Life Cycle Assessment & Life Cycle Cost Analysis of a Reinforced Concrete Bridge Deck

A case study comparing conventional, epoxy-coated, continuously galvanized, and stainless steel rebar

On behalf of the International Zinc Association

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On behalf of thinkstep AG and its subsidiaries

Document prepared by	**Nicholas Santero**
Title	Senior Consultant
Signature	
Date	July 13, 2015
	Maggie Wildnauer
Title	Consultant
Signature	M Wildnauer
Date	July 13, 2015
Quality assurance by	**Peter Shonfield**
Title	Technical Director
Signature	P. Shonfield
Date	July 13, 2015
Under the supervision of	**Susan Murphy**
Title	NA Service Delivery Manager
Signature	Susan Fredlund Murphy
Date	July 13, 2015

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Executive summary

Reinforced concrete is comprised of two basic materials: concrete and steel reinforcing bar (rebar). The compressive strength of the concrete is complemented by the tensile strength of the steel, creating a versatile and resilient structure that is used ubiquitously in construction applications. This project examines the rebar component of the reinforced structure and the effect that different rebar types have on the economic and environmental performance of a reinforced concrete structure over its life cycle.

Using life cycle cost analysis (LCCA) and life cycle assessment (LCA), the following types of rebar are examined in this project:

- Black steel
- Epoxy-coated steel
- Continuously galvanized steel
- Stainless steel[1].

The corrosion characteristics, costs, and environmental impacts of each rebar type (as used in a reinforced concrete bridge deck) are evaluated over a 100-year analysis period. Because corrosion depends on climate region and exposure conditions, four different scenarios are examined:

- Calgary: Parking Garage exposure
- Jacksonville: Tidal Zone exposure
- Nashville: Urban Highway exposure
- Tucson: Rural Highway exposure.

The results of the LCA demonstrate that the use of continuously galvanized rebar provides environmental benefits over epoxy-coated and black steel when in moderate- to highly-corrosive exposure scenarios due to its superior corrosion resistance. In highly-corrosive environments, stainless steel outperforms all other rebar alternatives. In exposure scenarios where corrosion risk is low (represented by Tucson), the environmental impacts between the rebar types are similar to one another, with a slight advantage to the structure using black steel. An example of the results for global warming potential is shown in Figure E-1.

[1] The stainless steel evaluated in this study is SAE 316, which is considered a "true stainless." There are a variety of other steel alloys available, including low-alloy products that are known to have a lower price and lower performance. This study only evaluates the high-performing and industry-standard stainless steel rebar.

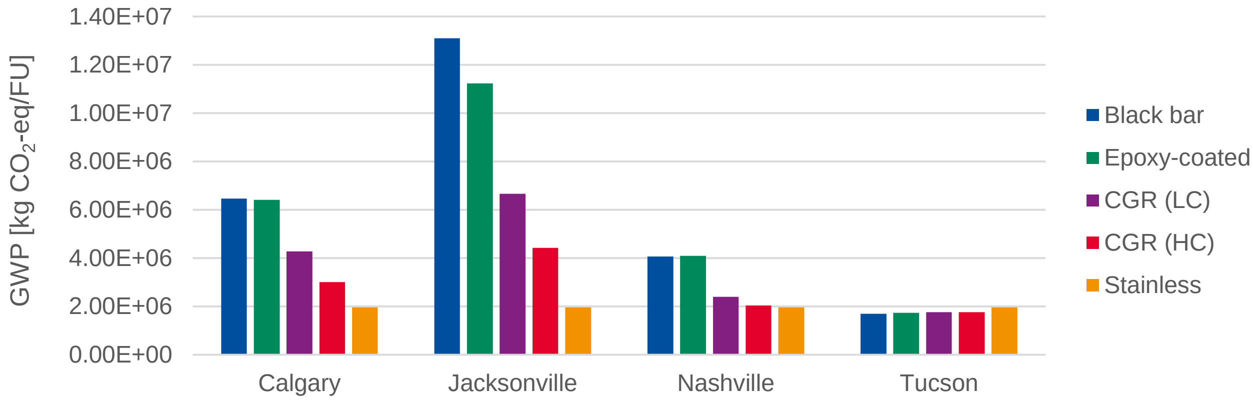

Figure E-1: Total life cycle GWP for all rebar and exposure scenarios

The LCCA results demonstrate that the continuously galvanized rebar has a lower net present cost than all other rebar types under all conditions; the exception is in low corrosion environments (represented by Tucson), where black steel has a slightly lower net present cost. The results are marginally sensitive to discount rate; lower discount rates favor structures with lower first costs (e.g., black steel), while higher discount rates favor structures with higher first costs and lower maintenance and reconstruction costs (e.g., stainless steel).

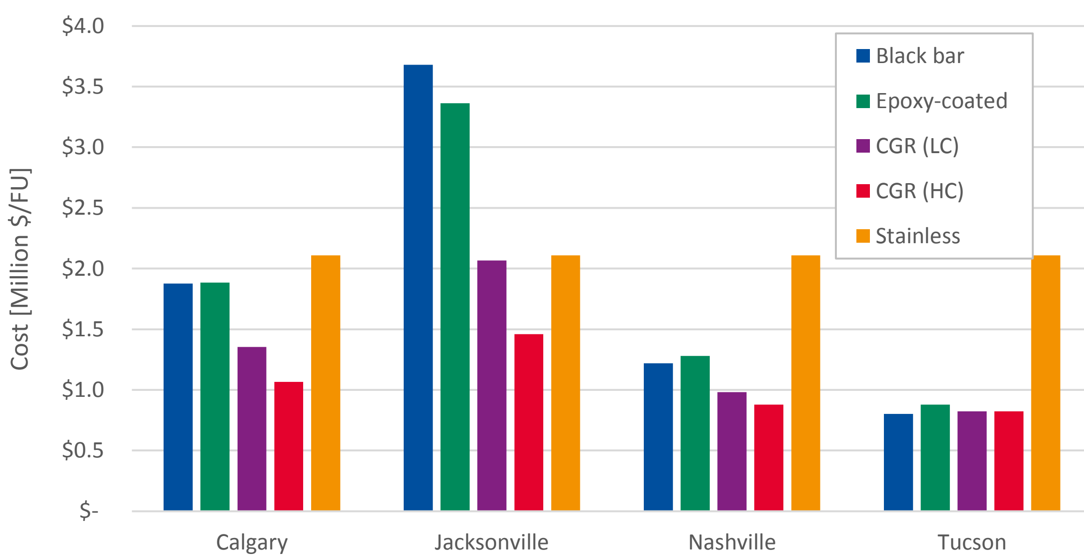

Figure E-2: Complete life cycle NPC for all rebar and exposure scenarios

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Acronyms

ACI	American Concrete Institute
AP	Acidification Potential
EOL	End-of-Life
EP	Eutrophication Potential
CGR	Continuously Galvanized Rebar
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	High Corrosion Threshold
ILCD	International Life Cycle Data System
ISO	International Organization for Standardization
LC	Low Corrosion Threshold
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
SFP	Smog Formation Potential
USGS	United States Geological Survey

Glossary (ISO 14040/44:2006)

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Functional Unit

Quantified performance of a product system for use as a reference unit.

Close loop & open loop

A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.

An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

Cradle-to-grave

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of life.

Life cycle

A unit operations view of consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. This includes all materials and energy input as well as waste generated to air, land and water.

Life Cycle Assessment - LCA

Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle.

Life Cycle Inventory - LCI

Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact assessment - LCIA

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation

Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

1. Introduction

Reinforced concrete is comprised of two basic materials: concrete and steel reinforcing bar (rebar). The compressive strength of the concrete is complemented by the tensile strength of the steel, creating a versatile and resilient structure that is used ubiquitously in construction applications. This project examines the rebar component of the reinforced structure and the effect that different rebar types have on the economic and environmental performance of a reinforced concrete structure over its life cycle.

Conventional reinforcing steel bar, also known as black steel or black bar, is unfinished tempered steel. This type of rebar is prone to corrosion under certain conditions. When rebar corrosion occurs, its structural characteristics are jeopardized; moreover, the rebar corrosion products are more voluminous and induce significant stresses within the concrete, increasing the risk of failure of the reinforced concrete structure. To mitigate this risk, different coatings and steel alloys are used for the rebar, which can delay the effects of corrosion. The effectiveness of the corrosion-resistance varies between each type of rebar, as do the costs and environmental impacts. Using life cycle cost analysis (LCCA) and life cycle assessment (LCA), the following types of rebar are examined in this project:

- Black steel
- Epoxy-coated steel
- Continuously galvanized steel
- Stainless steel.

The corrosion characteristics, costs, and environmental impacts of each rebar type (as used in a reinforced concrete bridge deck) are evaluated over a 100-year analysis period. Because corrosion depends on climate region and exposure conditions, four different scenarios are examined:

- Calgary: Parking Garage exposure
- Jacksonville: Tidal Zone exposure
- Nashville: Urban Highway exposure
- Tucson: Rural Highway exposure.

This study was commissioned by the International Zinc Association (IZA) and conducted by thinkstep, Inc. thinkstep engaged CTLGroup (an engineering and materials science firm) to provide the engineering analyses, including the construction, service life, and maintenance details associated with each scenario.

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2. Goal and Scope

2.1. Goal

The goal of this study is to assess the life cycle economic and environmental impacts associated with four different types of steel reinforcing bar (rebar) when installed in a continuously reinforced concrete bridge deck. The study observes impacts over a 100 year-analysis period at four different climate locations: Calgary, Nashville, Jacksonville, and Tucson.

The results of this study will explore the relationship between service life and both costs and environmental impacts. IZA intends to use this study internally to inform future research activities on galvanized rebar.

This study utilized ISO 14040 principles when conducting the LCA. As the results are intended for internal use only, no critical review is necessary and the study is conformant with ISO standards. Should the results be made public the study will need to undergo a third-party critical review to remain conformant with ISO standards.

2.2. Functional unit

The reinforced concrete structure examined in this report is a bridge deck. The function of the bridge deck is to provide a driving surface for vehicles over a bridge structure, supporting both static and dynamic loads associated with vehicle travel. The structural design is based on the engineering expertise of CTLGroup. The functional unit is described in Table 2-1.

Table 2-1: Functional unit definition

Functional unit definition	
Functional unit	One 10,000 m^2, 25 cm thick reinforced concrete bridge deck, 6 cm rebar coverage over a 100-year analysis period.
Reference unit	The total volume of the deck is 2,500 m^3 and includes the following materials: • 233.1 tonnes of rebar (29.7 m^3) • 5,742 tonnes of concrete (2470 m^3) Additional material is required over the analysis period due to maintenance and replacement schedules.
Quantification	Service life as determined by the Life-365 modeling software. Maintenance schedule as defined by the Life-365 modeling software and CTLGroup. Material content as defined by CTLGroup.

2.3. Product Description

The reinforced concrete bridge deck serves as an installation scenario through which four different types of rebar are compared. Black steel rebar (also known as black bar) is unfinished tempered steel manufactured in accordance with ASTM A615. It provides no additional corrosion protection and can be used in any structural reinforcement application. Epoxy-coated rebar is black bar coated with an epoxy resin in accordance with ASTM A775. Galvanized rebar is black bar coated with a layer of zinc. Currently, ASTM A767 specifies rebar galvanized using the hot dip method. This study, however, is assessing continuously galvanized rebar, specified under recently-approved ASTM A1094. For both epoxy-coated and galvanized rebar, the additional protection against corrosion leads them to be selected as reinforcement for exposed structures, such as pavements treated with deicing salts or marine structures. The stainless steel rebar is grade SAE 316 and is specified by ASTM A955. This type of rebar is generally selected for marine environments or for infrastructure projects that are intended to have a long service life. There are a variety of other steel alloys available, including low-alloy products that are known to have a lower price and lower performance. This study only evaluates the high-performing and industry-standard stainless steel rebar.

2.4. Service Life and Maintenance

2.4.1. Service Life

CTLGroup conducted an analysis to estimate the service life of a hypothetical bridge deck, holding all variables constant other than changing the type of reinforcing steel and geographical location. For this analysis, four different types of reinforcing steel were considered: black steel, epoxy-coated black steel, continuously galvanized steel (CGR), and stainless steel. For the bridge deck, service life was defined as “the Owner's stated expectation for the number of years that the structure will function without needing major concrete rehabilitation” and “the number of years before major restoration is necessary given minimal maintenance to the structure during its life”. It is measured as “the summation of the corrosion initiation period (Ti) and the corrosion propagation period (Tp) for a given concrete system.” [2] This is one definition of service life and others may define it differently.

Life-365 defines the propagation period (time to propagation) as the time necessary for sufficient corrosion to occur to cause an unacceptable level of damage to the structure or structural member under consideration[3]. Corrosion damage in reinforced concrete is due to the expansion of reinforcement corrosion product in the concrete, which leads to cracking and spalling. A common approach is to assign a fixed time duration for the propagation period based on empirical observations due to the complexity of the corrosion process and lack of hard data.

To demonstrate that a particular combination of concrete mixture proportions, reinforcing steel type, depth of cover, and exposure can achieve a particular service life requires the use of service life modeling software. Such software models the increasing concentration of chloride ions as a function of depth in

[2] http://www.wbdg.org/ccb/DOD/UFGS/UFGS%2003%2031%2029.pdf; Valid 4/6/2015

[3] http://www.life-365.org/download/Life365_v2.2.1_Users_Manual.pdf; Valid 6/4/2015

the concrete as it relates to achieving a critical concentration associated with the initiation and progression of corrosion of the reinforcing steel. Other durability concerns, such as freeze/thaw, sulfate attack, alkali-silica reactivity, and delayed ettringite formation, are assumed to be addressed through compliance with specified prescriptive or performance requirements, although the industry has not yet determined a life expectancy associated with these other mechanisms.

For the purposes of this project it is assumed that the above definition for service life is appropriate. In this regard it is assumed that the projected service life only depends on corrosion resulting from chloride ions concentrating at the depth of the reinforcing steel and the corrosion resistance of the reinforcing steel.

Software

There are a variety of service life modeling software packages that model the rate of chloride ion ingress to the depth of reinforcing steel. All of these modeling software packages assume that the concrete starts with no chloride contamination and, furthermore, that the concrete cover over the reinforcing steel is uniform and free of cracking. This second assumption is important and is a recognized weakness of service life modeling, because crack-free concrete cannot be guaranteed. Cracking of the concrete has the potential to "short circuit" the ability of the concrete cover to slow the ingress of chloride ions, as a crack can provide a ready pathway for chlorides to penetrate to the depth of the reinforcing steel. There is no commonly accepted method for evaluating the effects of cracks, whether unrepaired or repaired, due to the probabilistic nature of cracks and the debated uncertainty of how they affect the corrosion mechanism. As a result, cracking is often simply ignored in the modeling. In practice, measures are implemented in the design to minimize cracking and maintenance regimes are set up to seal/fill cracks.

It is important to note that all service life modeling software uses extrapolations and projections based on assumptions and limited data. The validity of extrapolations and/or projections over a 70+ year prediction period is, at best, far from certain. For this reason, service life modeling software provides a <u>prediction</u> of the time until "major" corrosion-related repairs may be required. This is thought to be adequate for this project, which is focused on a relative comparison of performance between identical structures using different types of steel. But it is noted that the output of service life modeling software is <u>not a guarantee</u> of a particular time of repair-free concrete. Nobody can/should claim or guarantee that a reinforced concrete structure will last a particular extended period of time. Instead, the results of the modeling should be considered projections using commonly-accepted assumptions based on the industry's current level of knowledge, and that the bulk of the reinforced concrete is forecast to last for a particular period of time free of corrosion-related distress.

CTLGroup selected a commonly accepted service life modeling software package called Life-365 to conduct the modeling of the bridge deck for this project. This software is appropriate for the project as the analysis is to compare different types of reinforcing steel and the composition of the concrete is not being evaluated. Life-365 is a free software program (available from: www.Life-365.org) which estimates the time for a sufficient concentration of chloride ions to diffuse through the concrete cover (in accordance with Fick's second law of diffusion) to the depth of the reinforcing steel to initiate corrosion, and for corrosion to propagate such that repairs are required. Version 2.2.1 is the current version of the software as of the date of this report and was used for the analysis.

Service Life Inputs

The inputs for Life-365 were developed based on input from the IZA and other published research. The variables required by Life-365 are listed below.

- Type of Structure: 25 cm thick deck/slab
  Evaluated over 10,000 m^2
  Total volume of 2,500 m^3

- Reinforcing Depth: 4, 5, 6, 7, and 8 cm
  Maintenance scenarios based on 6 cm depth

- Water/Cementitious Ratio: 0.42 *w/cm* with 20% slag replacement

- Corrosion Threshold:

Black Steel:	Ct = 0.05% wt. conc.	(Source: Life-365)
Epoxy-coated Steel:	Ct = 0.05% wt. conc.	(Source: Life-365)
CGR Steel (low corrosion, LC):	Ct = 0.10% wt. conc.	(Source: Yeomans 2004)
CGR Steel (high corrosion, HC):	Ct = 0.20% wt. conc.	(Source: Yeomans 2004)
316 Stainless Steel:	Ct = 0.50% wt. conc.	(Source: Life-365)

- Time to Propagation:

Black Steel:	6 years	(Source: Life-365)
Epoxy-coated Steel:	9 years	(Source: Pianca 2005)
CGR Steel (LC):	20 years	(Source: Yeomans 2004)
CGR Steel (HC)	20 years	(Source: Yeomans 2004)
316 Stainless Steel:	6 years	(Source: Life-365)

- Exposure Location:

Calgary – Parking Garage	Max Surface Concentration = 0.80% wt. conc. Time to Build to Max = 17 years
Jacksonville – Tidal Zone	Max Surface Concentration = 0.80% wt. conc. Time to Build to Max = 1 year
Nashville – Urban Highway	Max Surface Concentration = 0.68% wt. conc. Time to Build to Max = 53 years
Tucson – Rural Highway	Max Surface Concentration = 0.56% wt. conc. Time to Build to Max = 400 years

The corrosion threshold and time to propagation values assumed for black steel and stainless steel are the default values from Life-365, as is the corrosion threshold for epoxy coated steel. These assumptions are supported by literature reviewed by ACI 365 (ACI 2000). The time to propagation for epoxy-coated steel was amended from the Life-365 default value of 20 years based on research provided by IZA showing that epoxy coating only provides 1-5 years of additional corrosion protection compared to bare black steel (Pianca 2005). The CGR steel was modeled based on research provided by IZA that showed CGR steel has a threshold at least 2.5 times that of black steel and delays the time to onset of corrosion by 4-5 times (Yeomans 2004). The corrosion threshold was modeled as a high (HC) and low (LC) value of 0.20% and 0.10% respectively and the assumptions are only valid for CGR with proper coating depths. The selection of a high and low corrosion threshold allows a minimum and maximum range of CGR results to be presented. The time to propagation for CGR was selected as 20 years, which mimicked the default value of epoxy-coated steel in Life-365 and is an assumption based on the cited literature. Corrosion thresholds and times to propagation for all steels are often subjective and there are often disagreements in literature where results are based on accelerated tests and not actual in-situ field data. The values used in our analysis are provided by Life-365 and recognized values based on the cited literature.

