HISTORICAL LIFE CYCLE COSTS OF STEEL & CONCRETE GIRDER BRIDGES

Prepared For
American Iron & Steel Institute
Steel Marketing Development Institute
Short Span Steel Bridge Alliance
National Steel Bridge Alliance
American Galvanizers Association

Michael G. Barker, PhD, PE
Professor
Civil & Architectural Engineering
University of Wyoming

May 31, 2016

Executive Summary

Since the early 1990's, the Federal Highway Administration (FHWA) has promoted the consideration of Life Cycle Costs Analysis (LCCA) in the design and engineering of bridges. LCCA determines the "true cost" of bridge alternatives considering the time value of money. The Life Cycle Cost analyses employed in this study uses the Perpetual Present Value Cost (PPVC) of bridge alternatives for an equivalent comparison between the alternatives.

Over the years, the author has worked with state departments of transportations and local county engineers on effective and economical bridge construction. A frequent question that arises during meetings is the difference in Life Cycle Costs between steel and concrete girder bridges. Both the concrete industry and the steel industry site various anecdotal advantage above the other for the Life Cycle Costs over the life of the bridge. There has historically been a healthy competition between material types for new bridge construction. However, there is industry and owner confusion on how the different types of bridges compare on a Life Cycle Cost basis.

This study developed useful owner information on historical Life Cycle Costs for typical steel and concrete state bridges in Pennsylvania. Typical bridges are defined in the study as those with concrete decks supported by steel rolled beams, steel plate girders, precast concrete boxes, or precast concrete beams. PennDOT historical records for bridges built between 1960 and 2010 were used to develop a database for the Life Cycle Cost study. Initial and maintenance costs considered include total project costs (more than just superstructure) as recorded in the PennDOT records. The PennDOT database used for the Life Cycle Cost analyses only includes a subset of the total bridge inventory due to missing cost and date data for a majority of the individual bridges. The database consists of 1186 state bridges out of 6587 (18% of the eligible inventory) built between 1960 and 2010.

The initial costs, Life Cycle Costs, and future costs of the 1186 bridges in the database are examined with respect to variability in bridge type, bridge length, number of spans, and bridge life. The steel bridges in the database are also examined with respect to protective coating systems. Consideration of the specific numbers and any conclusions must be taken in the context that the results represent the bridges that made it into the database, and the database is not as comprehensive as desirable for drawing conclusions. Therefore, interpreting the tables and figures showing comparisons of initial costs, Perpetual Present Value Costs, maintenance and future costs, and bridge life is left to the reader.

A conclusion that can be drawn is that all the types of bridges are fairly competitive in both Initial Costs and Perpetual Present Value Costs. The average initial costs vary from \$174/ft^2 to \$226/ft^2 and the average Perpetual Present Value Costs vary between \$218/ft^2 (Pretressed I Beam) and \$278/ft^2 (Prestressed Adjacent Box). For bridge life, the lowest average life was 73 years (Pretressed I Beam) and the longest was 82 years (Steel I Beam). The coefficient of variation (standard deviation / mean) of the PPVC was approximately 20%, which is considerably high. With the relatively small differences in the PPVC averages, given the dispersion of the PPVC costs (standard deviation), any of the bridge types may have the least Perpetual Present Value Cost for a given project.

Even though this research was limited to only a subset of PennDOT bridges, the analyses demonstrate the potential benefits of LCC analysis for bridge construction and management. A study of a more comprehensive database of bridges on the initial costs, Life Cycle Costs and future costs of different types of bridges over a diverse set of circumstances would be very useful for bridge owners and managers. With a more comprehensive database, not only would there be a more accurate comparison of bridge types, an accurate comparison of design details, such as jointless decks, rebar coatings, steel protection systems, and other construction details could be completed.

Acknowledgements

This study is a result of the author's discussions with state and county bridge engineers' questions on Life Cycle Costs of bridges. The work is an attempt to give bridge owners Life Cycle Cost data so that they can make informed decisions in their bridge programs.

The author would like to acknowledge financial support from the Steel Marketing Development Institute, the National Steel bridge Alliance, and the American Galvanizers Association.

