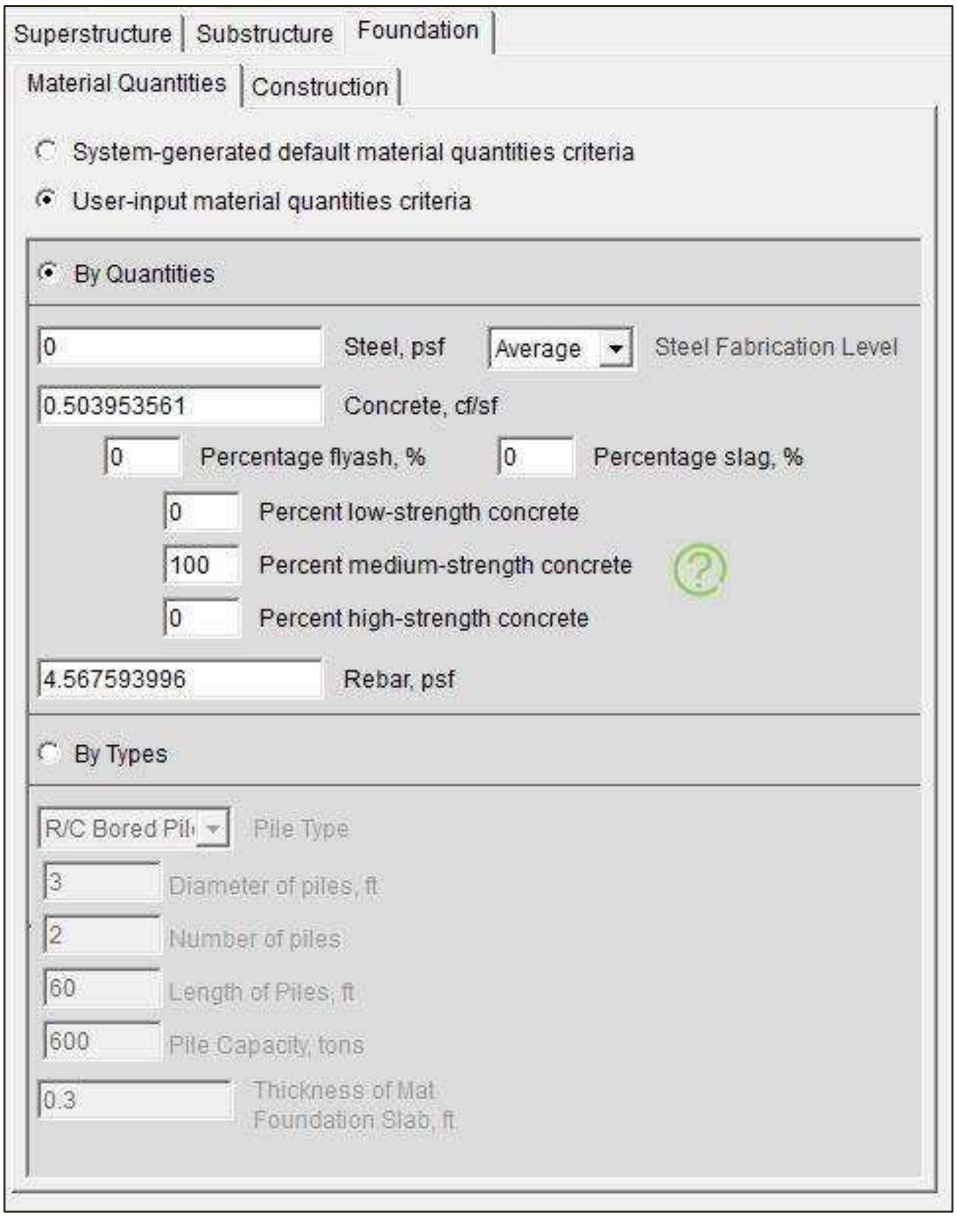

Figure 3.7: Data input section for materials in the foundation (EA Tool, 2013)

After applying the EA program with the inputs mentioned above as well the above mentioned assumptions, it returned the amount of CO_2 equivalents in tons produced during the production and transportation of materials for the bridge as shown in Figure 3.8. This procedure is repeated for all bridges within the sample size to get the total amount of CO_2 produced in the materials used for construction of each bridge.