The exposure conditions are the default values in Life-365 for the selected locations. The scenarios were chosen to show how the different types of reinforcement would perform in a variety of environments. The titles of parking garage, marine tidal zone, urban and rural highway do not describe the structure but are the exposure conditions being modeled on the structure. The structure is the same 25 cm bridge deck for all exposure locations. The differences of exposure locations are shown above with respect to maximum surface concentration and time to build to maximum concentration. The other input based on exposure location is the annual temperature profile for the chosen city.

Service Life Modeling Results

The estimated years to corrosion initiation using Life-365, based on the inputs stated previously, are shown in Table 2-2 through Table 2-5.

Table 2-2: Time to Initiation: Calgary – "Parking Garage" Exposure

	Time to Initiation, years				
Depth of Cover, cm	Black bar	Epoxy-coated	CGR (LC)	CGR (HC)	Stainless Steel
4	9	9	13	19	76
5	13	13	18	28	130
6	16	16	22	36	150+
7	22	21	30	50	150+
8	26	26	36	61	150+

Table 2-3: Time to Initiation: Jacksonville – "Tidal Zone" Exposure

	Time to Initiation, years				
Depth of Cover, cm	Black bar	Epoxy-coated	CGR (LC)	CGR (HC)	Stainless Steel
4	2	2	3	6	55
5	4	4	6	13	105
6	6	6	9	19	147
7	9	9	15	31	150+
8	12	12	20	41	150+

Table 2-4: Time to Initiation: Nashville – "Urban Highway" Exposure

	Time to Initiation, years				
Depth of Cover, cm	Black bar	Epoxy-coated	CGR (LC)	CGR (HC)	Stainless Steel
4	18	18	28	44	150+
5	25	25	37	55	150+
6	30	30	43	63	150+
7	38	38	52	78	150+
8	44	43	59	90	150+

Table 2-5: Time to Initiation: Tucson – "Rural Highway" Exposure

Depth of Cover, cm	Time to Initiation, years Black bar	Epoxy-coated	CGR (LC)	CGR (HC)	Stainless Steel
4	77	76	127	150+	150+
5	92	91	148	150+	150+
6	103	102	150+	150+	150+
7	119	118	150+	150+	150+
8	131	130	150+	150+	150+

The black bar and epoxy-coated have the same time to initiation because they have the same corrosion threshold; any slight discrepancy is due to rounding within Life-365. The Life-365 software was set with an analysis limit of 150 years; thus, any scenario with a longer time to initiation is listed as "150+".

2.4.2. Maintenance Plan

The maintenance plan was developed using today's best practices to fully capture the in-service life of a bridge deck. Minor repairs were not included as size and occurrence are unpredictable and would be relatively constant over all types of rebar. Sealants were not included as they would also have an equal effect on all types of rebar. The maintenance plan is built around completing a full length, partial depth overlay at the time to initiation of chloride ions on the rebar (calculated using Life-365). This overlay will be completed in three parts:

1. Hydrodemolition to 1.5 cm below the rebar (depth of cover is 6 cm for the maintenance study)
2. Cleaning of rebar and surrounding concrete to remove present chloride ions to the greatest extent possible
3. Placement of a concrete overlay using the same mixture proportions as in the original construction.

The overlay would essentially be treated as a new construction bridge deck from a service life standpoint but, because it is impossible to remove every single chloride ion during the cleaning process, the time to initiation of this overlay is estimated at 80% of the original calculated value. Once 80% of the time to initiation is complete for the overlay the time to propagation would start and the deck will be taken to its end of life. The in-service life of the bridge deck would be $T_{total} = Ti + 0.8Ti + Tp$. Figure 2-1 illustrates the maintenance schedule.

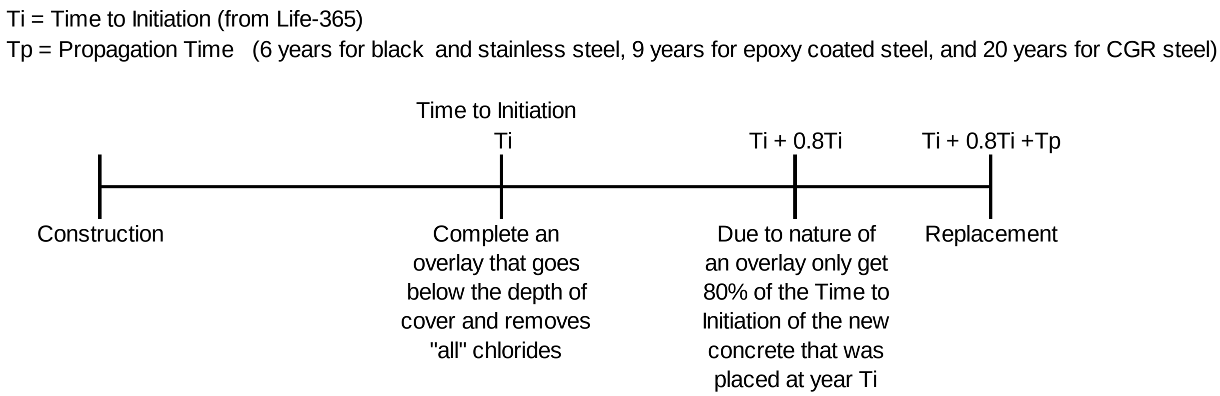

Figure 2-1: Maintenance Schedule

The year of repair activity for each location is shown in Table 2-6. The maximum lifetime considered in the service life modeling was 150 years. Empirical data for performance of bridges are typically limited to 75 years, so extrapolations beyond that period are theoretical. Although the Life-365 model is capable of running service life models for 500 years, 150 years was chosen for this project as a maximum for accuracy considerations. The activities listed as in Table 2-6 as “150+” are for scenarios that have a time to initiation longer than the 150-year modeling period. Once replaced, the maintenance schedule cycle is then repeated until the end of the analysis period, which was chosen to be 100 years. For example, in the case of the black bar alternative in Calgary, the structure would have been replaced in Year 35, and would be due again for a reconstruction at Year 70.

Table 2-6: Maintenance Schedule

	Year of Repair Activity				
City / Activity	Black bar	Epoxy-coated	CGR (LC)	CGR (HC)	Stainless Steel
Calgary - Parking Garage					
Phase 1 Overlay (Ti)	16	16	22	36	150+
Start of Propagation (Ti + 0.8Ti)	29	29	40	65	150+
Replacement (Ti + 0.8Ti + Tp)	35	38	60	85	150+
Jacksonville - Tidal Zone					
Phase 1 Overlay (Ti)	6	6	9	19	150+
Start of Propagation (Ti + 0.8Ti)	11	11	16	34	150+
Replacement (Ti + 0.8Ti + Tp)	17	20	36	54	150+
Nashville - Urban Highway					
Phase 1 Overlay (Ti)	30	30	43	63	150+
Start of Propagation (Ti + 0.8Ti)	54	54	77	113	150+
Replacement (Ti + 0.8Ti + Tp)	60	63	97	133	150+

Tucson - Rural Highway					
Phase 1 Overlay (Ti)	103	102	150+	150+	150+
Start of Propagation (Ti + 0.8Ti)	185	184	150+	150+	150+
Replacement (Ti + 0.8Ti + Tp)	191	193	150+	150+	150+

2.4.3. Summary

The Life-365 service life modeling software was used to estimate the time of corrosion initiation for four types of reinforcing steel: black bar, epoxy-coated black bar, CGR steel, and stainless steel in a theoretical bridge deck. The reinforcing steel alternatives were evaluated in four geographical locations with exposure conditions representative to the location. As expected based on the corrosion threshold values, the stainless steel alternative had the longest service followed by the CGR alternatives. A repair and replacement schedule was developed and applied to the various locations. This is used in the subsequent LCA and cost analyses performed by thinkstep.

2.5. System Boundaries

The system under study uses cradle-to-grave system boundaries, including upstream production of the materials required for the deck, construction and demolition activities, maintenance and replacement (as needed), and end-of-life (EoL). Figure 2-2 presents the elements included and excluded in each life cycle stage.

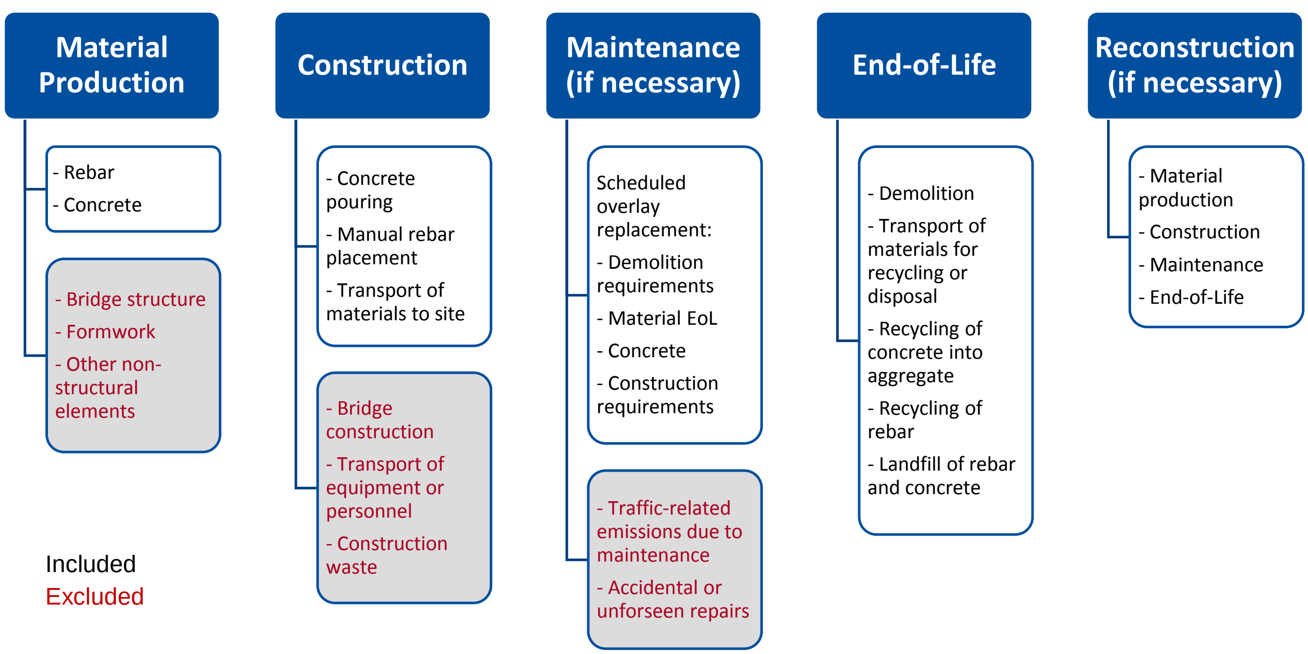

Figure 2-2: System Boundary

At the end of the analysis period, a credit for residual life is applied to those structures where service life still remains. This method is detailed in section 3.2.7. If no maintenance has been performed on the deck over the analysis period, it is assumed that the deck will fail at Year 100 for reasons other than rebar corrosion and no credit is given. By year 100 it is anticipated that other components of the bridge would be compromised (due to failure, corrosion, or fatigue as some examples), the structure could outlive its usefulness in regard to use or capacity, or the design may no longer meet current structural requirements. This assumption is addressed in sensitivity studies on both the LCA and LCCA results, sections 4.4.2 and 6.4.4, respectively.

2.5.1. Time Coverage

This study represents initial construction in 2015 and continued maintenance and operation for 100 years.

2.5.2. Technology Coverage

This study covers the technology of the continuously reinforced concrete bridge deck, as designed using the parameters in section 2.4. Technologies are representative of current US practices for manufacturing black bar, epoxy-coated black bar, continuously galvanized rebar, and stainless steel rebar, as well as for constructing, maintaining a reinforced concrete bridge deck. Current technologies have been applied to future maintenance and replacement activities.

2.5.3. Geographical Coverage

While the four locations used to model different climate scenarios are Calgary, Nashville, Jacksonville, and Tucson, the background data on environmental impacts and costs are intended to represent average values within the United States. The results of this study are only applicable to the specific exposure scenarios listed in section 2.4.1.

2.6. Allocation

Co-product allocation was not necessary in the foreground processes, as there are no co-products known or considered in construction of the bridge deck. Various co-product treatment techniques, including co-product allocation and system expansion, are used in the background data.

End-of-life allocation is used to account for recycling of steel scrap at the end of life. The “value of scrap” approach is applied, which is essentially an avoided burden/EoL recycling allocation method that has been endorsed by the World Steel Association (The World Steel Association 2011). At the end of life, a fraction of the steel is assumed to be recovered for recycling. The scrap required for the initial manufacturing process is looped back as an input, while the remaining recovered material undergoes the recycling process (e.g., cleaning and remelting) and is recast into a steel ingot. A credit is applied to the system for the mass of this steel ingot that is equivalent to a primary steel ingot (i.e., assumes no downcycling).

Residual life of the structure at the end of the analysis period is credited back to the system using a straight-line depreciation approach, which credits the impacts in proportion to the service life remaining divided by the total service life. This methodology is presented in section 3.2.7.

2.7. Cut-off Criteria

Cut-off criteria refer to the criteria for which processes within the system boundaries are excluded due to lack of significant influence on the overall results. No cut-off criteria were applied in this study. All reported data were incorporated and modeled using best available LCI datasets.

2.8. Selection of LCIA Methodology and Types of Impacts

A set of impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-7. IPCC AR5 global warming potentials where used, as they are the most current values, while the latest TRACI 2.1 methodology was selected for the remaining impact categories. TRACI 2.1 is currently the only impact assessment methodology framework which incorporates US average conditions to establish characterization factors.

Global warming potential and non-renewable primary energy demand were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked. Climate change is of high public and institutional interest and deemed to be one of the most pressing environmental issues of our times.

Eutrophication, acidification, and smog formation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

Ozone depletion potential was chosen because of its high political relevance, which has led to the worldwide ban of more active ozone-depleting substances, with the phase-out of less active substances to be completed by 2030. Current exceptions to this ban include the application of ozone depleting chemicals in nuclear power production. In addition, the uncontrolled burning of biomass (e.g., slash-and-burn) is known to result in ozone-depleting emissions.

Table 2-7: Impact Assessment Descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	IPCC AR5 [IPCC 2013]
Eutrophication Potential (EP)	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg N equivalent	TRACI 2.1 [Bare 2012] , [EPA 2012]
Acidification Potential (AP)	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	TRACI 2.1 [Bare 2012] , [EPA 2012]
Smog Formation Potential (SFP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg O_3 equivalent	TRACI 2.1 [Bare 2012] , [EPA 2012]
Ozone Depletion Potential (ODP)	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.	kg CFC-11 equivalent	TRACI 2.1 [Bare 2012] , [EPA 2012]
Non-Renewable Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	[Guinée 2001]

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.9. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints. Data quality guidelines are as follows:

- Measured primary data are considered to be of the highest precision, followed by calculated and estimated data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves.
- Consistency refers to modeling choices and data sources. The goal is to ensure that differences in results occur due to actual differences between product systems, and not due to inconsistencies in modeling choices, data sources, emission factors, or other.
- Representativeness expresses the degree to which the data match the geographical, temporal, and technological requirements defined in the study's goal and scope.

An evaluation of data quality with regard to these requirements is provided in the interpretation chapter of this report.

2.10. Assumptions and Limitations

The Life-365 software provides the total mass of rebar used but does not specify the size. This study assumes #4 rebar was used. This affects the amount of epoxy and zinc used in the respective finishing process. #4 rebar has the highest surface area to weight ratio among the rebar sizes typically used for concrete pavement (#4-#7) and therefore it is a conservative overestimate.

As the continuous galvanization process for rebar is relatively new, data on its energy requirements are unavailable and therefore hot dip galvanization has been used in its place. Continuous galvanization is promoted as being more efficient and having a reduced cost; therefore, it can be assumed that the hot dip galvanizing process is a conservative overestimate.

It should be noted that the finishing materials and processes have a small contribution to the total results so neither of these assumptions would affect the final conclusions (see section 4).

2.11. Software and Database

The LCA model was created using the GaBi 6 Software system for life cycle engineering, developed by thinkstep AG. The GaBi 2014 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

3. Life Cycle Inventory (LCI) Analysis

3.1. Data Collection

3.1.1. Material Quantities

The material quantities are calculated from the design specified by CTLGroup and detailed in section 2.4.1. This includes the concrete mix, density, and volume, as well as the total mass of rebar used.

3.1.2. Fuels and Energy – Background Data

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 6 database 2014. Table 3-1 shows the most relevant LCI datasets used in modeling the product systems.