The professionals of the Pennsylvania Department of Transportation deserve special thanks. PennDOT Bridge Engineer Tom Macioce eagerly agreed to be part of the study, a welcome agreement given the difficulty the author had in securing bridge data. Gathering the necessary historical data was a daunting task. The engineers at PennDOT, and especially Civil Engineer Katherine Schopman, devoted many hours mining and verifying historical records so the author could develop an accurate bridge database for the Life Cycle Cost study.

Table of Contents

Table of Tables

Table of Figures

1 - Introduction

1.1 Background

Since the early 1990's, the Federal Highway Administration (FHWA) has promoted the consideration of Life Cycle Costs Analysis (LCCA) in the design and engineering of bridges. LCCA is an economic method to compare design alternatives over the entire life of the structure. The method considers not only initial costs, but also the future costs, their timing, and the service life of the bridge. LCCA determines the "true cost" of bridge alternatives, considering the time value of money, for an equivalent monetary comparison.

For instance, if one alternative has a high initial cost and no futures costs, LCCA can compare this to an alternative that has a lower initial cost and a major costly rehabilitation at 40 years. LCCA methods discount future costs to equivalent today costs for a direct economic comparison.

There has historically been a healthy competition between material types for new bridge construction. The most prevalent material types being used for typical bridges (those considered in this study) include steel rolled beams or plate girders and precast concrete box or beam superstructures with concrete decks. However, there is industry and owner confusion on how the different types of bridges compare on a Life Cycle Cost basis.

Both the concrete industry and the steel industry site various anecdotal advantage above the other for the Life Cycle Costs over the life of the bridge, and both are correct. Yes, given the competition between steel and concrete, different characteristics across the country's regions, diverse design and construction techniques employed by owners, varied maintenance program efforts, etc, sometimes steel may show an advantage and sometimes concrete may show an advantage. This is especially true for a bridge at an individual site, in a specific region, and with particular environmental characteristics.

Over the years, the author has worked with state departments of transportations and local county engineers on effective and economical bridge construction. A frequent question that arises during meetings is the difference in Life Cycle Costs between steel and concrete girder bridges. The discussion entails anecdotal information from the concrete industry and the steel industry. The concrete industry, using their projected maintenance and rehabilitation assumptions, can show that a precast beam bridge with integral abutments has lower Life Cycle Costs than a painted steel beam bridge with end deck joints in a northern state that uses road salt. The steel industry can show, with their assumptions, that a galvanized steel bridge with a jointless deck has a lower Life Cycle Cost in that same environment. Although the discussions are helpful, the issue remains unsettled. Owners want to consider LCC in bridge design decisions, but many are uncomfortable with this anecdotal discussion.

1.2 Objectives

The objective of this study was to develop useful owner information on historical Life Cycle Costs for typical bridges across the country. A database of bridges across the country was to be developed for the

Life Cycle Cost analyses. For each bridge in the database, the LCC analysis requires: the year built and the initial cost; dates and costs for repairs, maintenance and rehabilitations, and the reasons for the work; and the end-of-service life that may be actual or estimated. The intent was to develop historical Life Cycle Cost data for bridges owned by state departments of transportation (state) and those owned by counties (local). There is a significant difference between state and local bridges in both initial costs and maintenance costs.

The typical bridges in the study are simple- and multi-span "regular type" rolled steel, plate girder, precast I-beam, and precast box beam bridges. The years of inclusion were set to bridges built between 1960 (modern era for prestressed concrete and steel construction techniques) and 2010. Different geographical regions were to be included to examine wet and dry, cold and warm, and various environmental condition climates. For the steel bridges, the plan was to examine the influence of painted, weathering steel and galvanized protection systems. It was also desired to study the impact of other characteristics that would have an influence such as type of construction, deck material and joint details, deck rebar coatings, traffic volume and original design loads.

As stated above, the objective of this study was to develop useful owner information on historical Life Cycle Costs for typical state owned and local owned bridges across the country. The author worked with several select states and various select counties to develop a comprehensive database of bridges. However, the effort was, for the most part, unsuccessful. The data collection requirement of knowing each bridge's entire life of initial costs and future costs and dates was problematic for the owners due to the high amount of time and resources required to collect the data. Of the states contacted, only the Pennsylvania Department of Transportation had the necessary complete data for a subset of their bridge inventory. At the local level, although some counties had complete data for a few of their bridges, the number of bridges was small and using only a few bridges from a wide range of counties would not result in a consistent study, nor would the result be representative of county bridges.