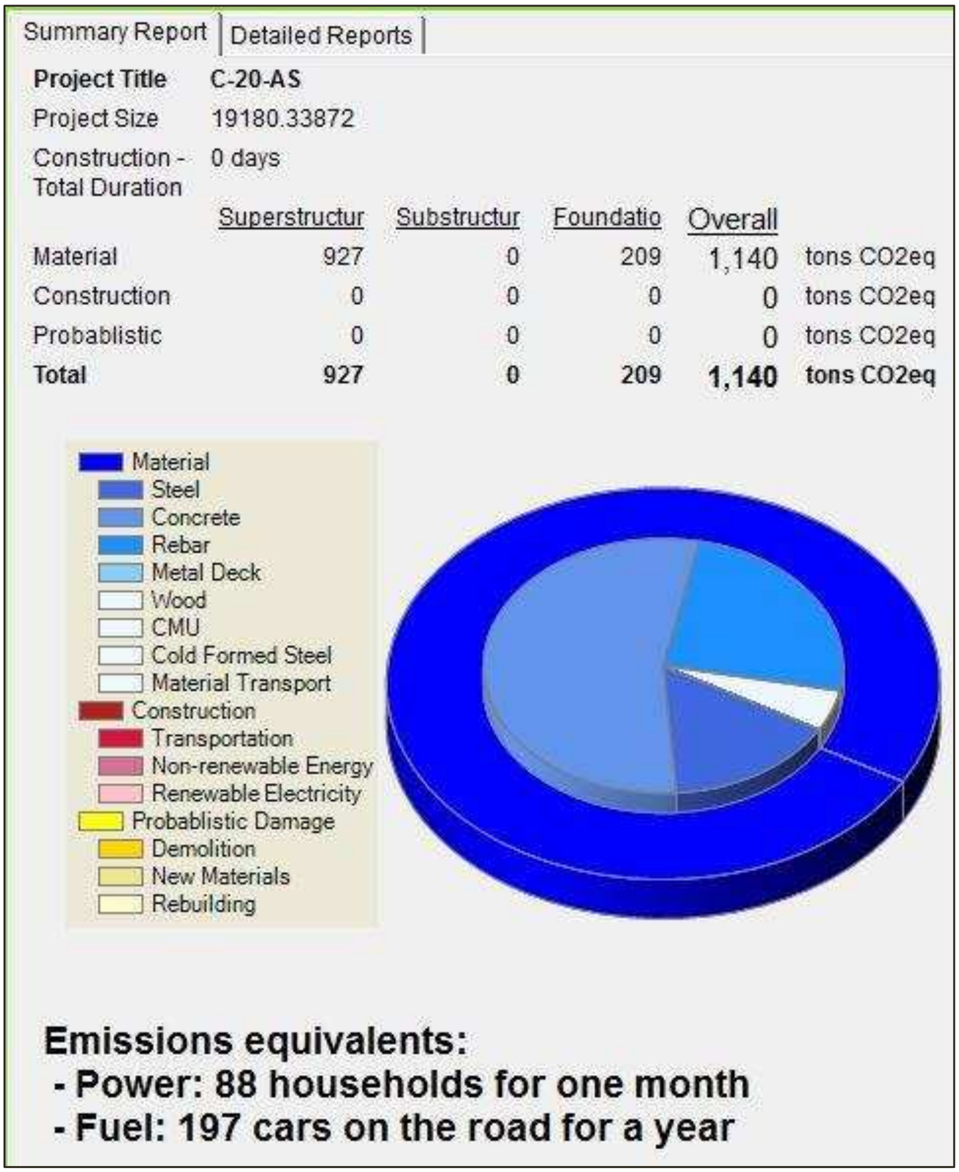

Figure 3.8: Analysis output for bridge C-20-AS (EA Tool, 2013)

It can be noticed from Figure 3.8 that the amount of equivalent CO_2 returned by the analyses is only for the production of concrete and steel and its transportation to the construction site. Doing so gives a good representation of GHG emissions solely from the use of such materials.

For analyses of alternatives for a specific bridge, the differences in CO_2 emissions for concrete vs steel construction techniques could be determined from contractor equipment and duration estimates. Additionally, differences in CO_2 emissions contributed by long-life maintenance and of life demolition could be estimated as well. To do so for a sample of 36 bridges exceeded the scope of this research.

After deriving the CO_2 consumption of each bridge before it began its service life, it is then normalized per square feet area of the deck, per lane as well as per unit width of each bridge using the Weibull plotting position. Results obtained are shown in the next section. Also a plot of total CO_2 consumption for all the bridges in the sample size was also obtained.

3.3 Results:

With the goal of developing a ranking system for sustainability of trunkline bridges, the bridges in the sample size obtained were analyzed for their CO_2 contribution. The main assumption being CO_2 contribution from bridges is an indicator of its sustainability along with other assumptions made in section 3.1 and by using the analysis method described in section 3.2 the bridges in the sample size were analyzed. After the analysis of each bridge, its CO_2 consumption was tabulated along with the CO_2 data from other bridges. The results were rank ordered to develop empirical cumulative distribution function as shown in Figure 3.9, 3.10, 3.11 and 3.12

Figure 3.9 shows the amount of CO_2 produced by bridges in Colorado based on the sample of 36 bridges. From the plot, it can be understood that at least 20% of the bridges in Colorado produced more than 4000 tons of CO_2 from solely the essential structural materials used in them with the minimum amount of CO_2 emission from the materials being 703 tons.