Table 3-1: Key energy datasets used in inventory analysis

Energy	Dataset name	Primary source	Year	Geography
Electricity	Electricity grid mix (eGrid)	PE	2010	US
Technical heat	Thermal energy from natural gas (eGrid)	PE	2010	US
Diesel	Diesel mix at filling station	PE	2011	US
Heavy fuel oil	Heavy fuel oil at refinery (0.3wt.% S)	PE	2011	US
Gasoline	Gasoline mix (regular) at filling station	PE	2011	US
Diesel combustion	Fork lifter (diesel consumption)	PE	2012	GLO
Gasoline combustion	Car petrol	PE	2012	GLO
Mechanical	Pumping of concrete (EN 15804 A5)	PE	2013	DE

3.1.3. Raw Materials and Processes – Background Data

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 6 database 2014. Table 3-2 shows the most relevant LCI datasets used in modeling the product systems. Documentation for all non-project-specific datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

Table 3-2: Key material datasets used in inventory analysis

Material	Dataset name	Primary source	Year	Geography
Stainless steel rebar	Stainless steel cold rolled coil (316)	Eurofer	2008	RER
Steel rebar	Steel rebar	worldsteel	2007	GLO
Cement	Portland cement, at plant	USLCI/ PE	2009	US
Coarse aggregate	Crushed stone 16/32	PE	2013	EU-27
Fine aggregate	Silica sand (Excavation and processing)	PE	2013	US
Water	Tap water from groundwater	PE	2013	US
Slag	Slag-tap granulate (EN15804 A1-A3)	PE	2013	DE
Epoxy resin	Epoxy resin (EP)	PE	2013	DE
Continuous galvanization	Hot dip galvanizing of structural steel sections	AGA	2013	US
Zinc	Special high grade zinc	IZA	2012	GLO

3.1.4. Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials to production and assembly facilities.

The GaBi 2014 database was used to model transportation. Truck transportation within the United States was modeled using the GaBi 6 US truck transportation datasets. The vehicle types, fuel usage, and emissions for these transportation processes were developed using a GaBi model based on the most recent US Census Bureau Vehicle Inventory and Use Survey (2002) and US EPA emissions standards for heavy trucks in 2007. The 2002 VIUS survey is the most current available data describing truck transportation fuel consumption and utilization ratios in the US, and the 2007 EPA emissions standards are considered by this study's authors to be the most appropriate data available for describing current US truck emissions.

3.1.5. Emissions to Air, Water, and Soil

Data for all upstream materials, electricity, and energy carriers were obtained from the GaBi 2014 database. The emissions (CO_2, NO_x, etc.) due to the use of electricity are accounted for with the use of the database processes.

3.2. Modeling

3.2.1. Material Production

The concrete mixture proportions are specified by CTLGroup. Information on ready-mix plant operating energy and inbound transportation of materials were obtained from the National Ready Mixed Concrete (NRMCA) study on the LCA of ready-mixed concrete manufacturers (Athena 2014).

Table 3-3: Concrete mixture proportions for one cubic meter of concrete (2,325 kg/m^3)

Material	Quantity	Unit
Cement	297	kg
Fine aggregate	688	kg
Coarse aggregate	1,110	kg
Slag	74	kg
Water	156	kg

Black bar is uncoated steel, modeled using worldsteel global rebar production averages. Epoxy-coated rebar is manufactured by heating the unfinished steel and spraying it with epoxy. A typical thickness for epoxy is 255 microns. Calculations for the epoxy quantity and thermal energy requirements (as seen in Table 3-4) can be found in Appendix A. The electricity quantity comes from a confidential industry source, while the inbound transport distances of the black bar and coating material are assumed to be the same as those of CGR.

Table 3-4: Epoxy-coating process

Material / energy	Quantity	Unit
Input		
Black bar	1,000	kg
Epoxy	12.8	kg
Thermal energy from natural gas	108	MJ
Electricity	110	kWh
Output		
Coated rebar	1,013	kg

The prescribed thickness for continuously galvanized rebar is 50 microns. Using #4 rebar this equates to 14.1 kg of zinc for every tonne of rebar. The hot dip galvanization process obtained from the industry average of the American Galvanizers Association (AGA) was used as a proxy for the continuous galvanizing process, modified to account for the difference in coating thickness.

The stainless steel rebar used in this study is grade SAE 316. In practice, multiple grades of stainless steel are used for rebar, including some with low allow contents that do not have the corrosion resistance as the 316 grade. This study evaluates only the grade SAE 316 stainless steel rebar.

3.2.2. Construction

Inbound transport of materials to the construction site is included in the assessment. While this can vary greatly depending on the location of construction, the average distance from a ready-mixed concrete plant in the US to a construction site is 22.9 km (14.2 miles).[4] The distance for steel was estimated to be 50 km (31.1 miles) from fabrication facility to construction site.

The energy required to pour the concrete is accounted for within the model, while the laying of the rebar for the bridge deck construction requires only manual labor.

3.2.3. Operation

The operation stage comprises the impacts from using the bridge deck for the duration of its service life. No operation stage impacts were included in the analysis, though they would be the same across all bridge types considered.

3.2.4. Maintenance

After the pavement has reached the time to initiation, an overlay is carried out as described in section 2.4.2. Hydrodemolition, using high-pressure water, is used to break up and remove the top 6 cm of concrete and clean the rebar. Table 3-5 shows the material and energy requirements per cubic meter of concrete (Lepech 2011).

Table 3-5: Hydrodemolition requirements per m^3 of concrete

Material / energy	Quantity	Unit
Diesel	1,188	MJ
Water	101,524	L

The maintenance includes the disposal of concrete (as described in the following section) as well as the impacts associated with placing the new concrete.

[4] http://www.sustainableconcrete.org/?q=node/42

3.2.5. End-of-Life

This life cycle stage comprises the impacts associated with deconstruction of the bridge deck at the end of its service life and the disposal and recycling of the concrete and rebar. Steel recycling uses the value of scrap allocation approach and assumes a 72% recovery rate (SRI 2014). The remaining rebar is sent to landfill. Concrete recycling assumes a 50% recycling rate (US EPA 2003). The recycled concrete is crushed into gravel using 0.0352 MMBtu/tonne of energy, with half coming from diesel fuel and half from electricity. The remaining concrete is sent to landfill.

Deconstruction requires diesel for breaking the concrete and gasoline to cut the steel reinforcement. Table 3-6 lists the energy requirements per cubic meter of reinforced concrete (Athena 1997).

Table 3-6: Demolition requirements per m^3 of reinforced concrete

Material / energy	Quantity	Unit
Diesel	124	MJ
Gasoline	12	L

3.2.6. Replacement

A full replacement includes the above stages of material production, construction, and EoL.

3.2.7. Residual Service Life

At the end of the analysis period the residual service life of each design is considered. Depending on the year of the most recent maintenance or replacement, a credit is applied to the system as follows:

$$Credit\ for\ remaining\ service\ life\ = \left(\frac{Years, remaining\ service\ life}{Years, total\ service\ life}\right) \times (Impact, initial\ construction)$$

This credit approach is equivalent to the straight-line depreciation approach commonly used in life cycle cost analyses.

4. Life Cycle Impact Assessment (LCIA)

4.1. Results

The life cycle impact assessment LCIA results for the Calgary scenario are presented in Tables 4-1 through 4-5. The results for the remaining exposure scenarios— Nashville, Jacksonville, and Tucson— can be found in Appendix B. The years of each overlay and replacement required to meet the 100-year analysis period are listed, along with their individual impacts. EoL and residual life activities after Year 100 are included because they are associated with construction activities that occurred within the analysis period. EoL represents includes demolition, landfilling, and any credits from recycling portions of the concrete and steel. Residual life accounts for the fraction of service life still remaining at Year 100. It is based on the next expected replacement or maintenance activity.

Table 4-1: Absolute LCIA results for black bar in Calgary

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,625	213	1,503,936	6.57E-03	93,931	10,485,177
16	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
35	Replacement #1	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
51	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
70	Replacement #2	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
86	Partial Overlay #3	2,564	136	505,082	1.14E-03	47,971	4,188,140
105	Next activity	Residual life based on year next activity would have been required					
105	EoL	927	61	191,389	2.73E-04	21,709	2,936,366
100	Residual Life	-675	-36	-132,916	-3.00E-04	-12,624	-1,102,142
	Total	**29,672**	**1,193**	**6,468,306**	**2.36E-02**	**478,208**	**51,726,907**

Table 4-2: Absolute LCIA results for epoxy-coated black bar in Calgary

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,729	221	1,546,513	6.57E-03	95,768	11,210,104
16	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
38	Replacement #1	7,665	282	1,741,358	6.73E-03	117,567	14,179,359
54	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
76	Replacement #2	7,665	282	1,741,358	6.73E-03	117,567	14,179,359
92	Partial Overlay #3	2,564	136	505,082	1.14E-03	47,971	4,188,140
114	Next activity	Residual life based on year next activity would have been required					
114	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-1,632	-86	-321,416	-7.26E-04	-30,527	-2,665,180
	Total	**29,054**	**1,168**	**6,417,905**	**2.29E-02**	**466,087**	**52,437,317**

Table 4-3: Absolute LCIA results for CGR (LC) in Calgary

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
22	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
60	Replacement #1	7,794	286	1,765,354	6.74E-03	119,697	14,324,258
82	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
120	Next activity	Residual life based on year next activity would have been required					
120	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-1,349	-71	-265,833	-6.00E-04	-25,248	-2,204,284
	Total	**19,367**	**772**	**4,274,770**	**1.52E-02**	**310,081**	**34,817,935**

Table 4-4: Absolute LCIA results for CGR (HC) in Calgary

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
36	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
85	Replacement #1	7,794	286	1,765,354	6.74E-03	119,697	14,324,258
121	Next activity	Residual life based on year next activity would have been required					
121	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-4,547	-167	-1,029,790	-3.93E-03	-69,823	-8,355,817
	Total	**13,606**	**541**	**3,005,731**	**1.07E-02**	**217,535**	**24,478,262**

Table 4-5: Absolute LCIA results for stainless steel rebar in Calgary

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	16,285	1,543	2,078,639	5.56E-02	143,142	18,998,026
150	Next activity	Past 100 year service life					
150	EoL	-2,062	-25	-119,577	-1.49E-03	-9,626	-1,209,123
100	Residual Life	-	-	-	-	-	-
	Total	**14,223**	**1,519**	**1,959,062**	**5.41E-02**	**133,515**	**17,788,902**

It should be noted that no residual life is associated with the scenarios where no maintenance occurs on the road over the 100-year service life. Without maintenance or replacement, it is assumed that the bridge deck will fail for reasons other than rebar corrosion.

Figure 4-1 presents the relative GWP results for initial construction only. Within typical steel rebar the finishing method (epoxy-coated or galvanization) has a small impact compared to the steel itself, while stainless steel has a high GWP, primarily due to the alloying elements used in the material. Construction burdens associated with pouring the concrete are small (~0.1%) compared to those associated with the materials. Additionally, the differences between the black bar, epoxy-coated, and CGR types are small (approximately 1%).

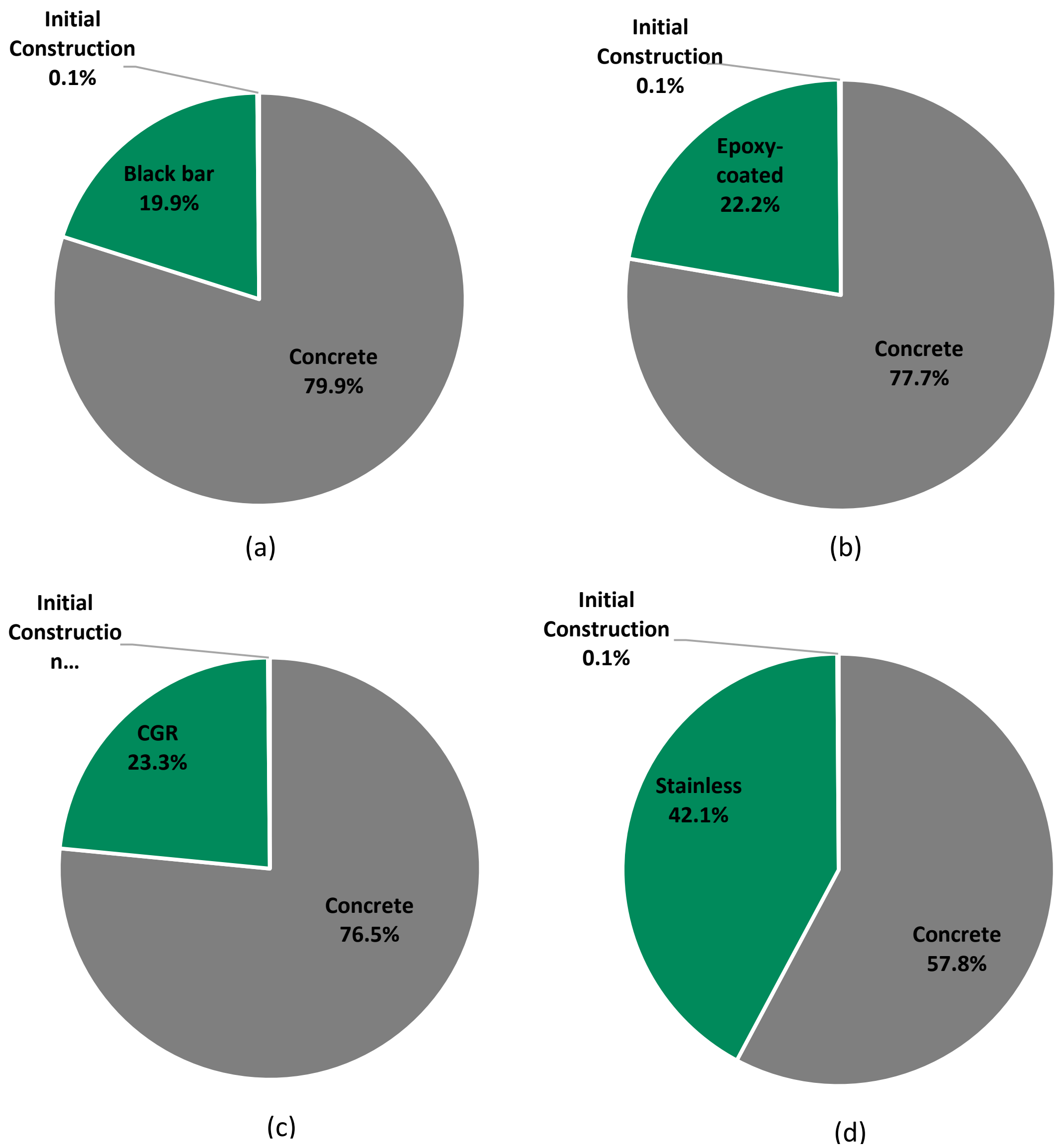

Figure 4-1: Relative initial construction GWP for (a) black bar, (b) epoxy-coated, (c) CGR, and (d) stainless steel rebar

4.2. Comparison

The following figures show the total lifetime impacts of all rebar and exposure scenarios. In Figure 4-2, stainless steel has the lowest GWP for the Calgary and Jacksonville scenarios. In Nashville CGR (HC) has the lowest impact, though CGR (LC) and stainless steel have comparable totals. Finally, while Tucson is comparable for all five rebar scenarios, black bar is slightly lower and stainless steel is slightly higher overall.

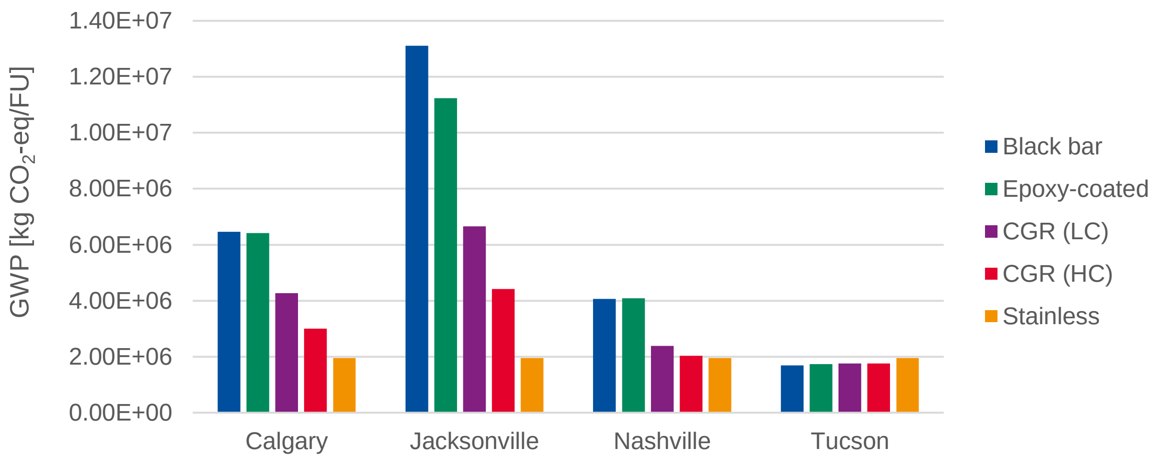

Figure 4-2: Total life cycle GWP for all rebar and exposure scenarios

In Figure 4-3 the AP results show that CGR (HC) has the lowest impact for Nashville and Calgary, while stainless steel has the lowest impact for Jacksonville. Finally, in Tucson, the results are equivalent for all types of rebar with the exception of stainless which has the highest impact.