Therefore, although the study was intended to examine state and local bridges across the country, the study was limited to state owned bridges in Pennsylvania. Also, the PennDOT database used for the Life Cycle Cost analyses only includes a subset of the total bridge inventory due to missing data for the majority of the individual bridges. The final Life Cycle Cost database consists of 1186 state bridges out of 6587 built between 1960 and 2010. This means the database represents 18% of the inventory. The report describes the criteria applied to development of the PennDOT bridge database that is used for the Life Cycle Cost analyses.

1.3 Summary of Results

The report presents the Life Cycle Cost analyses for the bridge database. The initial costs, Life Cycle Costs, and future costs of the 1186 bridges in the database are examined with respect to variability in bridge type, bridge length, number of spans, and bridge life. The steel bridges in the database are also examined with respect to protective coating systems.

The database must be considered only a snapshot of the total PennDOT bridge inventory. The criteria removed 82% of the eligible bridges built between 1960 and 2010, mostly due to incomplete initial cost, maintenance records and external contract records. If these records were complete, the database would be much larger and the resulting Life Cycle Cost analyses would more accurately represent the PennDOT bridge inventory. Consideration of the specific numbers and any conclusions must be taken in the context that the results represent the bridges that made it into the database, and the database is not as comprehensive as one would like.

However, the study shows that all the types of steel and concrete bridges are fairly competitive in both average Initial Costs and average Life Cycle Costs. With the dispersion of costs (standard deviation) any of the bridge types may have the least Life Cycle Cost for a given project.

1.4 Benefits and Future Work

This historical Life Cycle Cost study was limited to state bridges in Pennsylvania. Even though this research was limited to only a subset of PennDOT bridges, the analyses demonstrate the potential benefits of LCC analysis for bridge construction and management. A study of a more comprehensive database of bridges on the initial costs, Life Cycle Costs and future costs of different types of bridges over a diverse set of circumstances would be very useful for bridge owners and managers. Although extending this work would take considerable effort, other states and counties could be contacted in an effort to obtain a comprehensive bridge database.

2 - Life Cycle Costs

2.1 Introduction

Life Cycle Costs (LCC) analysis is an economic tool that allows comparison of competing project alternatives. For instance, does spending additional funds now that will reduce future maintenance costs make economic sense? A difficulty in comparing alternatives, even when represented in the same terms such as dollars, is that when the dollars are spent has an influence on equivalency due to inflation and discounting.

2.2 Time Value of Money and Discount Rate

Expenditures that occur at various times in the future will have values that depend on the time of the expenditure. A dollar in 1990 has more purchasing power than a dollar in 2014. This is called inflation. Expenditures that occur at various times in the future also must consider the opportunity value of time. Delayed expenditures (future) have the opportunity for economic return (for instance interest) that could be earned on the delayed monies. A dollar today is worth significantly more than a dollar in ten years because the dollar today could be invested and earn interest. This is called discounting. An effective Discount Rate (DR) that considers the effect of inflation (removes inflation) can be determined so that initial and future expenditures can be used to discount cash flow (time value of money) using constant (today) dollars. The DR (effective) will take care of the inflation (due to using constant today dollars) and the discounting for value of time (opportunity for economic return). The present value cost of a future cost (in today's constant dollars) occurring at year N with an effective discount rate of DR is:

$$Present\ Value\ Cost = Future\ Cost(1 + DR)^{-N}$$

For instance, if a concrete deck repair would cost \$1000 today, but it occurs 20 years in the future, at a discount rate of 2.3% the present value cost of that repair in the future is:

$$Present\ Value\ Cost = \$1000(1 + 0.023)^{-20} = \$634.58$$

With inflation, the actual cost in 20 years will exceed the constant dollar today cost of \$1000, but the \$634.58 invested today will grow over the 20 years at an interest rate (greater than the discount rate) that will be able to pay for the inflated actual cost at year 20. The effective Discount Rate allows Time Value of Money analysis using today's costs (constant dollars) and removes the need to consider inflation and discounting separately.