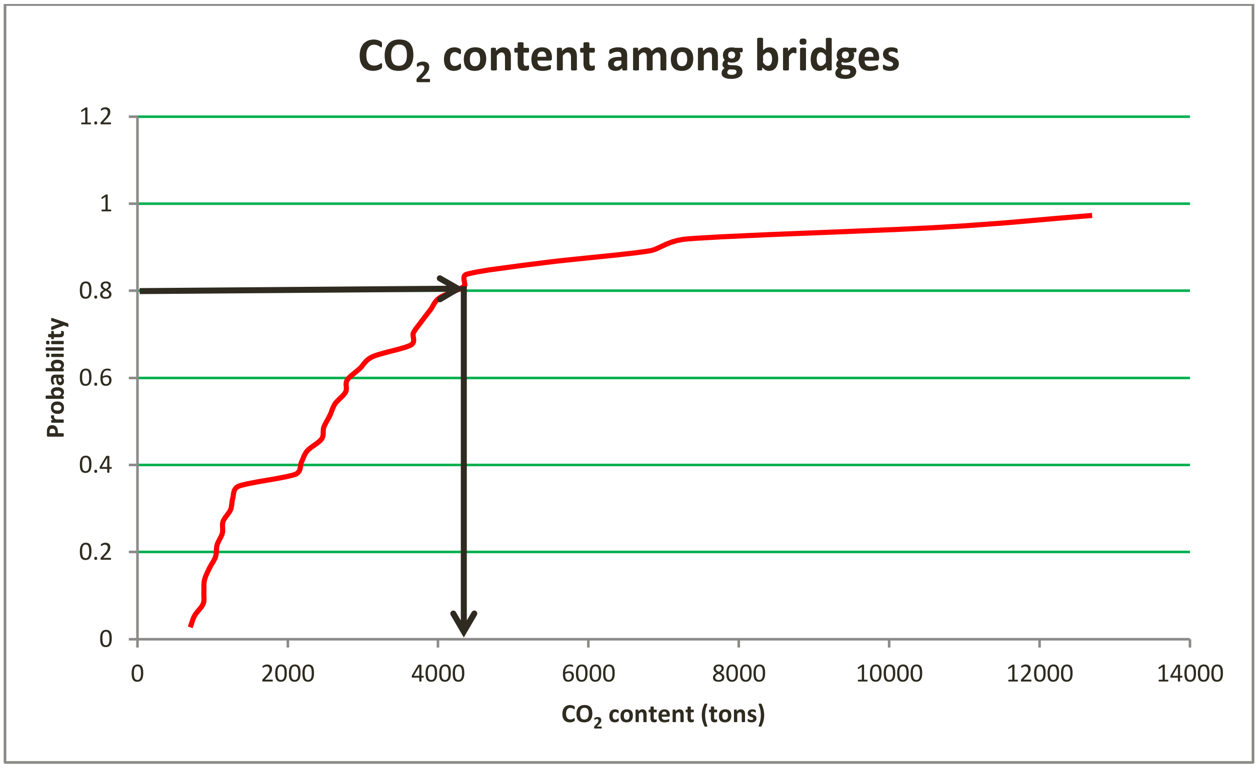

Figure 3.9: CO_2 content among bridges in Colorado

Figure 3.10 shows the cumulative distribution function of CO_2 content in tons per square feet area of the deck. It suggests the amount of CO_2 emission is in direct correlation with the deck area. By using the probability scale on the y axis, it is possible to derive the probability of achieving the status of sustainability which is determined by using the ranking system discussed later.

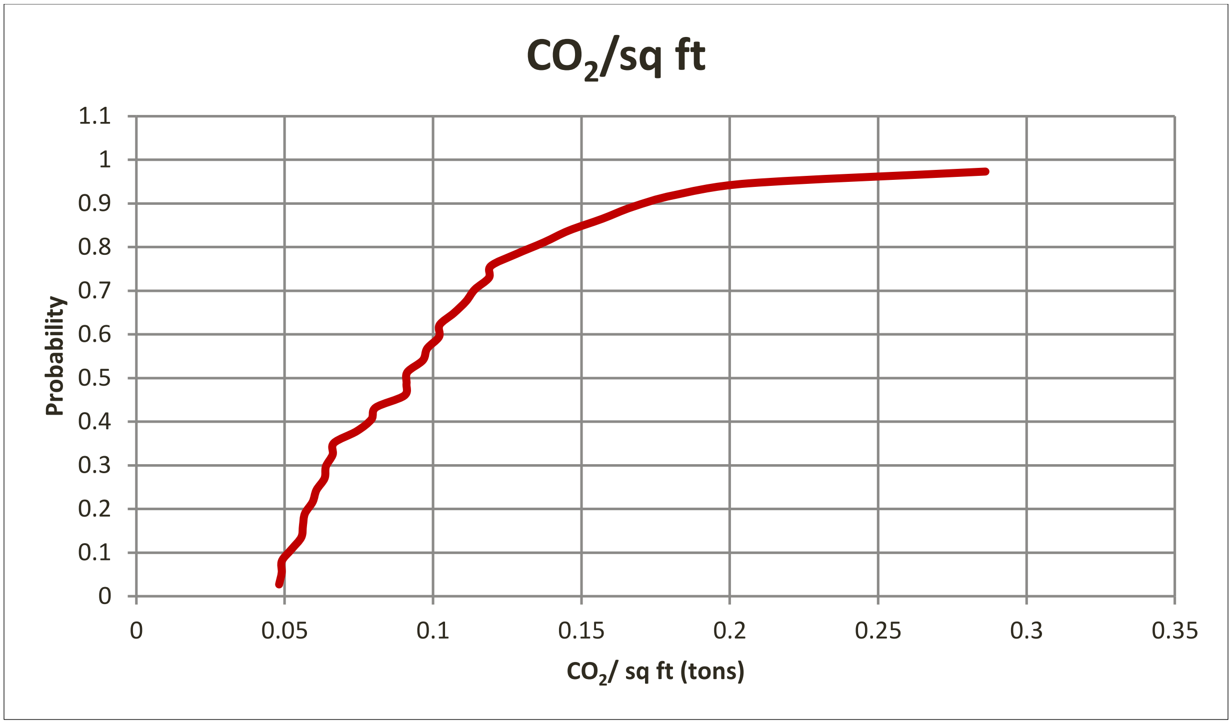

Figure 3.10: CO_2 content per square feet area of deck

Figure 3.11 shows the amount of CO_2 content in tons present per lane of any given bridge.