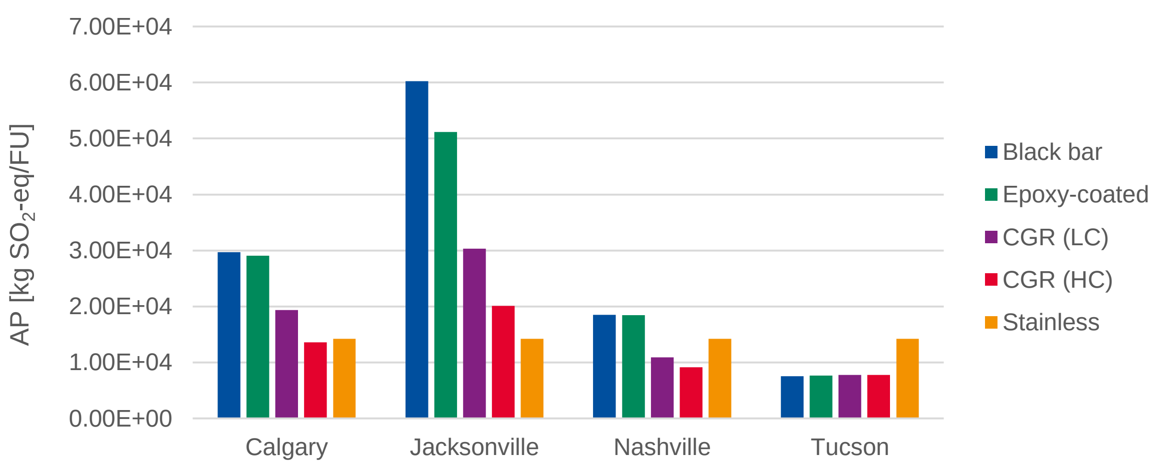

Figure 4-3: Total life cycle AP for all rebar and exposure scenarios

Figure 4-4 shows the EP results. For all exposure scenarios, with the exception of Tucson, CGR (HC) has the lowest impact, followed by CGR (LC). Stainless steel has a higher impact compared to the other types of rebar due to the upstream production of stainless steel. In Tucson the results are comparable across all other types of rebar though black bar is slightly lower.

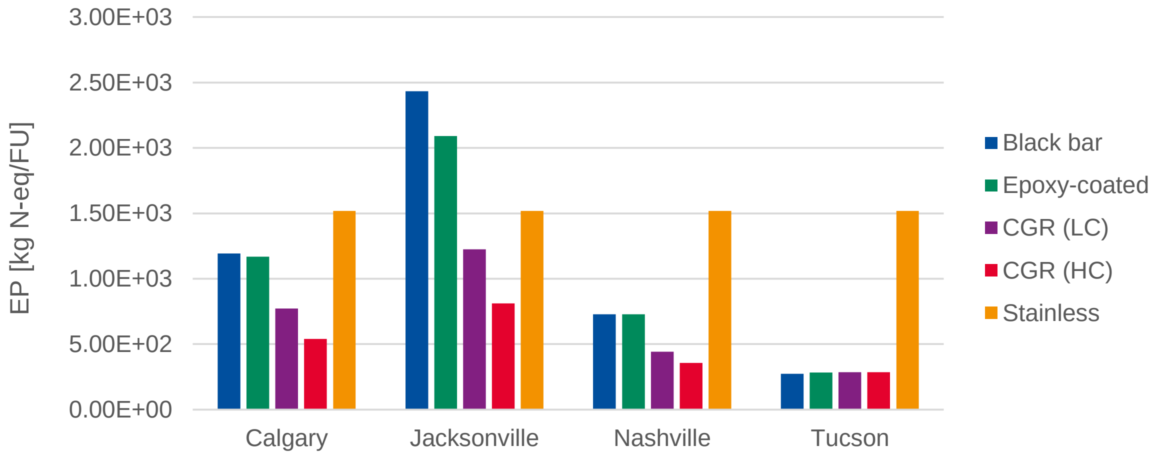

Figure 4-4: Total life cycle EP for all rebar and exposure scenarios

In Figure 4-5 it can be seen that the stainless steel ODP impacts are the highest across all exposure scenarios. There are similar trends for ODP as EP, with CGR (HC followed by LC) having the lowest impacts and the results being comparable across the black bar, epoxy-coated, and CGR types for the Tucson scenario. ODP is typically associated with electricity generation; in particular, nuclear energy tends to contribute significantly to ODP due the refrigerants used as coolants. The spike in ODP for stainless steel can be attributed to the electricity grid mix used in the manufacturing data. The results seen in Figure 4-6 and Figure 4-7 show the total SFP and PED, respectively, with trends the same as those seen in the GWP figures.

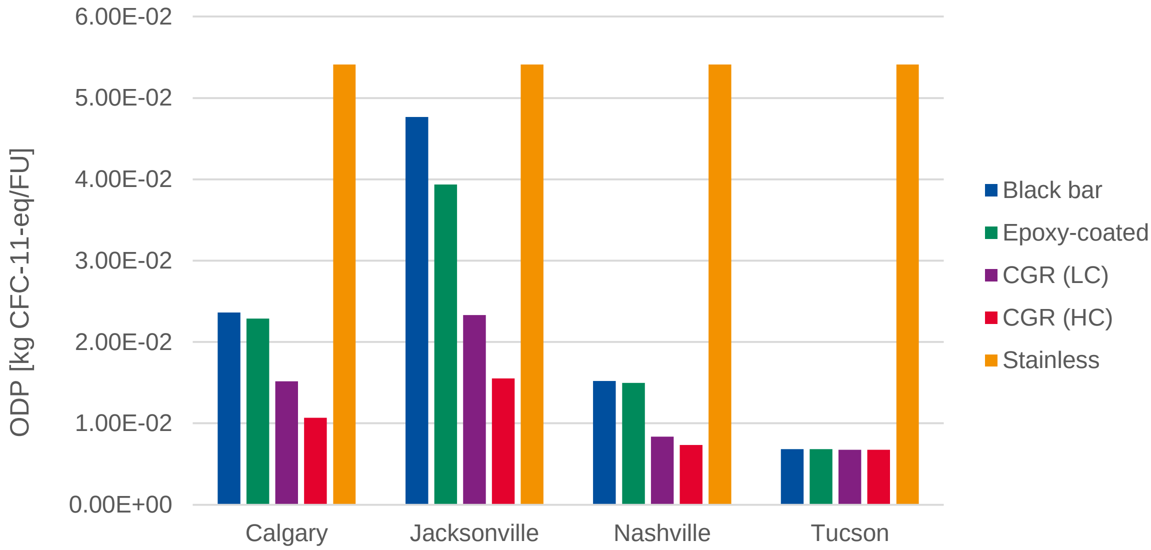

Figure 4-5: Total life cycle ODP for all rebar and exposure scenarios

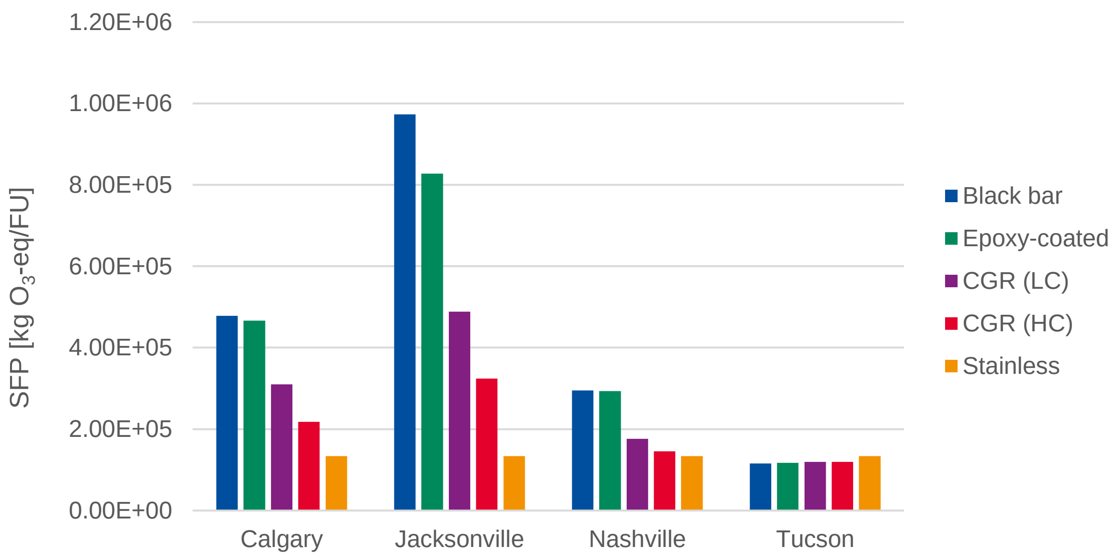

Figure 4-6: Total life cycle SFP for all rebar and exposure scenarios

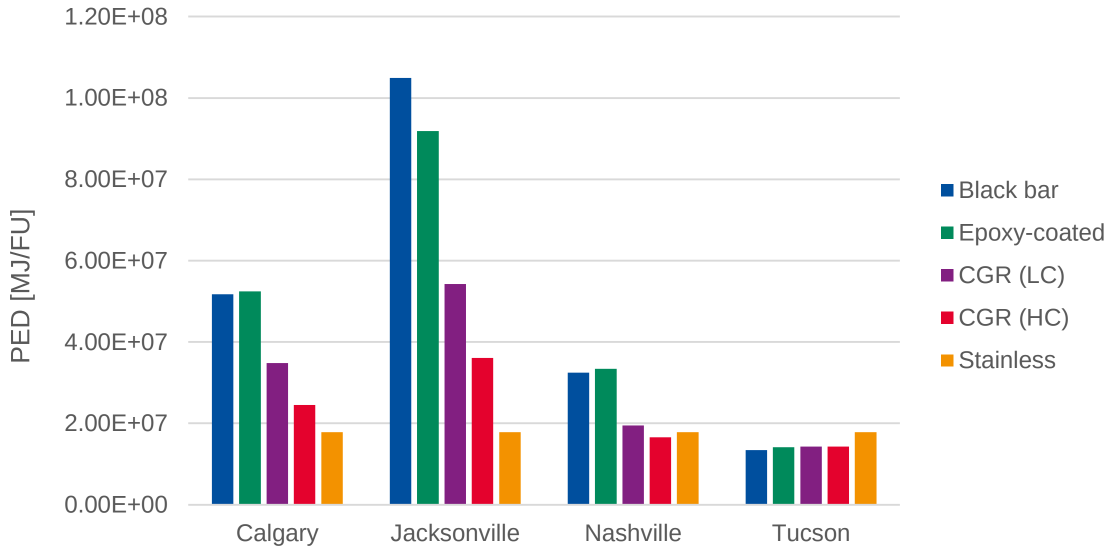

Figure 4-7: Total life cycle PED for all rebar and exposure scenarios

4.3. Time series comparison

Figure 4-8 through Figure 4-11 show the GWP results over time. Each chart shows an impact at Year 0 due to initial construction. The larger jumps in impact are due to replacements while the smaller jumps are due to overlays. At Year 100 the EoL and residual life impacts are combined to show either a credit (reduction in impact) or burden (increase in impact).

For Calgary, the CGR scenarios show a lower impact than the black bar and epoxy-coated rebar between Year 36 and Year 38. Stainless steel begins to have a lower total impact between Year 60 and Year 85. In Jacksonville these break even points occur earlier in the analysis period: between Year 17 and Year 20 for black bar and epoxy-coated and between Year 36 and Year 54 for stainless steel.

In the Nashville scenario, black bar and epoxy-coated rebar begin to have a higher impact than CGR between Year 60 and Year 63. While the CGR (HC) scenario always has a lower impact than stainless steel, the CGR (LC) scenario only surpasses the stainless steel impact at Year 97. Finally, in Tucson, the impacts are all comparable with the exception of stainless steel which has the highest GWP.

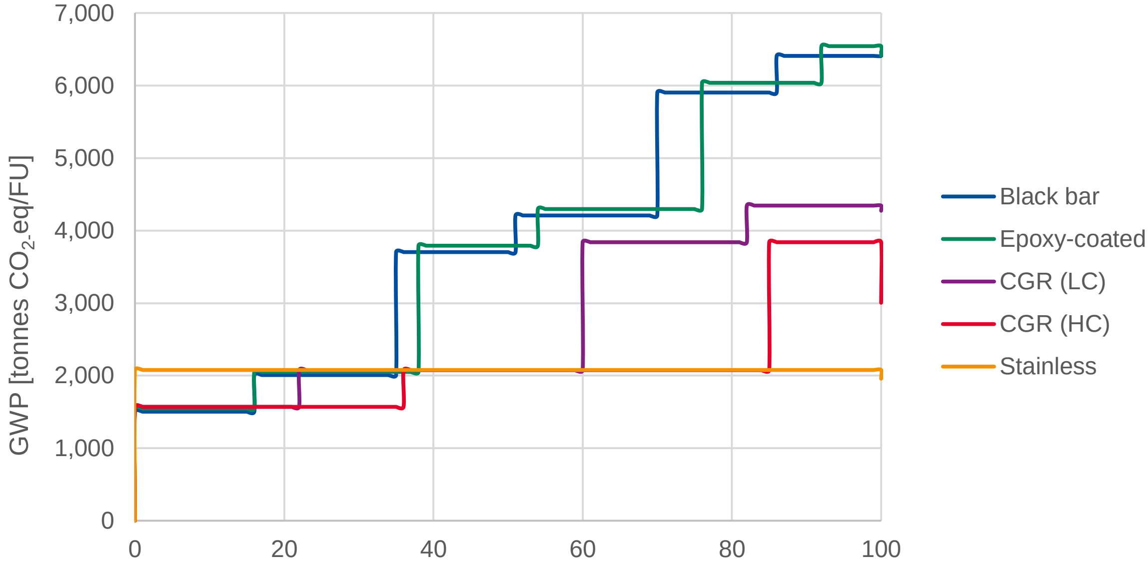

Figure 4-8: Time series comparison of GWP for all rebar scenarios in Calgary

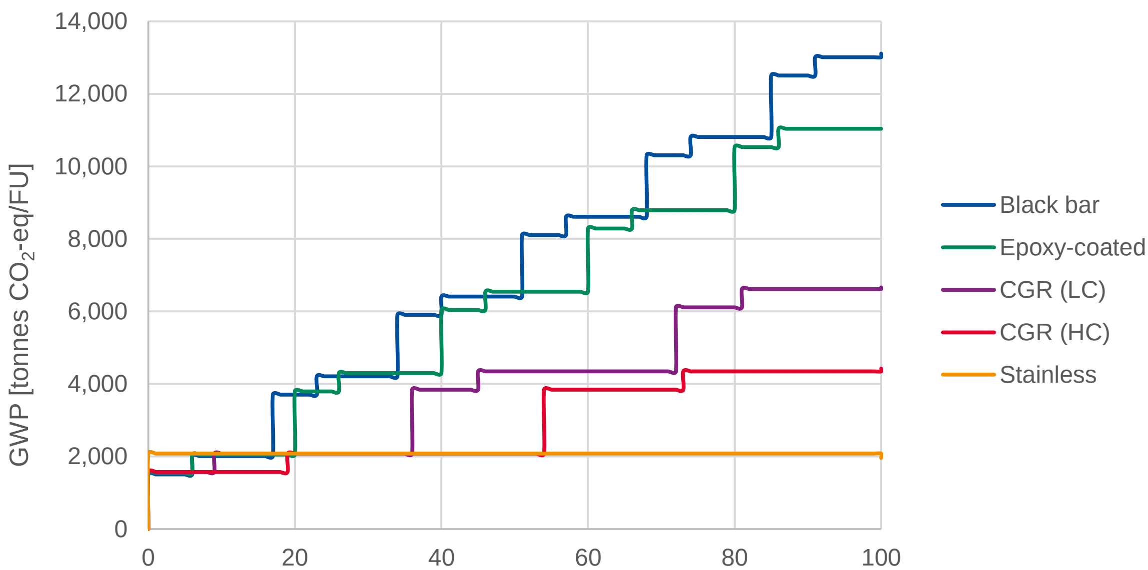

Figure 4-9: Time series comparison of GWP for all rebar scenarios in Jacksonville

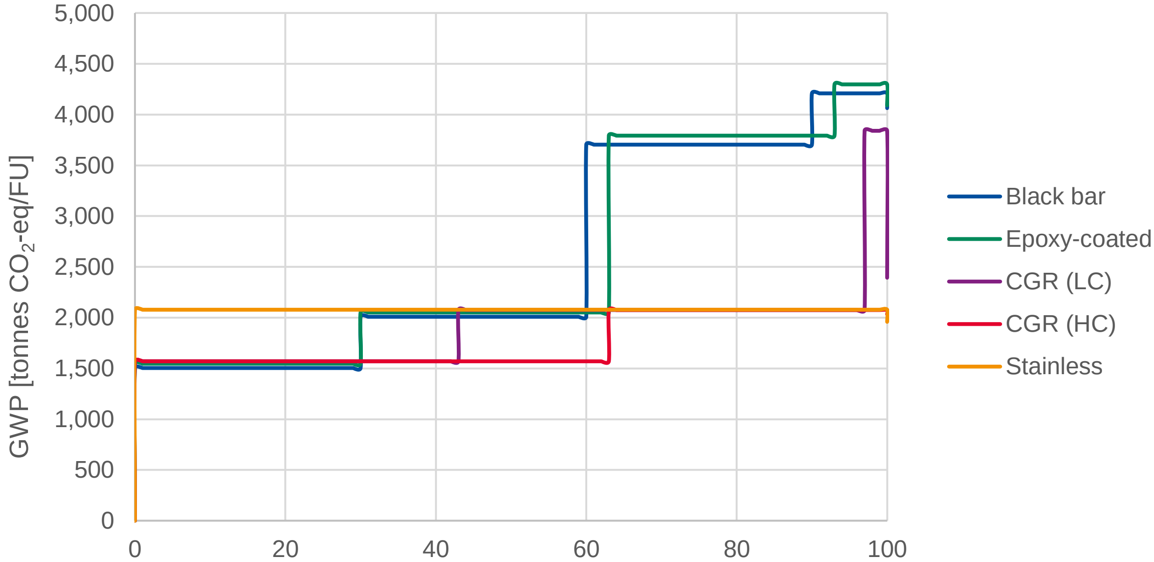

Figure 4-10: Time series comparison of GWP for all rebar scenarios in Nashville

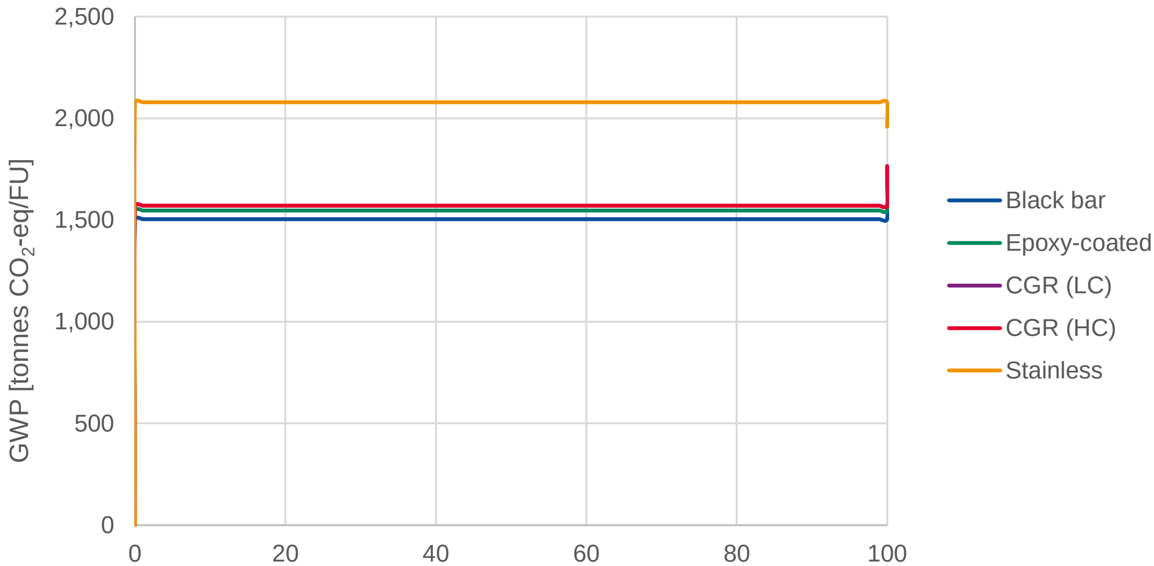

Figure 4-11: Time series comparison of GWP for all rebar scenarios in Tucson

4.4. Sensitivity Analyses

Sensitivity analyses were performed to test the robustness of the results towards uncertainty and main assumptions. These analyses were performed for two topics: (1) the construction and demolition impacts and (2) the treatment of residual life.