Discount rate has various meanings for different industries such as banking, the Federal Reserve, pensions and insurance companies. For LCC analysis, the discount rate represents the effective interest rate, accounting for inflation, used to discount cash flow (time value of money). The discount rate used in this work is taken from the Federal Office of Management and Budget Circular No. A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*, Appendix C.

The OMB Circular No A-94 defines nominal and real discount rates for current and past years. The real discount rate is the effective discount rate that accounts for inflation. Table 1 presents historical real discount rates based on interest rates on treasury notes and bonds of specified maturities.

Table 1: OMB Circular A-94 Historical Real Discount Rates

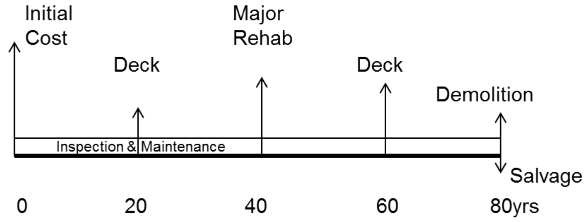
Year	Treasury Notes and Bonds Maturity					
	3 Year	5 Year	7 Year	10 Year	20 Year	30 Year
1979	2.8	3.4	4.1	4.6	#N/A	5.4
1980	2.1	2.4	2.9	3.3	#N/A	3.7
1981	3.6	3.9	4.3	4.4	#N/A	4.8
1982	6.1	7.1	7.5	7.8	#N/A	7.9
1983	4.2	4.7	5	5.3	#N/A	5.6
1984	5	5.4	5.7	6.1	#N/A	6.4
1985	5.9	6.5	6.8	7.1	#N/A	7.4
1986	4.6	5.1	5.6	5.9	#N/A	6.7
1987	2.8	3.1	3.5	3.8	#N/A	4.4
1988	3.5	4.2	4.7	5.1	#N/A	5.6
1989	4.1	4.8	5.3	5.8	#N/A	6.1
1990	3.2	3.6	3.9	4.2	#N/A	4.6
1991	3.2	3.5	3.7	3.9	#N/A	4.2
1992	2.7	3.1	3.3	3.6	#N/A	3.8
1993	3.1	3.6	3.9	4.3	#N/A	4.5
1994	2.1	2.3	2.5	2.7	#N/A	2.8
1995	4.2	4.5	4.6	4.8	#N/A	4.9
1996	2.6	2.7	2.8	2.8	#N/A	3
1997	3.2	3.3	3.4	3.5	#N/A	3.6
1998	3.4	3.5	3.5	3.6	#N/A	3.8
1999	2.6	2.7	2.7	2.7	#N/A	2.9
2000	3.8	3.9	4	4	#N/A	4.2
2001	3.2	3.2	3.2	3.2	#N/A	3.2
2002	2.1	2.8	3	3.1	#N/A	3.9
2003	1.6	1.9	2.2	2.5	#N/A	3.2
2004	1.6	2.1	2.4	2.8	3.4	3.5
2005	1.7	2	2.3	2.5	3	3.1
2006	2.5	2.6	2.7	2.8	3	3
2007	2.5	2.6	2.7	2.8	3	3
2008	2.1	2.3	2.4	2.6	2.8	2.8
2009	0.9	1.6	1.9	2.4	2.9	2.7
2010	0.9	1.6	1.9	2.2	2.7	2.7
2011	0	0.4	0.8	1.3	2.1	2.3
2012	0	0.4	0.7	1.1	1.7	2
2013	-1.4	-0.8	-0.4	0.1	0.8	1.1
2014	-0.7	0	0.5	1	1.6	1.9
2015	0.1	0.4	0.7	0.9	1.2	1.4

Table 1 shows that the discount rate was fairly high in the 1980s, lower in the 1990s, and considerably low in recent years. This work uses (somewhat arbitrarily) the discount rates from 2011 in the Life Cycle Cost analyses. The thought is that 2011 is fairly recent and the very recent discount rates (2015) will tend to increase as the economy improves. It is acknowledged that this selection is subjective, but realizing that as long as the discount rate is consistent across the bridge database, the difference between small changes of discount rate would be minimal. Where the value of the discount rate would have a significant impact would be where one bridge has a higher initial cost and lower future costs compared to a bridge with lower initial cost and higher future costs. These situations are not prevalent in the final LCC bridge database. This work also assumes a long term investment outlook and uses the 30 year maturity level. Therefore, from Table 1, the discount rate used for the Life Cycle Cost analyses in this work is 2.3%.