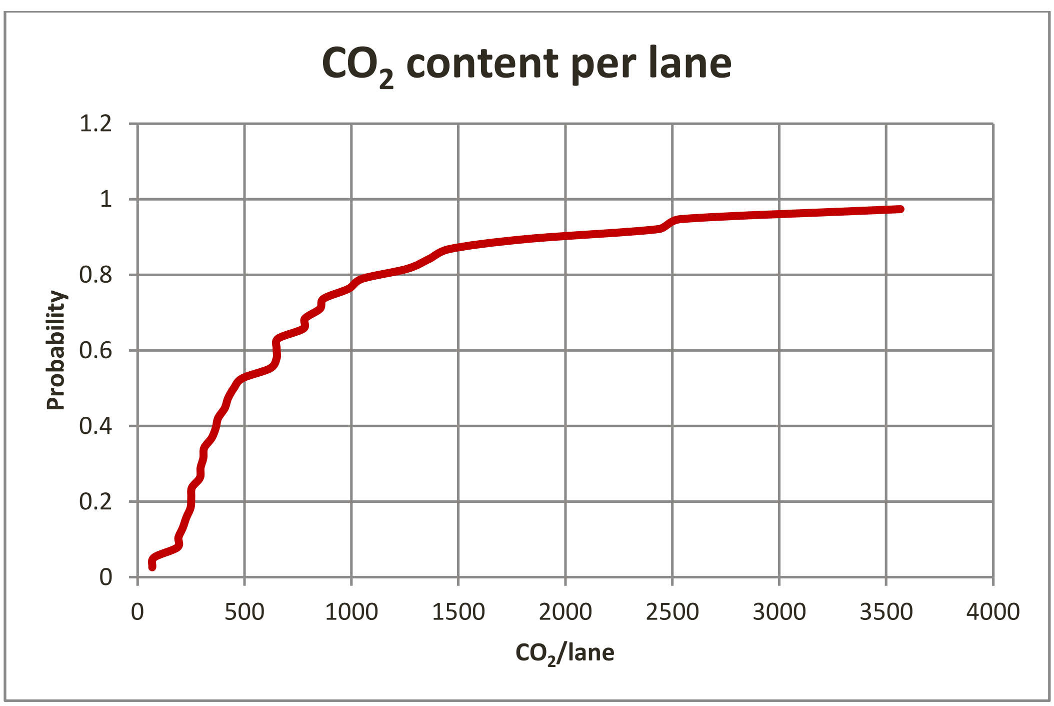

Figure 3.11: CO_2 content per (12'feet wide) lane

Figure 3.12 shows the CO_2 content in tons per unit width of the bridge. For this plot, areas occupied by a strip of bridge deck of length 1 foot spanning the total width of lanes were considered. It was then used to divide the total amount of CO_2 contribution by the bridge which was repeated for the bridges in the sample size. Graphs such as this also correlates to the CO_2 content per lane of a bridge suggesting wider bridges contribute to higher CO_2 emissions obviously since they are larger and require more construction materials.