4.4.1. Construction & Demolition

To assess the influence of construction on the final conclusions, the environmental impacts from construction and demolition activities were doubled (the 2x construction scenario) and compared to the baseline scenario. Table 4-6 shows the percent difference doubling the impacts from construction has compared to the baseline scenario. It can be seen that though differences could be anywhere from 0% to 20%, the black, epoxy-coated, and CGR all changed at close to the same rate. Stainless steel changed less due to the lack of maintenance or replacement activities.

Figure 4-12 shows the GWP trends for the baseline and 2x construction scenarios. While the impacts go up slightly for the alternative scenario, the overall trends and conclusions remain the same.

The largest percent difference was seen in the EP results, presented in Figure 4-13. Again, the impacts increase but overall the conclusions remain unchanged.

Table 4-6: Percent difference of doubled construction impacts as compared to the baseline scenario

	AP	EP	GWP	ODP	SFP	PED, nr
Calgary						
Black bar	7%	20%	5%	0%	14%	9%
Epoxy-coated	7%	18%	5%	0%	13%	8%
CGR (LC)	6%	17%	4%	0%	12%	8%
CGR (HC)	6%	17%	4%	0%	12%	7%
Stainless	1%	1%	1%	0%	4%	2%
Jacksonville						
Black bar	8%	21%	5%	0%	14%	9%
Epoxy-coated	8%	20%	5%	0%	15%	9%
CGR (LC)	7%	19%	5%	0%	14%	8%
CGR (HC)	7%	19%	5%	0%	14%	8%
Stainless	1%	1%	2%	0%	5%	2%
Nashville						
Black bar	6%	17%	4%	0%	12%	8%
Epoxy-coated	6%	16%	4%	0%	12%	7%
CGR (LC)	7%	20%	5%	0%	14%	9%
CGR (HC)	5%	15%	4%	0%	11%	7%
Stainless	1%	1%	2%	0%	5%	2%
Tucson						
Black bar	3%	6%	2%	0%	5%	3%
Epoxy-coated	3%	6%	2%	0%	5%	3%
CGR (LC)	2%	6%	2%	0%	5%	3%
CGR (HC)	2%	6%	2%	0%	5%	3%
Stainless	1%	1%	2%	0%	5%	2%

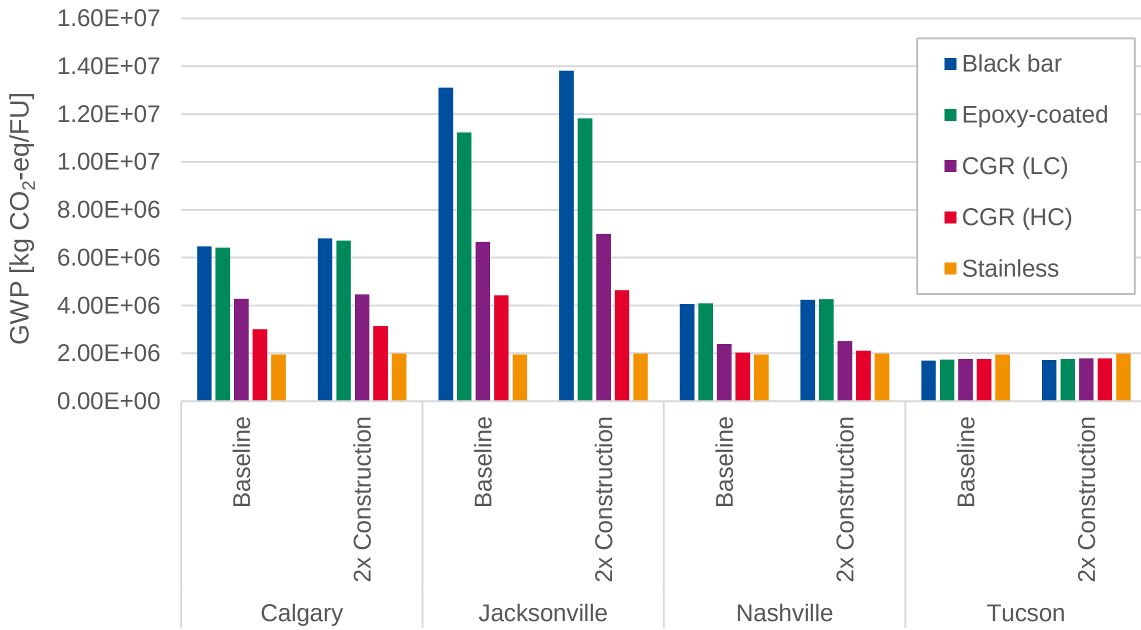

Figure 4-12: Total life cycle GWP impacts for the baseline and 2x construction scenarios

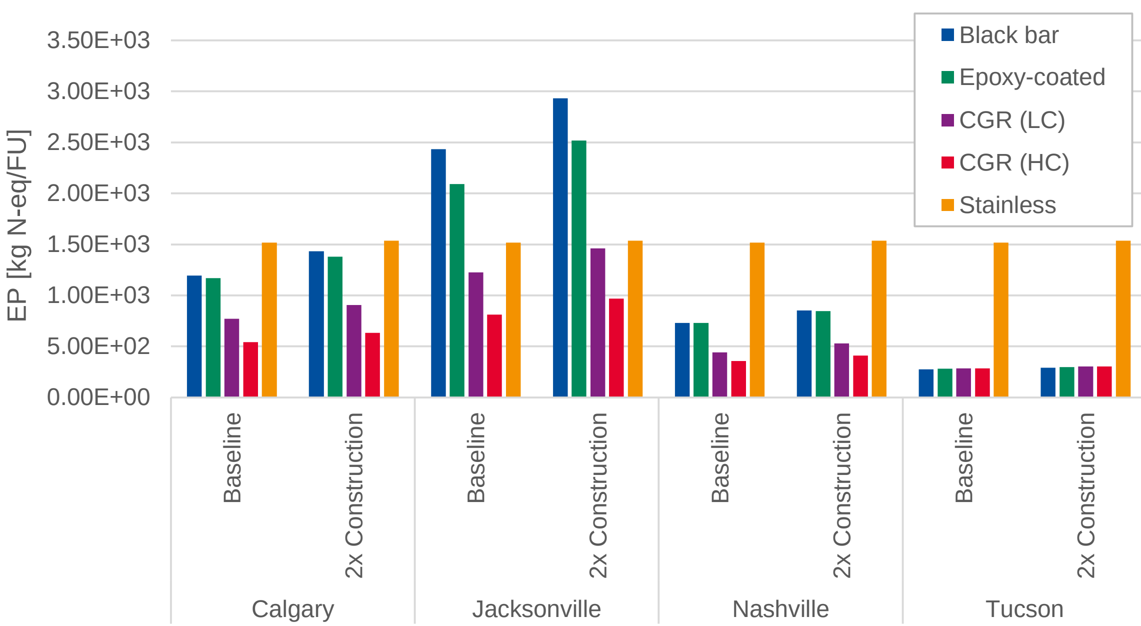

Figure 4-13: Total life cycle EP impacts for the baseline and 2x construction scenarios

4.4.2. Residual Service Life

The baseline scenario does not give residual service life credit to structures that do not require maintenance during the analysis period, under the assumption that the deck would fail for reasons other than rebar corrosion. This affects the results for all rebar types within the Tucson scenario, but only the stainless steel results in the remaining exposure scenarios. The following figures show the results for both the baseline scenario and the residual life credit scenario.

Figure 4-14 presents the results for GWP across all exposure scenarios. While the conclusions for Calgary and Jacksonville were not affected, the Nashville alternative scenario shows stainless steel as the lowest burden, as opposed to the baseline scenario where it was comparable to CGR (HC). In Tucson, CGR and stainless steel are lower than black bar and epoxy-coated in the alternative scenario, while the baseline scenario shows slightly higher stainless steel burdens and comparable burdens for the other rebar types.

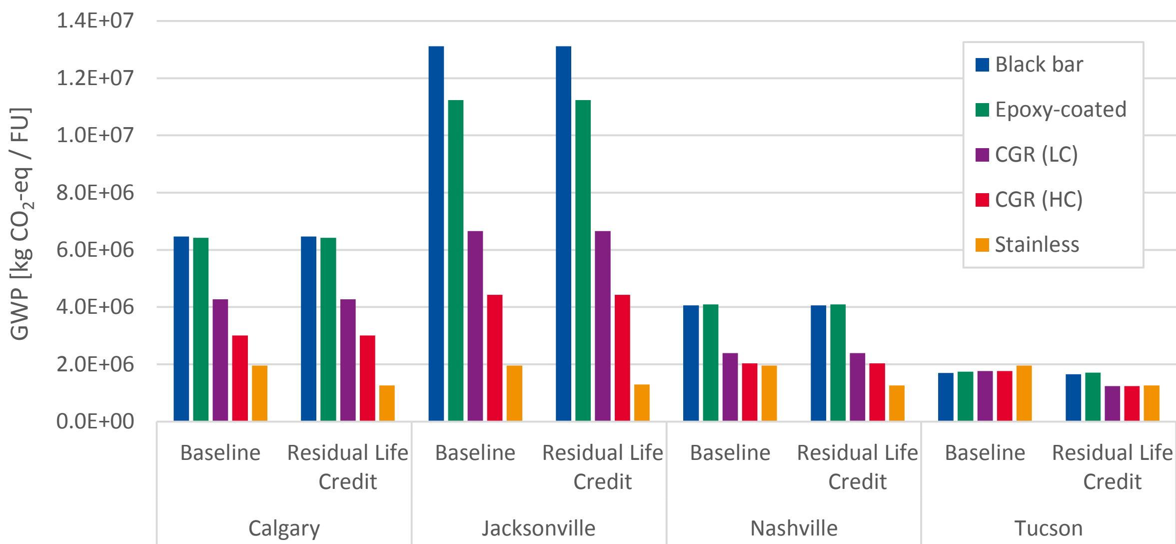

Figure 4-14: Total life cycle GWP impacts for the baseline and residual life credit scenarios

Figure 4-15 presents the baseline and residual life credit AP results for all exposure scenarios. In Calgary and Nashville, the stainless steel burden is now lower than the other rebar types, though only by a small amount in Nashville. For Jacksonville, the conclusions did not change. In Tucson, stainless steel remains the highest burden but the CGR scenarios are now the lowest burden.

Figure 4-16 presents the baseline and residual life credit EP results for all exposure scenarios. In Calgary, the reduced stainless steel burden results in black bar and epoxy-coated having the highest environmental burden, while CGR remains the lowest. The Jacksonville scenario shows the stainless steel burden falling between the two CGR scenarios. In Nashville and Tucson, stainless steel continues to have the highest burden. CGR in Tucson is now slightly lower than black bar and epoxy-coated.

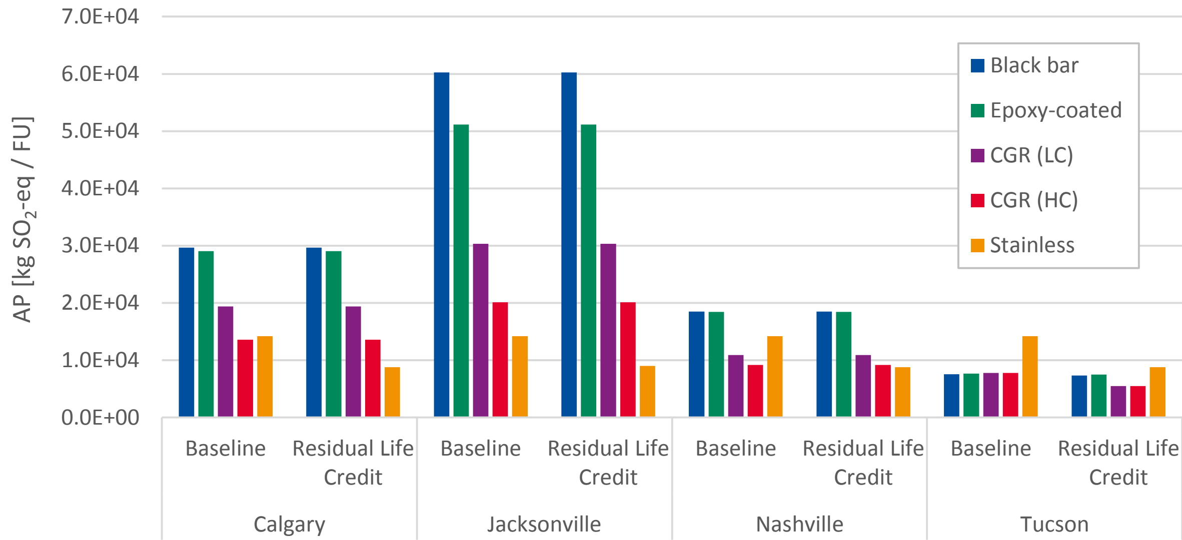

Figure 4-15: Total life cycle AP impacts for the baseline and residual life credit scenarios

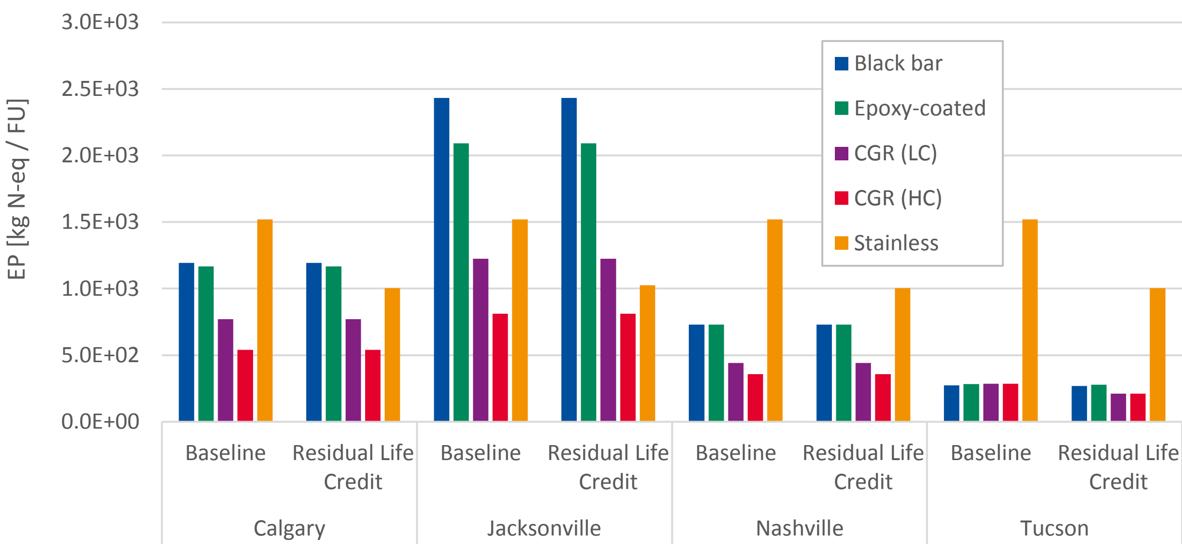

Figure 4-16: Total life cycle EP impacts for the baseline and residual life credit scenarios

Figure 4-17 presents the ODP results for the baseline and residual life credit scenarios, for all exposures considered. The conclusions for Calgary and Nashville did not change. In Jacksonville, stainless steel is no longer the highest burden, though CGR still continues to be the lowest. In Tucson, the change in conclusion is the same as with the EP results.