2.3 Life Cycle Cost Analysis

Life cycle cost analysis represents the “total” cost of a bridge over the life of the bridge and results in an equivalent life cycle cost amount. The cost amount is typically represented by either an Equivalent Uniform Annual Cost (EUAC) or a Present Value Cost (PCV). The EUAC is the life cycle cost amount annualized over the life of the bridge. The PVC represents a present amount that, at a given discount rate (DR), will be enough to pay the initial cost of the bridge and all future costs that are associated with the bridge over its life. This study uses the Present Value Cost in the Life Cycle Cost Analyses.

The data required for the LCC analysis are the initial cost and any future costs and their time frames associated with the bridge over the life of the bridge. Figure 1 demonstrates a LCC analysis for an academic bridge example that has an 80 year life. It assumes future maintenance and rehabilitation costs and the timing of those costs as shown in Figure 1.



For an Initial Cost (IC)
Assume:
Deck = 5% IC (every 20 years)
Rehab = 20% IC (every 40 years)
Demo = 10% IC
Salvage = -3% IC
Main/Ins = 0.1% IC per year

Figure 1: Life Cycle Cost Analysis Example Bridge

The initial cost of the bridge is IC. Deck repair is assumed to cost 5% of the initial cost and to occur every 20 years (except for a major rehabilitation year). The major rehabilitation occurs at 40 years and costs 20% of the initial cost. Demolishing the bridge at 80 years costs 10% of the initial, but there is salvage materials that return 3% of the initial cost (negative is to make the salvage a benefit). Yearly regular maintenance and inspection costs are assumed to be 0.1% of the initial cost. These cost numbers are only used here to demonstrate the LCC analysis and do not necessarily represent a real bridge example. The time value of money equations can be found in any economics book.

The present value cost for all costs associated with this example bridge is:

$$PVC = IC[1 + 0.05(1 + 0.023)^{-20} + 0.05(1 + 0.023)^{-60} + 0.20(1 + 0.023)^{-40} + 0.10(1 + 0.023)^{-80} - 0.03(1 + 0.023)^{-80} + 0.001\frac{(1 + 0.023)^{-80} - 1}{0.023(1 + 0.023)^{-80}}] = 1.17IC$$

The idea is that if the owner invested 1.17 times the initial cost now, the bridge could be built and all future costs would be covered with the extra 17% of the initial cost for a bridge lasting 80 years.

However, when comparing bridges that have different bridge lives, a present value cost by itself is not sufficient. For instance, if this bridge lasts 80 years with a PVC = 1.17IC, it cannot be directly compared to the present value cost of a bridge that lasts only 60 years. Therefore, a common method to directly compare bridges with different life spans is to use either Equivalent Uniform Annual Costs (EUAC) or a Perpetual Present Value Cost (PPVC). Both are equivalent in terms of use for alternative comparisons and the PPVC is used in this work.

The Perpetual Present Value Cost (PPVC) is determined by assuming that at the end of the bridge's life, it is replaced by an identical bridge into perpetuity. This is demonstrated in Figure 2.

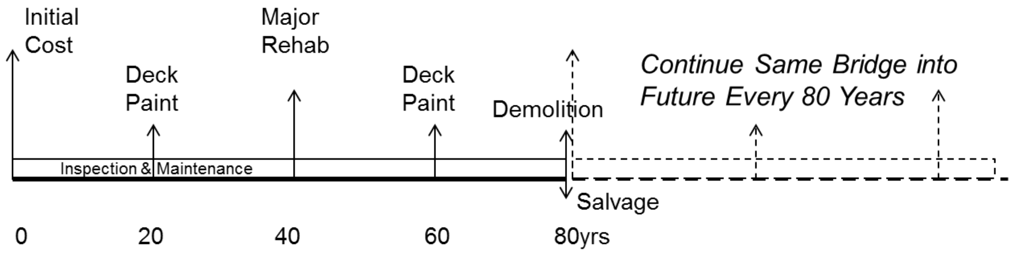


Figure 2: Perpetual Life Cycle Cost Analysis Example Bridge

The PPVC for all costs associated with this bridge into perpetuity is:

$$PPVC = PVC\left[\frac{(1 + 0.023)^{80}}{(1 + 0.023)^{80} - 1}\right] = 1.17IC[1.19] = 1.40IC$$

The idea is that if the owner invested 1.40 times the initial cost now, the bridge could be built and all future costs, including replacing the bridge every 80 years, would be covered with the extra 40% of the initial cost for a bridge lasting into perpetuity. The benefit of using the PPVC is that it allows direct comparisons between any set of bridges.