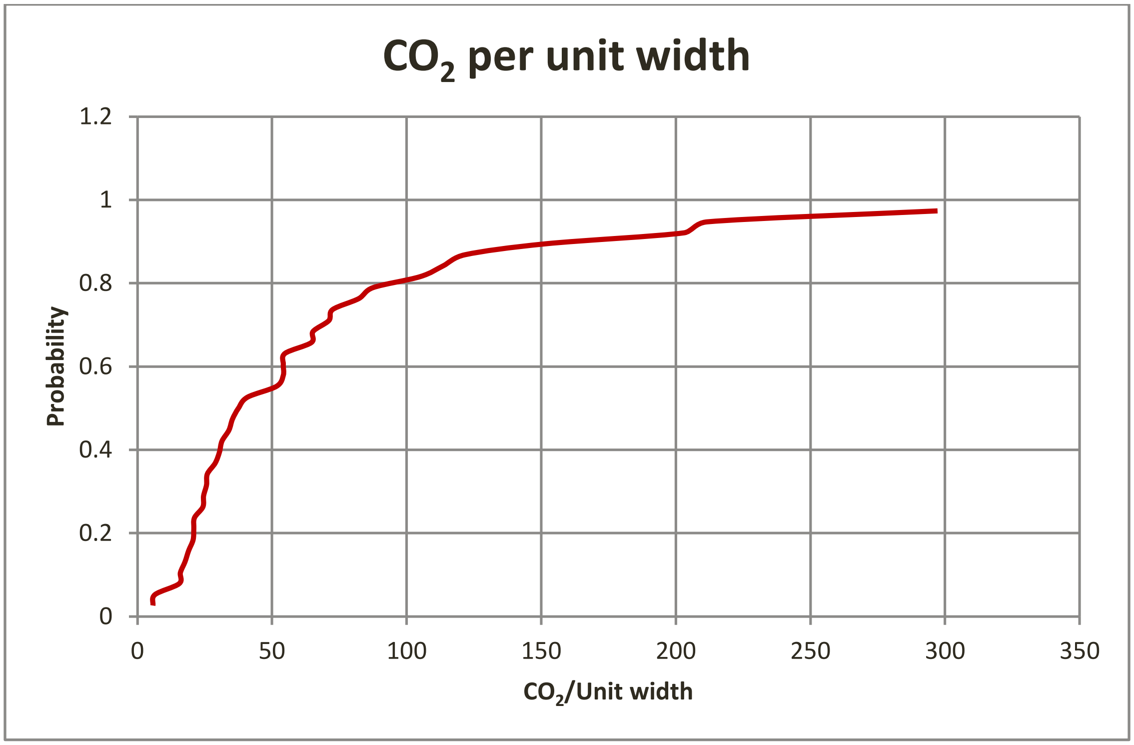

Figure 3.12: CO_2 content per unit width (1 feet) of bridge

3.4 Discussion:

The reason for the existence of general/universal sustainable rating systems is that they provide guidance for designing and constructing structures of a sustainable nature. By having such rating systems, it also becomes easier for its stakeholders to save time and money by targeting and turning their design and construction process toward the attributes deemed to be beneficial. Evidence indicates that the sustainable buildings do attract higher rents than conventional buildings and also enjoy higher rates of rental growth (CBRE, 2009). Improved marketability for sustainable buildings is the main current competitive advantage which reduces vacancy times and hence income losses (McKee, 1998). Such advances greatly help route the attention of suppliers into making environmentally friendly materials to satisfy the rating systems and may motivate public entities such as CDOT to invest in eco-friendly infrastructure projects.

The study started out with the compilation of a number of green building rating systems available and analyzing their potential for application to bridges. Criteria in the rating systems fit to be applied into bridges were grouped under general categories of sustainability in materials, energy, site selection, air quality and water usage. After grouping the criteria, one of the criteria, material sustainability in terms of carbon footprint was then used as a surrogate for general sustainability and illustrated in Chapter 3. After making assumptions described in section 3.1 and under the procedure described in section 3.2, results were obtained as shown in section 3.3. Using the analyses results and with the primary objective of developing a preliminary rating system for quantifying sustainability in bridges, a simple rating system was formulated. It is developed with the idea of eventually extending the concept of sustainability to more than material usage in a bridge and to provide a general guideline on how to achieve further quantification of sustainability in bridges. A breakdown of the proposed rating system is shown in Table 3.10.

Table 3.10: Ranking system for CO_2 content per square feet

Position on CDF	Corresponding ranking	CO_2/sq ft (tons)
$0 \geq y \geq 0.2$	Superior	0-0.143
$0.2 > y \geq 0.5$	Excellent	0.143-0.164
$0.5 > y \geq 0.8$	Acceptable	0.164-0.217
$0.8 > y \geq 0.9$	Poor	0.217-0.291
$0.9 > y \geq 1.0$	Unacceptable	0.291-0.496

The above mentioned rating system in Table 3.10 is also shown in figure form in Figure 3.13. CO_2 per square feet was chosen for applying the ranking system since the area of the deck is directly proportional to the number of lanes as well as area per unit width of the bridge. The bridges subjected to the analysis only comply with the assumptions stated in section 3.1 and 3.2. While the ranking system outlined in Table 3.10 is somewhat arbitrary, it is not without logic. The divisions in the ranking boundaries generally align with changes in the slope of the CDF curve. For example, the ranking system effectively states that bridges that match those in the lower 20% be will deemed superior, while bridges matching those in the upper 20% will be poor or unacceptable. Figure 3.13 shows the division in the empirical CDF for clarity.