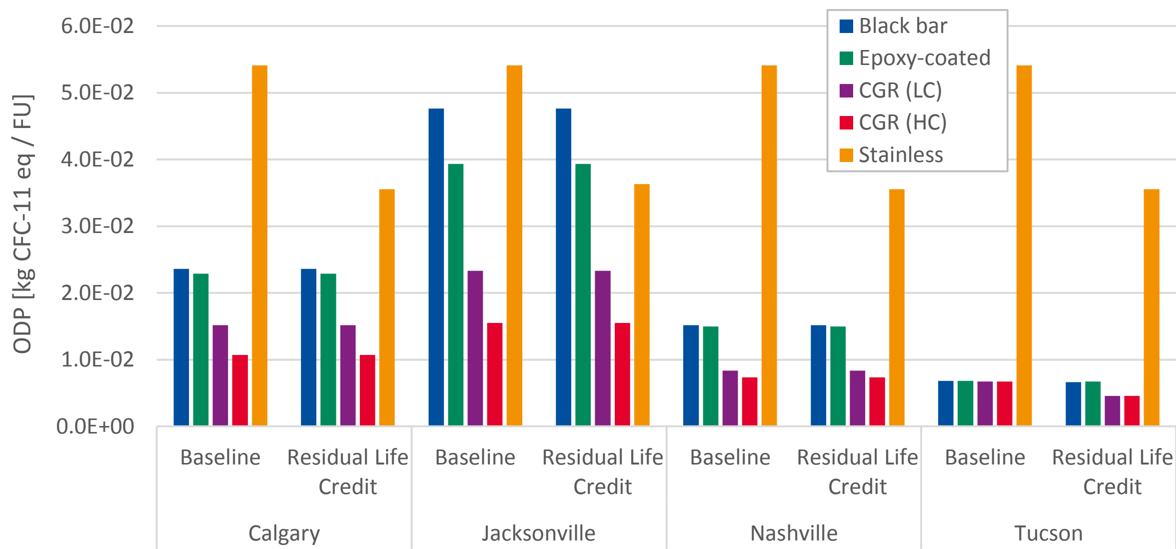

Figure 4-17: Total life cycle ODP impacts for the baseline and residual life credit scenarios

Figure 4-18 presents the baseline and residual life credit PED results for all exposure scenarios. The conclusions did not change for Calgary, Jacksonville, and Nashville. In Tucson, the results for CGR and stainless steel are comparable, but lower than epoxy-coated and black bar.

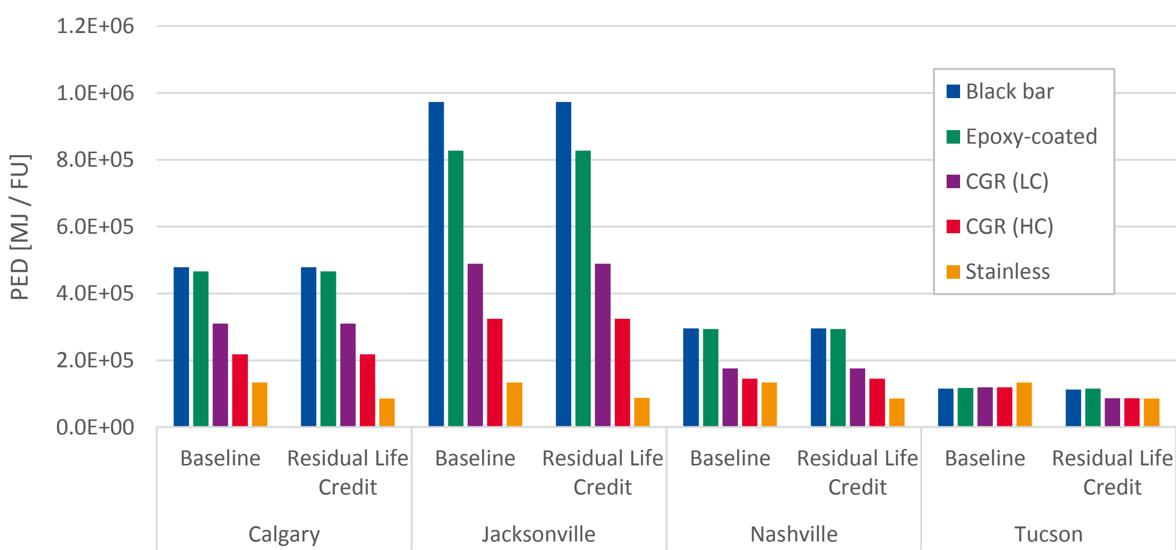

Figure 4-18: Total life cycle PED (non-renewable) for the baseline and residual life credit scenarios

5. LCA Interpretation

5.1. Identification of Relevant Findings

The following conclusions can be made based on the LCA results:

- Shorter time to build to maximum surface concentration of chloride ions (based on the exposure scenarios) leads to more replacements and maintenance periods over the analysis period, resulting in higher environmental impacts. The exception to this is stainless steel for which no maintenance was required within the analysis period.
- CGR leads to lower environmental impacts than black bar or epoxy-coated, with the exception of the Tucson scenario where the impacts were comparable.
- In Nashville, CGR can have comparable environmental impacts to those of stainless steel over the analysis period.
- In Tucson, where the exposure scenario is less severe, the increased corrosion threshold seen in stainless steel actually leads to increases in environmental impacts over the analysis period, as that level of threshold is not necessary for the environment.
- Differences in upstream rebar production are only consequential for stainless steel. For the other rebar types it is the associated service life that leads to different total impacts.
- There is moderate sensitivity in the conclusions for the treatment of residual life. The baseline analysis assumes that the maximum service life for a bridge deck is 100 years. When this constraint is removed, the impacts of some long-life scenarios are reduced. This is particularly relevant for some scenarios involving stainless steel.

5.2. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, industry data were used in combination with consistent background LCA information from the GaBi LCI database. It should be noted that the data sources used for cement, carbon steel rebar, and stainless steel rebar come from industry average sources—the Portland Cement Association, worldsteel, and EUROFER, respectively—and so underlying methodologies may differ. The LCI datasets from the GaBi LCI database are widely distributed and used with the GaBi 6 Software. These datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.2.1. Precision and completeness

- **Precision:** As the relevant foreground data are primary data or modeled based on primary information sources of the owner of the technology, no better precision is achievable within this project. All background data are either GaBi data with the documented precision or industry-average data**.**

- **Completeness:** Each unit process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted.

5.2.2. Consistency and reproducibility

- **Consistency:** To ensure consistency, all primary data were collected with the same level of detail, while all background data were sourced from either the GaBi databases or industry-average data sources. Across the industry-average data underlying methodologies may vary. Allocation and other methodological choices were made consistently throughout the model.

- **Reproducibility:** Reproducibility is supported as far as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modeling approaches.

5.2.3. Representativeness

- **Temporal:** All primary data were collected for the year 2015. All secondary data come from either the GaBi 6 2014 databases or industry-average sources, and are representative of the years 2006-2013. As the study is intended to compare the product systems for the reference year 2015, temporal representativeness is considered to be fair.

- **Geographical:** All primary and secondary data were collected specific to the countries / regions under study. Where country / region specific data were unavailable, proxy data were used (see section 3.1). Geographical representativeness is considered to be high.

- **Technological:** All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used (see section 3.1). Technological representativeness is considered to be high.

6. Life Cycle Cost Analysis

6.1. Methodology

This life cycle cost analysis (LCCA) follows the standards set forth in ISO 15686-5 for LCCA of buildings and constructed assets. Net present value (NPV) is used to evaluate the bridge deck from the perspective of the owner/operator. In order to better reflect that this analysis deals with costs rather than revenues, the term net present cost (NPC) is used in favor of NPV. Net present cost can be thought of as the amount of investment at Year 0 needed to fund the project through the analysis period. All costs are calculated using a 100 year analysis period.

The fundamental relationship used to calculate total NPC is relationship shown below:

$$NPC = \sum_{n=0}^{N} \frac{C_n}{(1+i)^n}$$

Where NPC = total net present cost of the bridge deck over 100 years

C = costs incurred in year n (present day)

N = analysis period (100 years)

n = year in which cost occurs

i = real discount rate

The discount rate is a key variable in the calculation of NPC. This rate reflects the time value of money. It is used to evaluate future costs in relation to present costs, accounting for the prevailing interest rate and (indirectly) the inflation rate. The discount rate is variable across time, as demonstrated in Figure 6-1. In the United States, the White House Office of Management and Budget suggests a discount rate to be used for a given year (1.4% as of December 2014)[5]; similar rates are established in other countries. Typical rates used by public agencies for long-term investments are between 1% and 8%, with spikes from 0% to nearly 14%. The Society of Environmental Toxicology and Chemistry (SETAC) recommends a 0.01% discount rate for long-term investments (Swarr et al. 2011).

A higher discount rate means has the effect of decreasing the NPC of future activities. This is due to the fact that interest has had time to accrue before being spent on the future investment. For civil engineering

[5] https://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

projects, future maintenance and reconstruction are highly affected by the discount rates, particularly those that occur decades in the future.

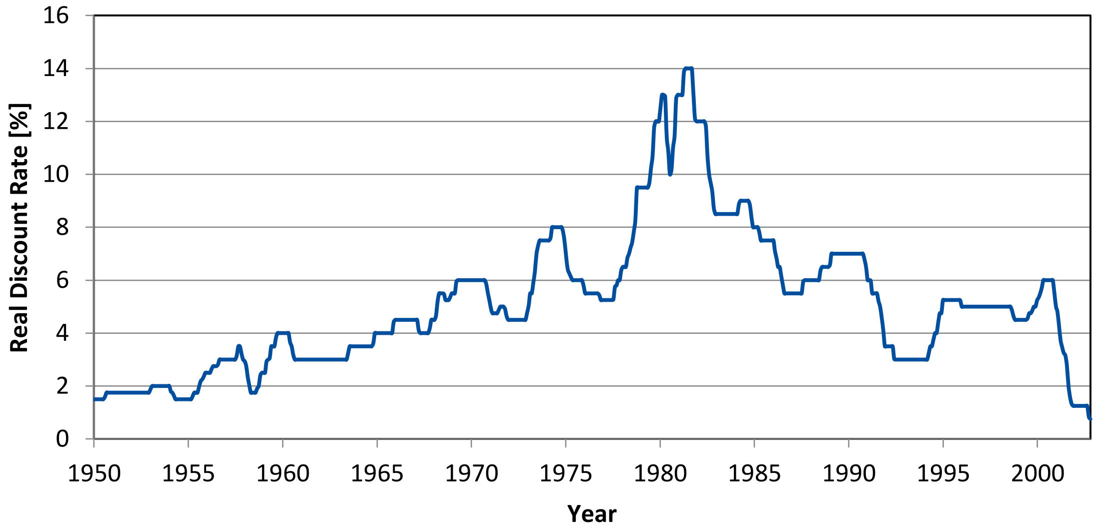

Figure 6-1: Historical discount rate, 1950 - 2002 (source: The Financial Forecast Center.org)

This analysis uses a 4.0% discount rate, following the Life-Cycle Benefit-Cost Analysis economic parameters suggested by the California Department of Transportation[6]. Given the variability and uncertainty, a sensitivity analysis is conducted for rates of 0.01%, 1.4%, and 10% in section 6.4.1.

6.2. Scope & Data

The scope of the LCCA is consistent with that of the LCA and includes the costs of materials, construction, maintenance, and deconstruction. At the end of the service life, a credit is given based on the remaining service years expected, following a linear depreciation schedule. While the NPC credited back is calculated at the end of the analysis period, the NPC of EoL activities is based on the expected year of disposal. The source of material cost data is the Life-365 software, while construction costs come from RS Means. The exception is the CGR cost data which comes from RS Means. Sensitivity analyses on construction and material costs are presented in section 6.4.

[6] http://www.dot.ca.gov/hq/tpp/offices/eab/benefit_cost/LCBCA-economic_parameters.html

Table 6-1: Unit costs of materials

Material	Unit cost (2015$)	Quantity
Concrete	\$100.01/m^3	2,470 m^3 initial construction; 750 m^3 overlay
Black bar	\$0.99/kg	233.1 tonnes
Epoxy-coated	\$1.32/kg	233.1 tonnes
CGR	\$1.08/kg	233.1 tonnes
Stainless	\$6.59/kg	233.1 tonnes

Table 6-2: Unit costs of construction and demolition activities

Activity	Unit cost (2015$)	Quantity
Construction		
Elevated slab	\$12.1/m^2	10,000 m^2
ES forms	\$56.8/m^2	10,000 m^2
ES reinforcing	\$606.3/tonne	233.1 tonnes
Total	\$311,499	Total initial construction activity costs
Overlay		
Hydro demolition	\$77.7/m^2	750 m^3
Concrete pouring	32.4/m^3	750 m^3
Total	\$801,482	Total overlay activity costs
EoL		
Demolition	\$271.4/m^3	2,470 m^3
Total	\$670,440	Total EoL activity costs

Table 6-3: Activity costs for each rebar type (before application of discount rate)

2015$	Black bar	Epoxy-coated	CGR (LC, HC)	Stainless
Initial Construction	\$789,323	\$866,246	\$810,092	\$2,094,683
Overlay	\$876,490	\$876,490	\$876,490	\$876,490
Replacement	\$1,459,763	\$1,536,686	\$1,480,533	\$2,765,123
EoL	\$670,440	\$670,440	\$ 670,440	\$670,440

6.3. Results

The LCCA results are presented below. Table 6-4 through Table 6-8 present the NPC associated with each activity within each rebar scenario, for Calgary exposure. The later an activity occurs in the analysis period, the less it costs.

Table 6-4: LCCA results for the black bar scenario in Calgary

Year	Activity	NPC (2015$)
0	Initial Construction	$789,323
16	Partial Overlay #1	$467,965
35	Replacement #1	$369,927
51	Partial Overlay #2	$118,590
70	Replacement #2	$93,745
86	Partial Overlay #3	$30,052
100	Residual Value	- $4,567
105	EoL	$10,911
	Total	**$1,875,946**

Table 6-5: LCCA results for the epoxy-coated scenario in Calgary

Year	Activity	NPC (2015$)
0	Initial Construction	$866,246
16	Partial Overlay #1	$467,965
38	Replacement #1	$346,193
54	Partial Overlay #2	$105,426
76	Replacement #2	$77,992
92	Partial Overlay #3	$23,751
100	Residual Value	- $11,044
114	EoL	$7,666
	Total	**$1,884,195**

Table 6-6: LCCA results for the CGR (LC) scenario in Calgary

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
22	Partial Overlay #1	$369,840
60	Replacement #1	$140,740
82	Partial Overlay #2	$35,157
100	Residual Value	- $9,134
120	EoL	$6,058
	Total	**$1,352,753**

Table 6-7: LCCA results for the CGR (HC) scenario in Calgary

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
36	Partial Overlay #1	$213,573
85	Replacement #1	$52,794
100	Residual Value	- $17,100
121	EoL	$5,825
	Total	**$1,065,185**

Table 6-8: LCCA results for the stainless steel scenario in Calgary

Year	Activity	NPC (2015$)
0	Initial Construction	$2,094,683
100	Residual Value	$0
100	EoL	$13,275
	Total	**$2,107,958**

The total life time NPC of each exposure scenario is presented in Figure 6-2. Within Calgary, Jacksonville, and Nashville, the CGR scenarios have the lowest total cost. In Tucson, everything but stainless steel is roughly equivalent in cost, with black bar slightly lower and epoxy-coated slightly higher than CGR. The shorter service life associated with the Jacksonville exposure scenario leads to high costs of black bar and epoxy-coated rebar.

Stainless steel rebar requires no replacements or maintenance in any of the exposure scenarios. In locations with harsh exposures, like Jacksonville, its high initial costs may be compensated for by its longevity. However, in less harsh environments, like Tucson, this longevity does not provide the same relative benefit as the alternatives also have longer lifetimes.

The time series comparison in Figure 6-3 shows that for Calgary, the CGR scenarios begin to become cheaper options at Year 16.

The Jacksonville results seen in Figure 6-4 show that the high initial cost of stainless steel is surpassed by black bar and epoxy-coated rebar at around Year 20. The CGR scenarios become cheaper alternatives to black bar and epoxy-coated rebar at Year 6.

In contrast to the above scenarios, the Nashville results in Figure 6-5 show CGR as the cheaper option only after about 30 years.

Finally, the results for Tucson seen in Figure 6-6 show no change in cost over the entire analysis period, which means the initial construction costs would drive the entire decision.