2.4 Sensitivity of PPVC

The Perpetual Present Value Cost will be sensitive to several variables in the Life Cycle Cost analysis. The primary variables are:

- Bridge Life
- Future Costs
  - Magnitude of Future Costs
  - Timing of Future Costs
- Discount Rate
- Within Steel Bridges – Coating Systems (Weathering Steel , Galvanized & Painted)

The next sections demonstrate the sensitivity using the example bridge from above. The Life Cycle Cost analysis of the PennDOT final LCC bridge database will attempt to examine these variables.

2.4.1 Bridge Life

Assuming the same generic future deck (5%IC @ 20 years), rehabilitation (20%IC @ 40 years), maintenance and inspection (0.1%IC yearly), demolition (10%IC) and salvage costs (-3%IC), Figure 3 shows the PPVC for bridges with a bridge life from 40 to 120 years.

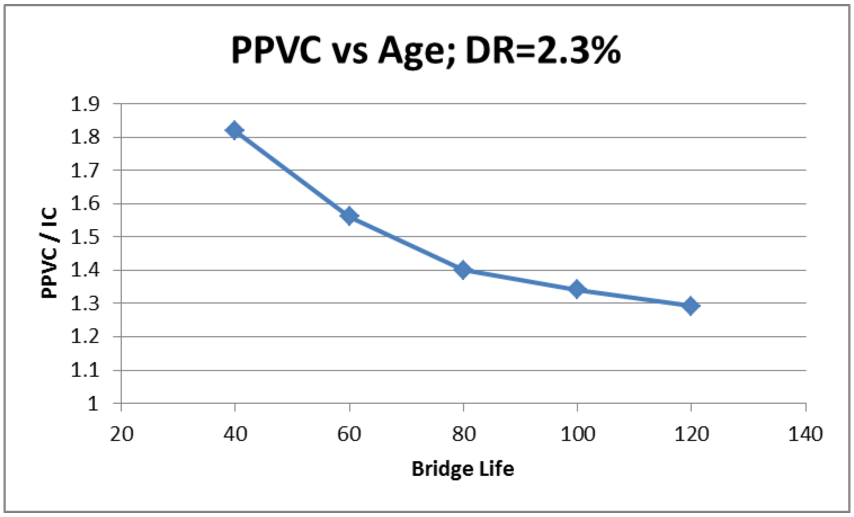


Figure 3: Perpetual Present Value Cost vs. bridge Life

It is clear that bridge life has a large impact on the PPVC. A bridge that lasts 80 years (previous example) has a PPVC of 1.40IC. But, if that bridge only lasts 40 years due to poor performance, the PPVC is over 1.80IC, a significantly large increase in Life Cycle Costs. However, if the bridge life can be extended to 120 years, the PPVC is lower than 1.30IC. This type of analysis can be used to analyze bridge preservation efforts.

2.4.2 Magnitude of Future Costs

To examine the sensitivity to the magnitude of future costs, Figure 4 compares the PPVC with 100% of all future costs considered to the PPVC where the future costs are assigned to be only 90% of the assumed values. The difference is rather small meaning that the PPVC is not all that sensitive to changes in the cost of the future cost.