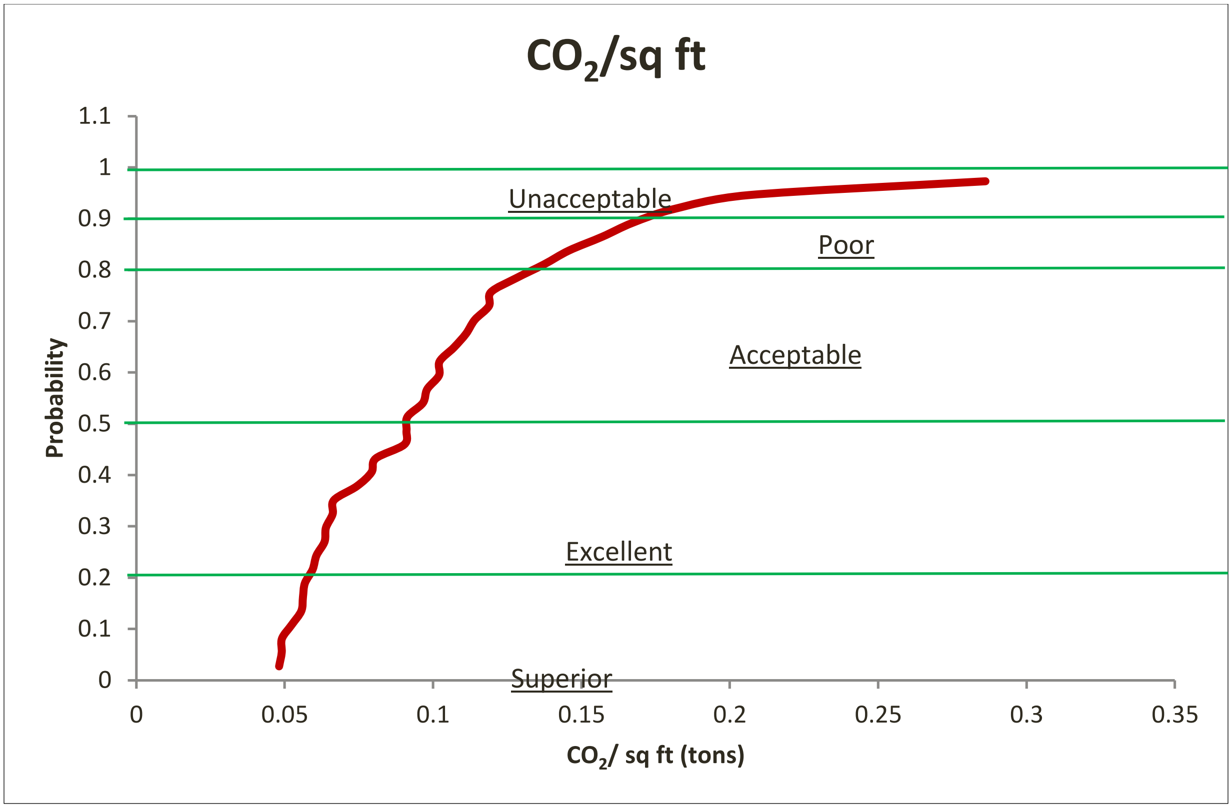

Figure 3.13: Ranking system for CO_2 content per square feet of deck area

Chapter 4- Summary, Conclusions and Recommendations

Recall the objective of this study was to develop a preliminary bridge sustainability rating system for trunkline bridges in the Mountain Plains region of the United States. Initially, a number of popular green building rating systems identified were assessed. They were analyzed to identify common characteristics among them in order to understand the most important attributes for sustainability in buildings and they were further refined for their applicability to bridges. After identifying certain criteria, one criterion- material sustainability in terms of carbon footprint, was selected as a surrogate for developing a ranking system for sustainability of bridges. Sustainability in materials were measured based on the equivalent amount of CO_2 emitted by the main materials (concrete and steel) used in the bridge.

Then, a sample of 36 bridges was selected based on a set of criteria and analyzed for its equivalent CO_2 contribution by the main material used in the construction. Analyses for this were done using the Environmental Analyses (EA) Tool developed by Skidmore, Owings & Merrill, LLP. After calculating the equivalent CO_2 contribution of each bridge's materials, they were normalized based on CO_2/square feet area, CO_2/lane and CO_2/ unit.CO_2/ square feet of deck area as shown in Figure 3.10, was chosen for developing the ranking system as described in Table 3.10 as well as in Figure 3.13.

Using basic rank-ordering for the CO_2 emissions per square foot of bridge deck allowed a simple statistical division to be made for five different sustainability ratings, namely superior, excellent, acceptable, poor and unacceptable. Each rating corresponds to a percentile within the 36 bridge population used in the analysis.

From analyzing the ranking of bridges, it was found that prestressed bridges have the least amount of CO_2/sq foot compared to steel bridges for this simplified approach. Among bridges ranked superior to excellent, 66.7% were presetressed bridges and 33.3% were steel bridges. Similarly, among bridges ranked from acceptable to poor, prestressed bridges comprised 14.3% of the sample size and the remaining 85.7% were steel bridges.

One of the major areas where the study could be improved in future analyses is in the sample size of the bridges considered as well as in incorporating direct and indirect GHG emission from the construction processes and end-of-life demolition. With the increase in size of the sample from 36, the ranking system developed can offer more credibility in awarding a specific bridge with its ranking. Similar to increasing the sample size, the number of materials considered in the prediction of CO_2 contribution of the bridge should also be increased. Since only concrete and steel are considered in this study, it should be expanded to include formwork (for cast in place concrete), asphalt pavement, sidewalk, architectural components, railings, street lamps etc. Furthermore, it can be expanded to include different direct and indirect processes that are essential for the construction and proper functioning of the bridge but is also an important factor in GHG contribution. Doing so can give precise results and hence help in deciding whether the bridge is sustainable not only during construction but also its operation.

The results of this study are preliminary and not intended to be used for applications related to design selection.