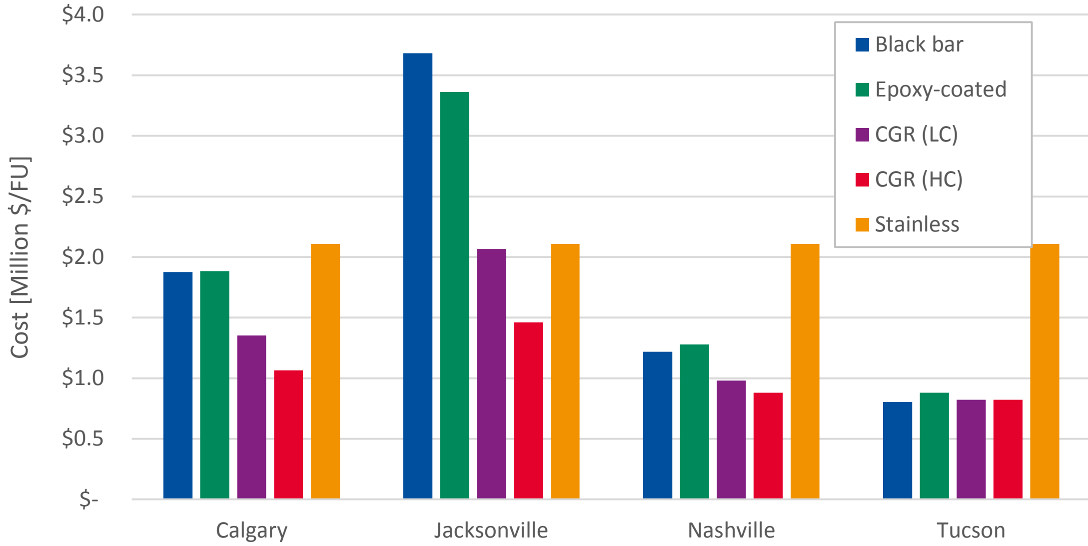

Figure 6-2: Complete life cycle NPC for all rebar and exposure scenarios

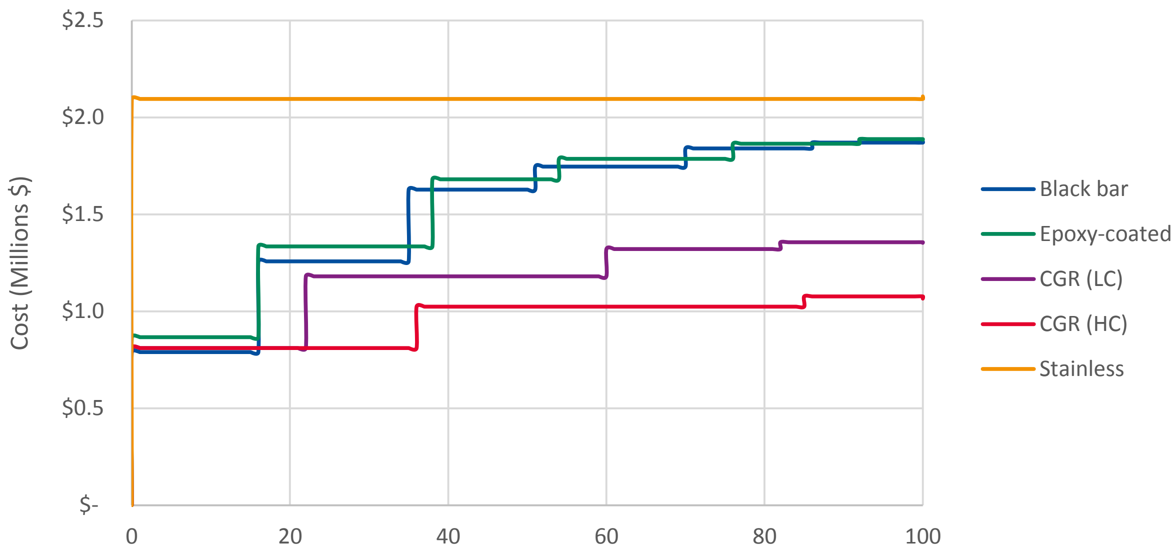

Figure 6-3: Time series comparison of LCCA results in Calgary

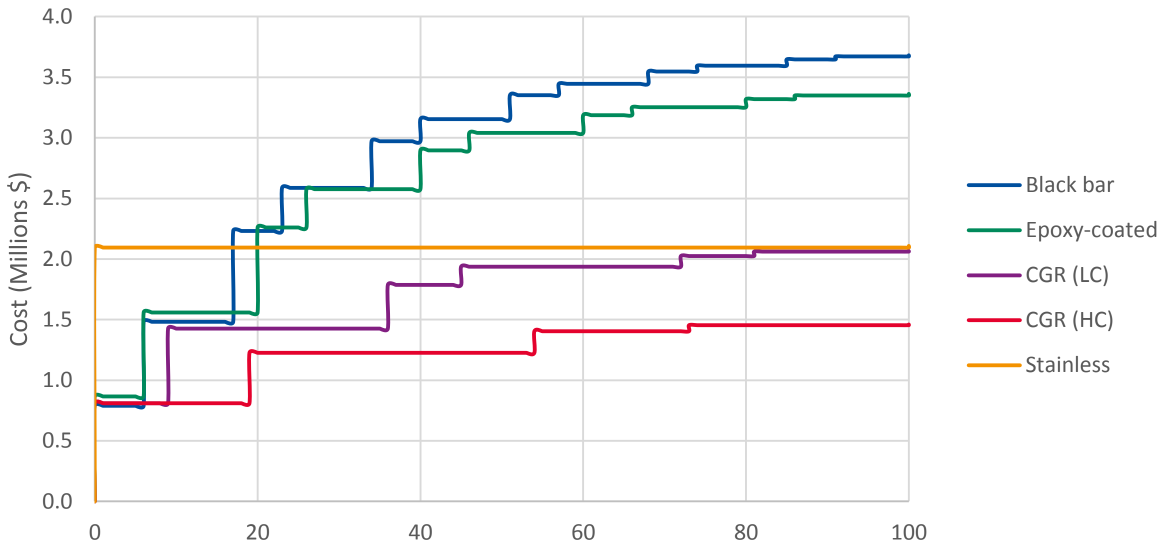

Figure 6-4: Time series comparison of LCCA results in Jacksonville

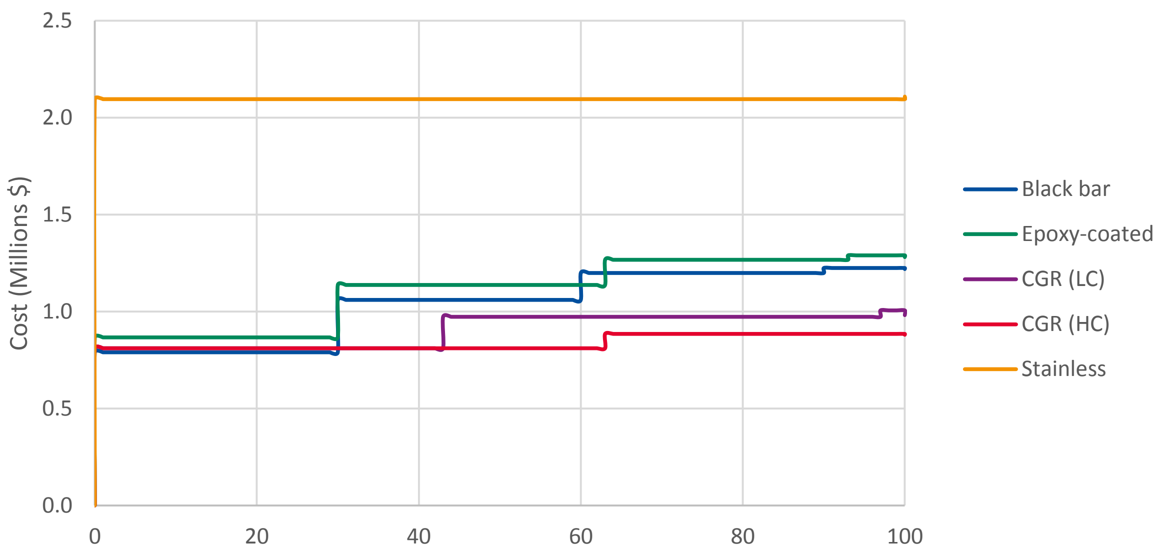

Figure 6-5: Time series comparison of LCCA results in Nashville

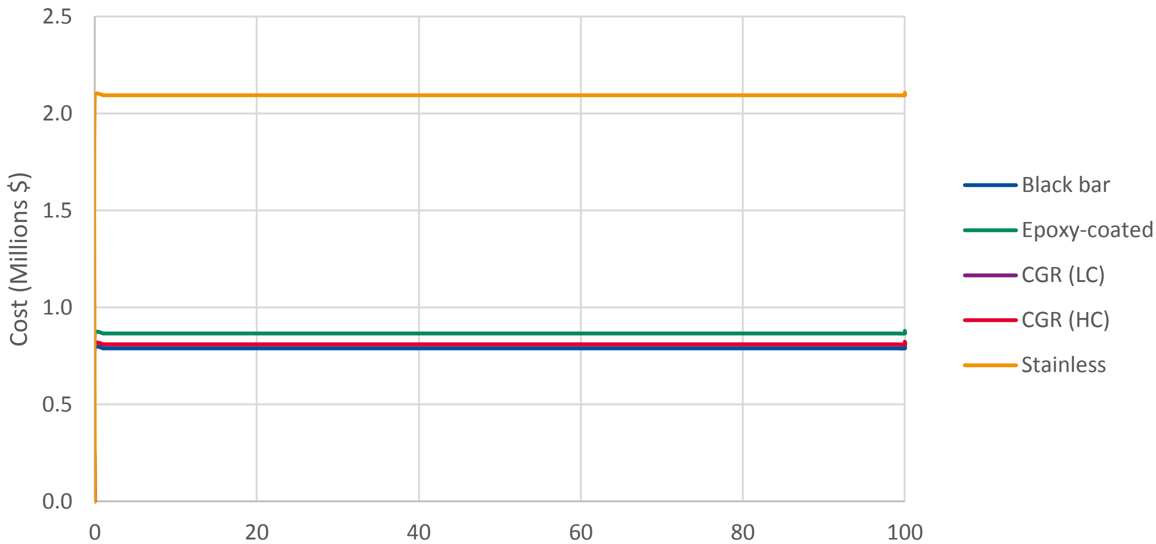

Figure 6-6: Time series comparison of LCCA results in Tucson

6.4. Sensitivity Analyses

6.4.1. Discount Rate

As discussed in section 6.1, the discount rate is a highly variable number. Figure 6-7 shows four different discount rates for each scenario: 0.01%, 1.4%, 4.0% (the baseline scenario), and 10%. Decreasing the discount rate leads to higher costs for later activities, increasing the effect of multiple replacement and maintenance activities, while increasing it causes the total NPC to be more dependent on initial construction costs than later maintenance activities. For Calgary, a 1.4% or 10% discount rate do not change the conclusion, but at 0.01% stainless steel has the lowest NPC. Within Jacksonville, both lower discount rates lead to stainless steel having the lowest NPC, compared to the baseline conclusion of CGR. With a 10% discount rate in Jacksonville, however, stainless steel has the highest NPC. The conclusions do not change for the Nashville and Tucson scenarios.

A higher discount rate is more conservative when comparing CGR to black bar and epoxy-coated rebar; however, a lower discount rate is more conservative when comparing CGR to stainless steel.

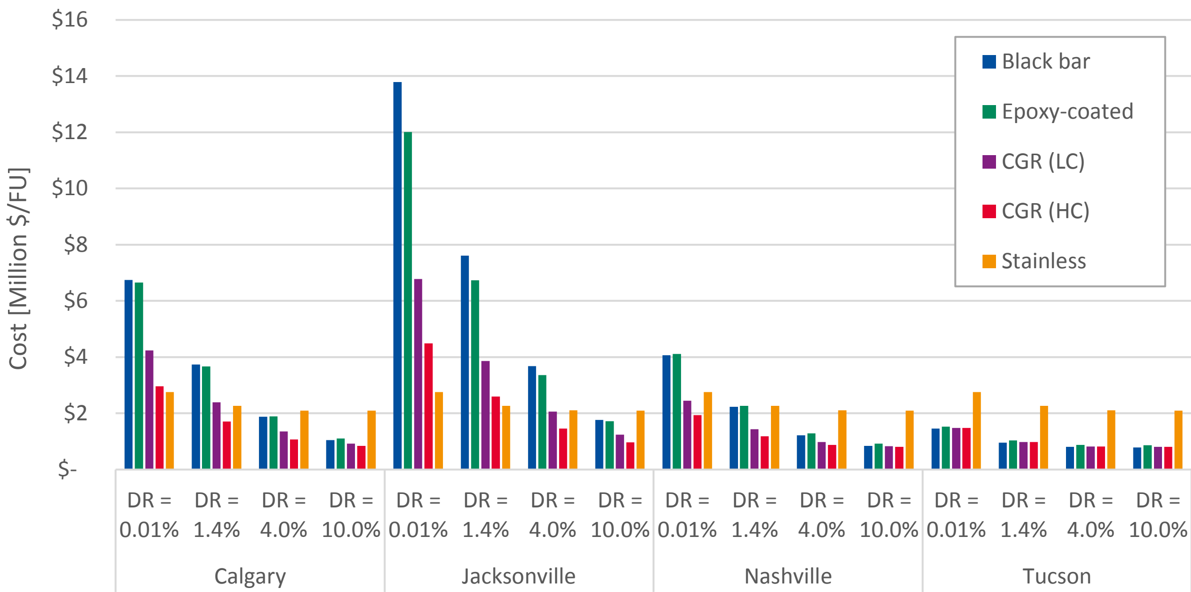

Figure 6-7: Discount rate sensitivity results

6.4.2. Construction Costs

Construction costs can vary significantly depending on location and time. Figure 6-8 shows three different scenarios: the first with no construction costs, the second with the baseline values presented in Table 6-2, and the third with the baseline costs doubled. Generally, the trends remain the same between the three different scenarios, with the exception of Jacksonville where doubling the construction impacts causes stainless steel to be comparable in NPC to CGR (HC).

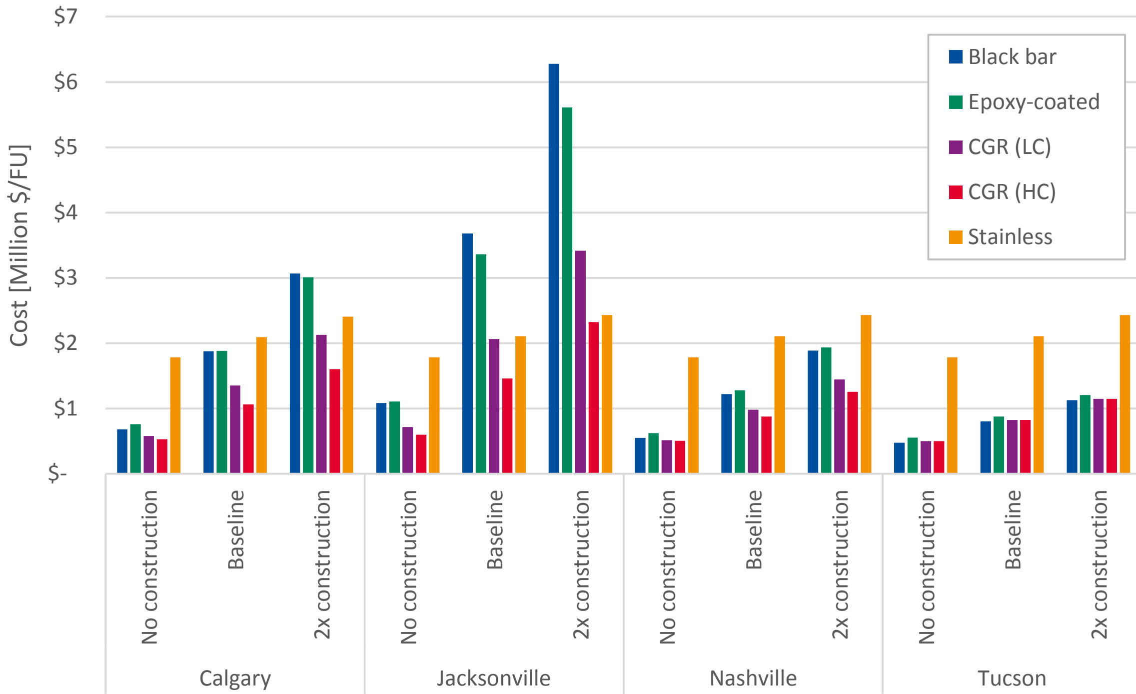

Figure 6-8: Construction cost sensitivity results (discount rate = 4.0%)

6.4.3. Material Costs

Material costs can vary depending on time and location of purchase. To assess the impact rebar costs have on the final results, the Federal Highway Administration (FHWA) was used as a second source for unit cost data. Table 6-9 shows the baseline material costs (taken from Life-365 and IZA) alongside the alternative costs from FHWA. The results, presented in Figure 6-9, show that rebar costs have very little effect on the total NPC and that the alternative cost scenario from FHWA does not change the conclusions of the study.

Table 6-9: Rebar unit cost scenarios

Material	Baseline	Alternative
Black bar	$0.99/kg	$1.06/kg
Epoxy-coated	$1.32/kg	$1.54/kg
CGR	$1.08/kg	$1.54/kg
Stainless	$6.59/kg	$5.51/kg

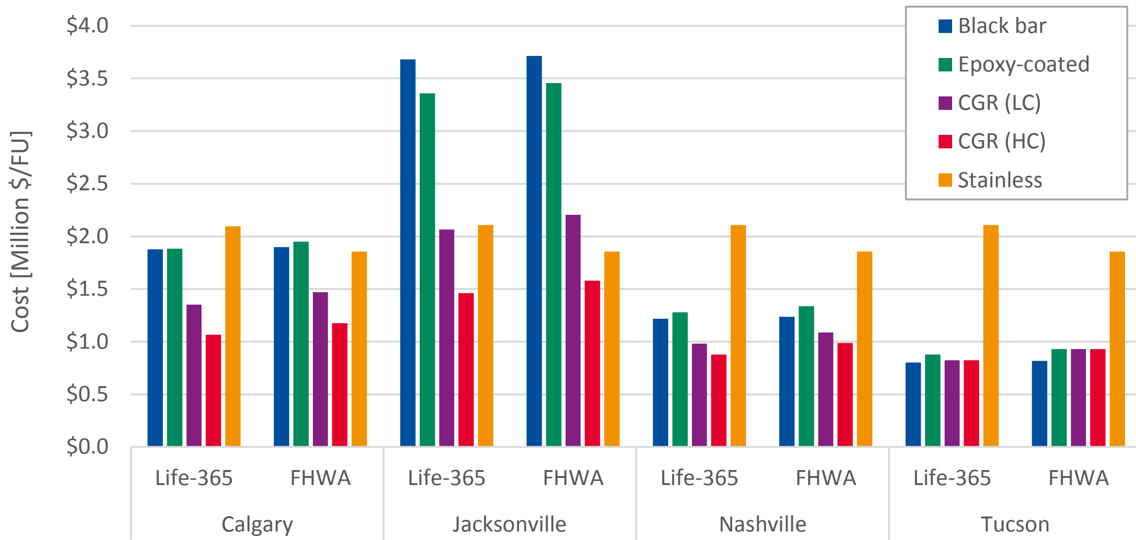

Figure 6-9: Rebar unit cost sensitivity results (discount rate = 4.0%)

6.4.4. Residual Service Life

The baseline scenario does not give residual service life credit to structures that do not require maintenance during the analysis period, under the assumption that the deck would fail for reasons other than rebar corrosion. To assess the impact this assumption has on the results, Table 6-10 shows the baseline scenario compared to a scenario where residual credit is awarded even when the deck has a longer service life than analysis period. The scenarios where the results changed are highlighted in blue. At most, the results reduced by 2%, which is not significant enough to alter the conclusions of the study.

It should be noted that the Life-365 software was set with an analysis period of 150 years; therefore, the maximum residual service life credit is calculated based on 150 years.