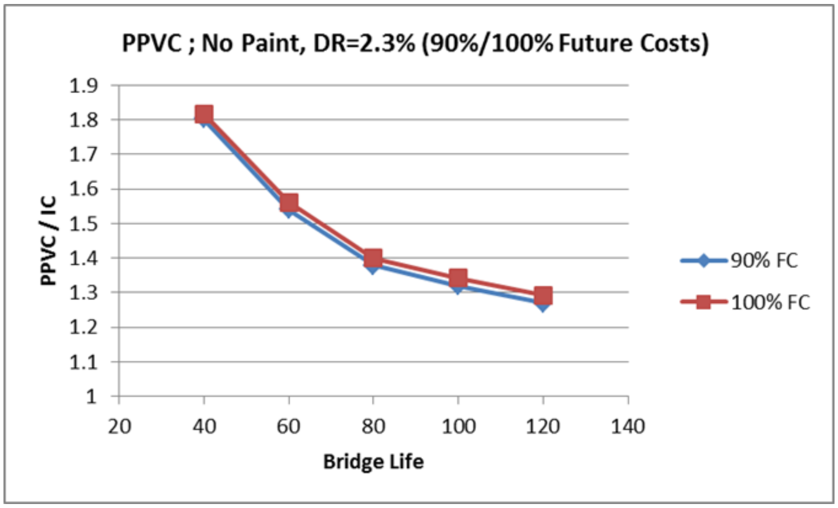


Figure 4: Perpetual Present Value Cost vs. Amount of Future Cost

2.4.3 Timing of Future Costs

Bridge preservation efforts and regular simple maintenance can extend bridge life and delay major rehabilitations and significant required maintenance. Life Cycle Cost analysis can determine the impact. Figure 5 demonstrates the effect for the example bridge.

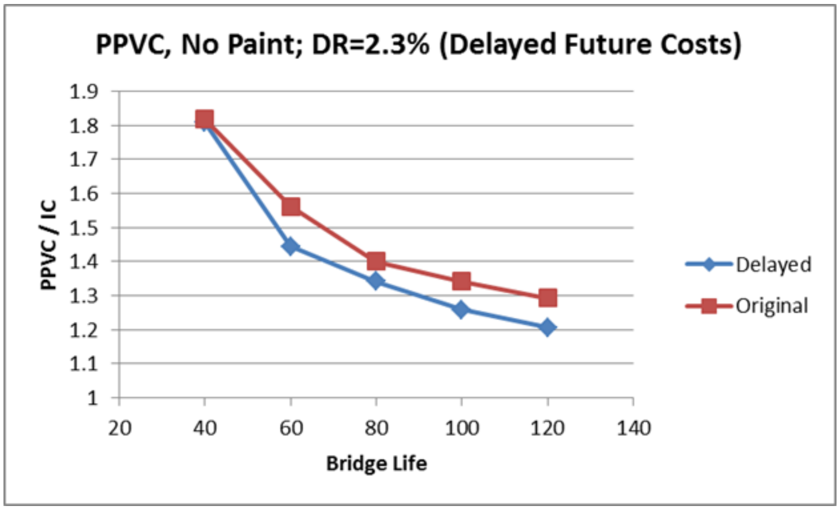


Figure 5: Perpetual Present Value Cost vs. Delayed Future Costs

If deck repair and major rehabilitation is delayed 50% (deck at 30 years vs. 20 and Rehab at 60 years vs. 40), the PPVC is significantly lowered. Of course at 40 years there is little difference since there is little future cost.

2.4.4 Discount Rate

The discount rate used for the PennDOT database is 2.3%. The decision to use 2.3% was explained earlier. However, there would be a direct impact on PPVC if the rate varied. Figure 6 illustrates a comparison of the PPVC between a discount rate of 2.3% and a rate of 5%. The 5% rate represents a similar set of circumstances used to select the 2.3% rate, except for the year 1995. In Figure 6, only the future costs (deck repair, rehabilitation, demolition and salvage) are considered to better show the comparison since initial costs would not change.