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Appendix A

BRIDGE KEY	LENGTH (m)	MAX SPAN	MAIN SPANS	DECK WIDTH (m)	FEATURE INTERCEPTED	FACILITY	YEAR BUILT
E-17-QN	95.77	48.80	2	14.72	I 25 ML	RAMP TO US 36 WB	1998
F-16-WO	122.77	47.55	3	19.20	WADSWORTH BLVD	RTD LIGHT RAIL	2010
F-16-XG	237.35	85.83	1	10.15	US 6 AND FRONTAGE RD	RTD LIGHT RAIL	2010
F-16-XE	466.80	82.30	3	6.10	US6 AND INDIANA	RTD LIGHT RAIL	2010
E-17-RC	101.35	58.34	2	32.92	I 25 ML	SH 53 ML	1992
E-17-NZ	166.45	68.98	3	21.34	I 25 ML R	RAMP TO I 76 WBND	1991
E-17-QS,QT	101.29	54.86	2	17.98	I 270 ML	I76 ML EBND & WBND	2003
E-17-QM	256.44	57.61	5	17.70	I 25 ML, RAMPS	I 270 WBND ML	1998
E-17-SW	599.54	85.34	8	14.33	I 70 ML	I 225 ML SBND	1994
E-17-OQ	121.01	46.33	3	41.15	28TH & 30TH AVE,SAND CRK	I 225 ML	1990
E-17-OO	211.84	51.41	5	31.39	I 25 ML	US 224 ML	1991
E-17-OC,OD	172.21	70.71	3	12.50	I 25 ML	I 76 ML EBND & WBND	1990
D-20-AT	139.90	36.60	4	9.30	I 76 ML R	RAMP TO I 76 EBND	1993
E-16-MR,MS	697.53	71.93	13	17.98	I 25 ML & RAMPS	I 70 ML EBND & WBND	1991
E-16-ND	589.00	64.01	11	10.97	I 25 ML, I 70 ML,RAMPS R	RMP I70EB TO I25NB	1992
E-16-OO	85.50	43.21	2	25.15	I 25 ML	20TH STREET	1994
E-16-PJ	167.18	66.45	3	11.28	RAMP TO I 70 WBND R	RAMP TO I 70 WBND	1993
E-17-ABJ	245.55	67.43	4	9.14	NWP	Ramp B	2003
E-16-NJ	136.55	47.98	3	54.44	BNSF RR, UP RR	I 70 ML	1992
G-17-CS	155.75	55.17	4	5.82	I25 ML	UPRR	2005
G-17-DA	171.45	67.06	3	12.50	I25 ML & PLUM CREEK	5TH ST.	2001
E-17-PC	70.41	50.29	3	10.67	RAMP TO I 70 WBND R	RAMP TO I 70 EBND	1993
B-16-GK	69.53	17.01	4	34.44	CACHE LA POUDRE RIVER	US 287 ML	1995
B-17-DS	98.48	57.99	3	33.60	I 25 ML	OLD SH 68 ML	1999
C-17-FO	73.36	36.42	2	18.17	US 34 BYPASS	SH 257 ML	1999

C-17-FP	80.53	41.00	2	18.17	US 34 BYPASS	SH 257 ML	1999
C-20-AS	160.17	31.39	5	11.13	S. PLATTE RIVER OVERFLOW	SH 39 ML	1996
C-20-AT	96.16	31.39	3	11.13	SOUTH PLATTE RIVER	SH 39 ML	1996
C-20-Q	151.33	37.79	4	11.28	SOUTH PLATTE RIVER	SH 144 ML	2001
C-21-BL	187.45	26.52	7	11.13	SOUTH PLATTE RIVER	SH 144 ML	1996
D-20-AS	118.45	23.77	5	12.34	KIOWA CREEK	I 76 ML EBND	1993
C-21-BM	106.70	52.70	2	14.17	I 76 ML R	RAMP TO I 76	1995
D-17-DJ	73.61	35.69	3	18.72	SH 119 ML	I 25 ML SBND	1998
E-16-QU	99.00	48.86	2	17.47	US 36 ML	88TH ST.	2000
D-15-BO	95.71	47.33	2	14.94	US 36 SPUR/BASELINE RD	US 36 WBND SPUR	1993
D-20-AR	118.42	23.70	5	12.32	KIOWA CREEK	I 76 ML WBND	1993

Appendix B

Table B1: Equivalent CO_2 content in 1kg of cement

For 1.0 kg of cement:	**Emission:**	**Unit**	**Factor**	**Emission**	**Unit**
Embodied carbon dioxide	0.92703	kg	1	0.92703	kg CO_2e
Other GHG's:					
Dinitrogen monoxide	0	kg	310	0	kg CO_2e
Methane	0.00004	kg	21	0.00083	kg CO_2e
Methane, HCC-30	0	kg	9	0	kg CO_2e
Nitrogen oxides	0.002503	kg	0	0	kg CO_2e
Nonmethane VOCs	0.00005	kg	0	0	kg CO_2e
Carbon monoxide	0.001105	kg	0	0	kg CO_2e
Total Equivalent Embodied Carbon dioxide:				0.92786	kg CO_2e

The emissions data for the manufacturing of sand and aggregates is determined by obtaining the required energy for the manufacture of 1 kg of the substance (in joules) and then multiplying this value by the known emissions associated with the production of 1 Mega-joule of energy, assuming average contributions from various sources for the production of that energy. The energy required for the manufacturing of sand and aggregates are given in the PCA Report (PCA, 2007) as 23.19 kj and 35.44 kj respectively. The emission value associated with 1 MJ of energy is given in Table 3.3 of this report. (SOM, 2013). Fly ash and silica manufacturing does not require any energy since they are the byproducts of other processes and they require no additional processing to be used in concrete other than its transportation. Slag manufacturing requires energy to be granulated, dewatered, crushed, ground and stored before adding to concrete. Therefore the upstream energy is taken equal to 0.72 MJ/ 1kg of slag given by PCA report (SOM, 2013 & PCA, 2007).

Additionally, the distance travelled by silica fume, fly ash and slag contributes to the equivalent CO_2 content. Such emissions are tabulated in the Table B2 organized based on the modes of transportation (PCA, 2007). Each mode applies to a corresponding fraction of the unit of material considered and emissions from each mode need to be summed; refer to the transportation emissions section of this report (Table 3.7) for data for 1 ton*km unit transport by each mode (SOM, 2013).