Table 6-10: Residual service life credit sensitivity results (discount rate = 4.0%)

	Black bar	Epoxy-coated	CGR (LC)	CGR (HC)	Stainless
Calgary					
Baseline	$1,875,946	$1,884,195	$1,352,753	$1,065,185	$2,107,958
Residual Life Credit	$1,875,946	$1,884,195	$1,352,753	$1,065,185	$2,082,726
Jacksonville					
Baseline	$3,680,943	$3,362,692	$2,065,742	$1,459,965	$2,107,958
Residual Life Credit	$3,680,943	$3,362,692	$2,065,742	$1,459,965	$2,083,524
Nashville					
Baseline	$1,218,505	$1,280,299	$980,861	$879,620	$2,107,958
Residual Life Credit	$1,218,505	$1,280,299	$980,861	$879,620	$2,082,726
Tucson					
Baseline	$802,598	$879,521	$823,367	$823,367	$2,107,958
Residual Life Credit	$800,669	$878,183	$806,614	$806,614	$2,082,726

6.5. Interpretation

The key takeaways from the life cycling costing exercise are summarized as follows:

- For all the baseline scenarios considered, the use of CGR (HC and LC) resulted in the lowest NPCs, with the exception of Tucson where black bar was the lowest NPC.
- Decreased discount rates lead to higher NPC, this change is most marked for those scenarios with more maintenance and replacement requirements.
- Increasing construction costs from the baseline further emphasizes differences in total NPC across rebar types, with the exception of stainless steel which requires only initial construction and final demolition at EoL. Decreasing construction costs leads to closer total NPC for black bar, epoxy-coated, and CGR types.

7. Synthesis & Discussion

This study included two CGR scenarios: a low and a high corrosion threshold. This represents the range of service life galvanized rebar would be expected to perform. Within this range, and under the Calgary, Jacksonville, and Nashville scenarios considered in this study, CGR shows improvement over black bar and epoxy-coated rebar for both environmental impacts and NPC. The decreased service life of these other rebar types leads to more frequent maintenance and replacement over the analysis period, rapidly multiplying both impacts and costs.

In Tucson it was seen that, due to the less severe exposure conditions, a longer rebar service life was not beneficial. Black bar, epoxy-coated rebar, and CGR were found to be comparable both in environmental impacts and cost, while stainless steel was significantly higher in both categories.

The use of continuously galvanized rebar, depending on the exposure scenario and climate considered, has the potential to reduce both lifetime environmental impacts and net present costs.

Further research on the continuous galvanization process would improve the underlying cost and environmental data of this study. Future studies may consider exploring the variation and uncertainty associated with the times to initiation and propagation of each type of rebar, as this informs the maintenance schedules which is a key indicator of total impact and cost.

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US EPA 2003	U.S. Environmental Protection Agency (2003). *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Clay Brick Reuse and Concrete Recycling*. Available here: http://www.epa.gov/epawaste/conserve/tools/warm/pdfs/ClayBrickandConcrete_11_07.pdf
Yeomans 2004	Yeomans, S.R., (Editor) (2004). *Galvanized Steel Reinforcement in Concrete*, Elsevier.

Appendix A – Calculations

CGR

Zinc quantity:

$$Thickness^{7} = 0.05mm$$

$$Density = 7140\frac{kg}{m^3}$$

$$SA^{8} = 9{,}356\ m^2$$

$$0.05mm\ \times \frac{1\ m}{1000\ mm} \times 9{,}356\ m^2 \times 7140\frac{kg}{m^3} = 3{,}340\ kg\ zinc$$

$$\frac{2{,}982\ kg\ zinc}{233{,}100\ kg\ steel} = 0.0143\ \frac{kg\ zinc}{kg\ steel}$$

Epoxy-coated rebar

Epoxy quantity:

$$Thickness^{9} = 0.255mm$$

$$Density = 1250\frac{kg}{m^3}$$

$$SA = 9{,}356\ m^2$$

$$0.255mm\ \times \frac{1\ m}{1000\ mm} \times 9{,}356\ m^2 \times 1250\frac{kg}{m^3} = 2{,}982\ kg\ epoxy$$

$$\frac{2{,}982\ kg\ epoxy}{233{,}100\ kg\ steel} = 0.0128\ \frac{kg\ epoxy}{kg\ steel}$$

Thermal energy:

$$Heat\ content\ of\ steel^{10} = 0.12\frac{Btu}{lb°\mathrm{F}}$$

$$T_0 = 60°\mathrm{F}$$

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[7] IZA, http://www.zinc.org/general/CGR_Brochure_9x12_vF[1].pdf
[8] 233,100 kg of No.4 rebar (12.7mm diameter)
[9] Choi et al. 1991
[10] http://www.engineeringtoolbox.com/specific-heat-metals-d_152.html

T_F[11] $= 450°\mathrm{F}$

$$(450°\mathrm{F} - 60°\mathrm{F}) \times 0.12 \frac{Btu}{lb°\mathrm{F}} \times \frac{2.205\ lb}{1\ kg} \times \frac{1\ MJ}{947.8\ Btu} = 0.109 \frac{MJ}{kg\ steel}$$

[11] http://epoxyinterestgroup.org/index.cfm/FAQ#

Appendix B – LCIA Results

Jacksonville

Table B-1: Absolute LCIA results for black bar in Jacksonville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,625	213	1,503,936	6.57E-03	93,931	10,485,177
6	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
17	Replacement #1	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
23	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
34	Replacement #2	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
40	Partial Overlay #3	2,564	136	505,082	1.14E-03	47,971	4,188,140
51	Replacement #3	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
57	Partial Overlay #4	2,564	136	505,082	1.14E-03	47,971	4,188,140
68	Replacement #4	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
74	Partial Overlay #5	2,564	136	505,082	1.14E-03	47,971	4,188,140
85	Replacement #5	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
91	Partial Overlay #6	2,564	136	505,082	1.14E-03	47,971	4,188,140
102	Next activity	Residual life based on year next activity would have been required					
102	EoL	927	61	191,389	2.73E-04	21,709	2,936,366
100	Residual Life	-466	-25	-91,833	-2.07E-04	-8,722	-761,480
	Total	**60,227**	**2,433**	**13,110,611**	**4.77E-02**	**972,942**	**104,896,618**

Table B-2: Absolute LCIA results for epoxy-coated black bar in Jacksonville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,729	221	1,546,513	6.57E-03	95,768	11,210,104
6	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
20	Replacement #1	7,665	282	1,741,358	6.73E-03	117,567	14,179,359
26	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
40	Replacement #2	7,665	282	1,741,358	6.73E-03	117,567	14,179,359
46	Partial Overlay #3	2,564	136	505,082	1.14E-03	47,971	4,188,140
60	Replacement #3	7,665	282	1,741,358	6.73E-03	117,567	14,179,359
66	Partial Overlay #4	2,564	136	505,082	1.14E-03	47,971	4,188,140
80	Replacement #4	7,665	282	1,741,358	6.73E-03	117,567	14,179,359
86	Partial Overlay #5	2,564	136	505,082	1.14E-03	47,971	4,188,140
100	Next activity	Residual life based on year next activity would have been required					
100	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-	-	-	-	-	-
	Total	**51,142**	**2,090**	**11,232,201**	**3.94E-02**	**827,691**	**91,837,494**

Table B-3: Absolute LCIA results for CGR (LC) in Jacksonville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
9	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
36	Replacement #1	7,794	286	1,765,354	6.74E-03	119,697	14,324,258
45	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
72	Replacement #2	7,794	286	1,765,354	6.74E-03	119,697	14,324,258
81	Partial Overlay #3	2,564	136	505,082	1.14E-03	47,971	4,188,140
108	Next activity	Residual life based on year next activity would have been required					
108	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-760	-40	-149,654	-3.38E-04	-14,214	-1,240,930
	Total	**30,315**	**1,224**	**6,661,385**	**2.33E-02**	**488,784**	**54,293,687**

Table B-4: Absolute LCIA results for CGR (HC) in Jacksonville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
19	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
54	Replacement #1	7,794	286	1,765,354	6.74E-03	119,697	14,324,258
73	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
108	Next activity	Residual life based on year next activity would have been required					
108	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-586	-31	-115,447	-2.61E-04	-10,965	-957,289
	Total	**20,131**	**812**	**4,425,155**	**1.55E-02**	**324,364**	**36,064,930**

Table B-5: Absolute LCIA results for stainless steel rebar in Jacksonville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	16,285	1,543	2,078,639	5.56E-02	143,142	18,998,026
147	Next activity	Past 100 year service life					
147	EoL	-2,062	-25	-119,577	-1.49E-03	-9,626	-1,209,123
100	Residual Life	Assumes concrete will have failed after 100 years without replacement					
	Total	**14,223**	**1,519**	**1,959,062**	**5.41E-02**	**133,515**	**17,788,902**

Nashville

Table B-6: Absolute LCIA results for black bar in Nashville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,625	213	1,503,936	6.57E-03	93,931	10,485,177
30	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
60	Replacement #1	7,552	274	1,695,325	6.84E-03	115,639	13,421,543
90	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
120	Next activity	Residual life based on year next activity would have been required					
120	EoL	927	61	191,389	2.73E-04	21,709	2,936,366
100	Residual Life	-1,709	-90	-336,722	-7.60E-04	-31,981	-2,792,093
	Total	**18,522**	**729**	**4,064,093**	**1.52E-02**	**295,240**	**32,427,273**

Table B-7: Absolute LCIA results for epoxy-coated black bar in Nashville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,729	221	1,546,513	6.57E-03	95,768	11,210,104
30	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
63	Replacement #1	7,665	282	1,741,358	6.73E-03	117,567	14,179,359
93	Partial Overlay #2	2,564	136	505,082	1.14E-03	47,971	4,188,140
126	Next activity	Residual life based on year next activity would have been required					
126	EoL	927	61	191,389	2.73E-04	21,709	2,936,366
100	Residual Life	-2,020	-107	-397,944	-8.98E-04	-37,796	-3,299,747
	Total	**18,428**	**729**	**4,091,482**	**1.50E-02**	**293,190**	**33,402,362**

Table B-8: Absolute LCIA results for CGR (LC) in Nashville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
43	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
97	Replacement #1	7,794	286	1,765,354	6.74E-03	119,697	14,324,258
140	Next activity	Residual life based on year next activity would have been required					
140	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-7,251	-266	-1,642,190	-6.27E-03	-111,346	-13,324,891
	Total	**10,902**	**441**	**2,393,331**	**8.36E-03**	**176,012**	**19,509,188**

Table B-9: Absolute LCIA results for CGR (HC) in Nashville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
63	Partial Overlay #1	2,564	136	505,082	1.14E-03	47,971	4,188,140
133	Next activity	Residual life based on year next activity would have been required					
133	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-1,209	-64	-238,110	-5.38E-04	-22,615	-1,974,409
	Total	**9,149**	**358**	**2,032,056**	**7.35E-03**	**145,046**	**16,535,412**

Table B-10: Absolute LCIA results for stainless steel rebar in Nashville

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	16,285	1,543	2,078,639	5.56E-02	143,142	18,998,026
150	Next activity			Past 100 year service life			
150	EoL	-2,062	-25	-119,577	-	-9,626	-1,209,123
100	Residual Life	-	-	-	-	-	-
	Total	**14,223**	**1,519**	**1,959,062**	**5.41E-02**	**133,515**	**17,788,902**

Tucson

Table B-11: Absolute LCIA results for black bar in Tucson

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,625	213	1,503,936	6.57E-03	93,931	10,485,177
103	Next activity			Past 100 year service life			
103	EoL	927	61	191,389	2.73E-04	21,709	2,936,366
100	Residual Life	-	-	-	-	-	-
	Total	**7,552**	**274**	**1,695,325**	**6.84E-03**	**115,639**	**13,421,543**

Table B-12: Absolute LCIA results for epoxy-coated black bar in Tucson

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,729	221	1,546,513	6.57E-03	95,768	11,210,104
102	Next activity			Past 100 year service life			
102	EoL	927	61	191,389	2.73E-04	21,709	2,936,366
100	Residual Life	-	-	-	-	-	-
	Total	**7,656**	**282**	**1,737,903**	**6.85E-03**	**117,476**	**14,146,470**

Table B-13: Absolute LCIA results for CGR (LC) in Tucson

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
150	Next activity			Past 100 year service life			
150	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-	-	-	-	-	-
	Total	**7,794**	**286**	**1,765,084**	**6.75E-03**	**119,690**	**14,321,681**

Table B-14: Absolute LCIA results for CGR (HC) in Tucson

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	6,858	225	1,570,240	6.59E-03	97,890	11,352,426
150	Next activity			Past 100 year service life			
150	EoL	936	61	194,845	1.60E-04	21,799	2,969,254
100	Residual Life	-	-	-	-	-	-
	Total	**7,794**	**286**	**1,765,084**	**6.75E-03**	**119,690**	**14,321,681**

Table B-15: Absolute LCIA results for stainless steel rebar in Tucson

Year	Phase	AP	EP	GWP	ODP	SFP	PED, nr
0	Initial Construction	16,285	1,543	2,078,639	5.56E-02	143,142	18,998,026
150	Partial Overlay #1			Past 100 year service life			
150	EoL	-2,062	-25	-119,577	-	-9,626	-1,209,123
100	Residual Life	-	-	-	-	-	-
	Total	**14,223**	**1,519**	**1,959,062**	**5.41E-02**	**133,515**	**17,788,902**

Appendix C – LCCA Results

Jacksonville

Table C-16: LCCA results for the black bar scenario in Jacksonville

Year	Activity	NPC (2015$)
0	Initial Construction	$789,323
6	Partial Overlay #1	$692,703
17	Replacement #1	$749,403
23	Partial Overlay #2	$355,615
34	Replacement #2	$384,724
40	Partial Overlay #3	$182,563
51	Replacement #3	$197,507
57	Partial Overlay #4	$93,723
68	Replacement #4	$101,395
74	Partial Overlay #5	$48,115
85	Replacement #5	$52,053
91	Partial Overlay #6	$24,701
100	Residual Value	- $3,155
102	EoL	$12,273
	Total	**$3,684,098**

Table C-17: LCCA results for the epoxy-coated scenario in Jacksonville

Year	Activity	NPC (2015$)
0	Initial Construction	$866,246
6	Partial Overlay #1	$692,703
20	Replacement #1	$701,324
26	Partial Overlay #2	$316,140
40	Replacement #2	$320,075
46	Partial Overlay #3	$144,282
60	Replacement #3	$146,078
66	Partial Overlay #4	$65,849
80	Replacement #4	$66,668
86	Partial Overlay #5	$30,052
100	Residual Value	$0
100	EoL	$13,275
	Total	**$3,362,692**

Table C-18: LCCA results for the CGR (LC) scenario in Jacksonville

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
9	Partial Overlay #1	$615,810
36	Replacement #1	$360,759
45	Partial Overlay #2	$150,054
72	Replacement #2	$87,906
81	Partial Overlay #3	$36,563
100	Residual Value	- $5,142
108	EoL	$9,700
	Total	**$2,065,742**

Table C-19: LCCA results for the CGR (HC) scenario in Jacksonville

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
19	Partial Overlay #1	$416,019
54	Replacement #1	$178,081
73	Partial Overlay #2	$50,040
100	Residual Value	- $3,967
108	EoL	$9,700
	Total	**$1,459,965**

Table C-20: LCCA results for the stainless steel scenario in Jacksonville

Year	Activity	NPC (2015$)
0	Initial Construction	$2,094,683
100	Residual Value	$0
100	EoL	$13,275
	Total	**$2,107,958**

Nashville

Table C-21: LCCA results for the black bar scenario in Nashville

Year	Activity	NPC (2015$)
0	Initial Construction	$789,323
30	Partial Overlay #1	$270,238
60	Replacement #1	$138,766
90	Partial Overlay #2	$25,689
100	Residual Value	- $11,570
120	EoL	$6,058
	Total	**$1,218,505**

Table C-22: LCCA results for the epoxy-coated scenario in Nashville

Year	Activity	NPC (2015$)
0	Initial Construction	$866,246
30	Partial Overlay #1	$270,238
63	Replacement #1	$129,863
93	Partial Overlay #2	$22,837
100	Residual Value	-$13,673
126	EoL	$4,788
	Total	**$1,280,299**

Table C-23: LCCA results for the CGR (LC) scenario in Nashville

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
43	Partial Overlay #1	$162,298
97	Replacement #1	$32,975
100	Residual Value	- $27,269
140	EoL	$2,765
	Total	**$980,861**

Table C-24: LCCA results for the CGR (HC) scenario in Nashville

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
63	Partial Overlay #1	$74,071
100	Residual Value	- $8,181
108	EoL	$3,639
	Total	**$879,620**

Table C-25: LCCA results for the stainless steel scenario in Nashville

Year	Activity	NPC (2015$)
0	Initial Construction	$2,094,683
100	Residual Value	$0
100	EoL	$13,275
	Total	**$2,107,958**

Tucson

Table C-26: LCCA results for the black bar scenario in Tucson

Year	Activity	NPC (2015$)
0	Initial Construction	$789,323
100	Residual Value	$0
100	EoL	$13,275
	Total	*$802,598*

Table C-27: LCCA results for the epoxy-coated scenario in Tucson

Year	Activity	NPC (2015$)
0	Initial Construction	$866,246
100	Residual Value	$0
100	EoL	$13,275
	Total	*$879,521*

Table C-28: LCCA results for the CGR (LC) scenario in Tucson

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
100	Residual Value	$0
100	EoL	$13,275
	Total	*$823,367*

Table C-29: LCCA results for the CGR (HC) scenario in Tucson

Year	Activity	NPC (2015$)
0	Initial Construction	$810,092
100	Residual Value	$0
100	EoL	$13,275
	Total	*$823,367*

Table C-30: LCCA results for the stainless steel scenario in Tucson

Year	Activity	NPC (2015$)
0	Initial Construction	$2,094,683
100	Residual Value	$0
100	EoL	$13,275
	Total	*$2,107,958*