Table B2: Equivalent CO_2 emission in

Material	**Truck**		**Rail**		**Barge**	
	Fraction	km	Fraction	km	Fraction	km
Fly ash, silica fume, slag	0.951	146	0.039	146	0.01	702

Table B3: Equivalent CO_2 content for different concrete strengths

	Low-strength Type Mix (kg)			**Average-strength Type Mix (kg)**			**High-strength Type Mix (kg)**		
Mixture	0% Fly Ash and Slag	5% Fly Ash, 5% Slag	10% Fly Ash, 10% Slag	0% Fly Ash and Slag	5% Fly Ash, 5% Slag	10% Fly Ash, 10% Slag	0% Fly Ash and Slag	5% Fly Ash, 5% Slag	10% Fly Ash, 10% Slag
Cement	0.093	0.084	0.074	0.132	0.119	0.106	0.2	0.18	0.16
Sand	0.286	0.286	0.286	0.273	0.273	0.273	0.25	0.25	0.25
Coarse Aggregate	0.571	0.571	0.571	0.545	0.545	0.545	0.5	0.5	0.5
Water	0.013	0.013	0.013	0.025	0.025	0.025	0.013	0.013	0.013
Fly Ash	0	0.005	0.009	0	0.007	0.013	0	0.01	0.02
Slag	0	0.005	0.009	0	0.007	0.013	0	0.01	0.02
TOTAL kg:	1	1	1	1	1	1	1	1	1
TOTAL kg CO2:	0.092	0.084	0.076	0.128	0.116	0.105	0.19	0.173	0.156

Table B4: Equivalent CO_2 content for each component in concrete

Substance (1 kg)	**kg CO_2 (equivalent)**
Cement	0.928
Sand	0.005
Coarse Aggregate	0.007
Fly Ash or Silica Fume	0.011
Slag	0.151

Appendix C

AS CONSTRUCTED

NO REVISIONS REVISED VOID

FEDERAL ROAD REGION NO.	DIVISION	PROJECT NUMBER	SHEET NO.
VIII	COLORADO	BRS 0039(3)	49-A

REVISIONS

SUMMARY OF QUANTITIES

	ITEM NO.	DESCRIPTION	UNIT	SUPER STRUCTURE	APPROACH SLAB	ABUT. 1	PIER 2	PIER 3	PIER 4	PIER 5	ABUT. 6	APPROACH SLAB	TOTAL
	202	REMOVAL OF BRIDGE	EACH										1
	206	STRUCTURE BACKFILL (FLOW-FILL)	C.Y.			117					168		285
	206	STRUCTURE BACKFILL (CLASS 1)	C.Y.			245					294		539
	403	HOT BITUMINOUS PAVEMENT (GRADING CX) (ASPHALT) (C 50)	TON	218	5							5	228
	502	STEEL PILING (HP12x74)	L.F.			1043					1043		2086
①	503	DRILLED CAISSON (60 INCH)	L.F.				221	221	221	221			884
②	503	CAISSON (SPECIAL)	L.F.				110.5						110.5
	513	BRIDGE DRAIN (SPECIAL)	EACH	6									6
	515	WATERPROOFING (MEMBRANE)	S.Y.	1982	47							47	2076
	518	BRIDGE EXPANSION DEVICE (0-4 INCH)	L.F.		34							34	68
	601	CONCRETE CLASS B (BRIDGE)	C.Y.			19					34		53
	601	CONCRETE CLASS D (BRIDGE)	C.Y.	717	24	20	53	54	55	55	20	24	1022
	601	STRUCTURAL CONCRETE COATING	S.F.	10486		485	930	955	975	984	666		15481
	602	REINFORCING STEEL	LB.	55776	3532	8157	15165	15420	15595	16385	9822	3532	143384
	602	REINFORCING STEEL (EPOXY COATED)	LB.	103210									103210
	603	24 INCH CORRUGATED STEEL PIPE	L.F.			60						60	120
	606	BRIDGE RAIL TYPE 10	L.F.	1135									1135
	618	PRESTRESSED CONCRETE UNIT (BULB T SECTION)(100 TO 105 FEET)	EACH	35									35
	625	CONSTRUCTION SURVEYING	L.S.										0.3
	626	MOBILIZATION	L.S.										0.3
	700	MINOR CONTRACT REVISIONS	F.A.										0.3

① INCLUDES APPROXIMATELY 643 C.Y. CONCRETE CLASS BZ (SPECIAL)

② INCLUDES APPROXIMATELY 81 C.Y. CONCRETE CLASS BZ (SPECIAL) and 120 L.F. of Permanent Casing (60 Inch).

NOTE:
REFER TO ROADWAY "STRUCTURE QUANTITIES LIST" SHEET FOR TABULATION OF SPUR DIKE QUANTITIES.

DEPARTMENT OF TRANSPORTATION

ALTERNATE A:
DRILLED CAISSON PIER FOUNDATIONS
S.H. 39 OVER SOUTH PLATTE RIVER
NEAR GOODRICH

SUMMARY OF QUANTITIES

Designer G. Tsiouvaras	Structure Numbers	C-20-AS	
Detailer T. Rick			
Drawing Number	B2-A of	36	Drawings

Revision Dates (Preliminary Stage Only)

NORTH BRIDGE