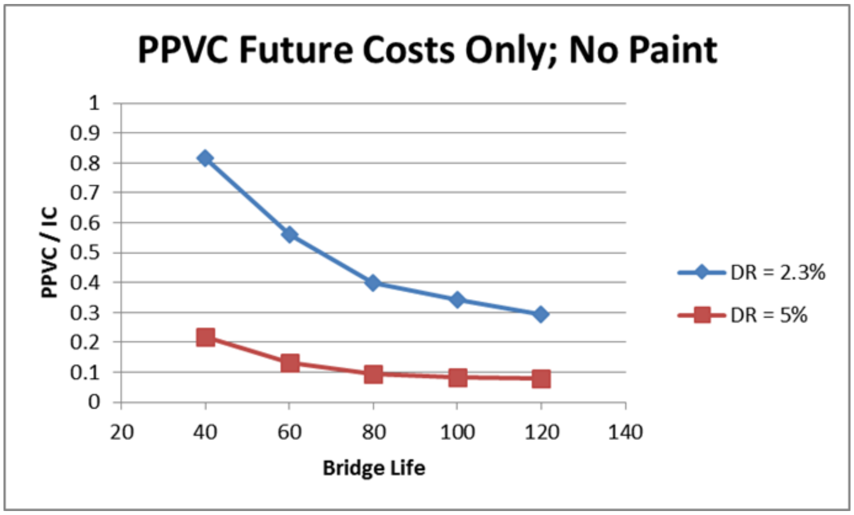


Figure 6: Perpetual Present Value Cost vs. Discount rate

The present value costs for the future maintenance significantly decrease with the higher discount rate. Using an accurate discount rate would be important for examining maintenance and rehabilitation alternatives within a bridge structure. However, when comparing bridges in a database, as long as the bridge histories are somewhat similar, the difference would be consistent over the bridge database. Where the value of the discount rate would have a significant impact in a database comparison analysis would be when one bridge has a higher initial cost and lower future costs compared to a bridge with lower initial cost and higher future costs. These situations are not prevalent in the final LCC bridge database.

2.4.5 Steel Bridge Coating Systems

Coating systems for steel bridges is an important maintenance and preservation issue. Using weathering steel, galvanizing or painting are required to protect the steel from corrosion. Each method of protection has initial costs and possibly required maintenance. Life Cycle Cost analysis can be used to examine the overall effectiveness of the different protection systems. For instance, galvanizing may have a higher initial cost, but if there is little to no future maintenance required, galvanizing may have a lower Life Cycle Cost than a lower initial cost system like painting that requires re-painting costs in the future. For the example bridge, Figure 7 compares the cost of future painting costs to the previous PPVC bridge. It is assumed that re-painting the bridge costs 7% of the initial cost and that is occurs every 20 years, except during the major rehabilitation year. This is not a true comparison of painted vs. galvanized or weathering steel since no difference in the initial cost was considered. However, it does demonstrate the impact from having to re-paint the bridge every 20 years.

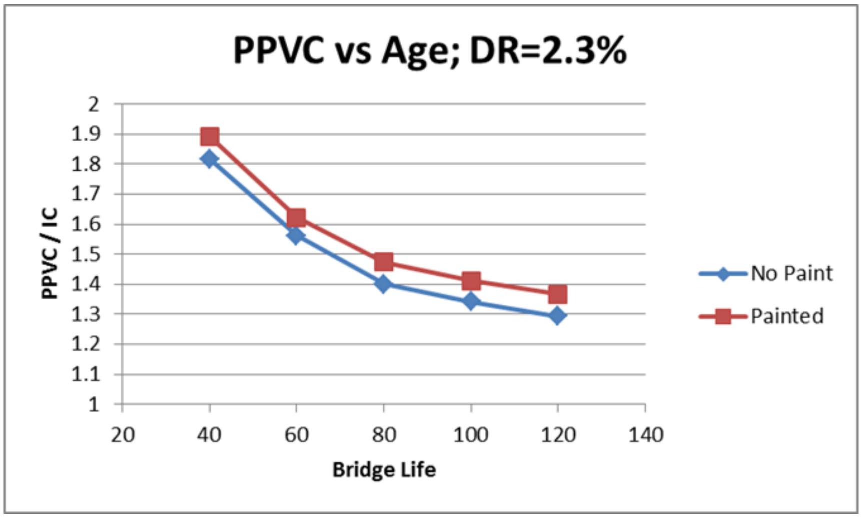


Figure 7: Perpetual Present Value Painted vs. Non-Painted

For a bridge that has an 80 year life, the PPVC for a non-painted bridge was 1.40IC. With a re-painting model of a 7%IC cost` every 20 years, the PPVC increases to 1.47IC, a 5% increase. Using Life Cycle Cost analysis, one can examine what additional initial cost would be "worth" not having to re-paint the bridge.

2.5 Summary of Life Cycle Costs

The Life Cycle Cost procedures developed in this chapter will be applied to the bridge database developed in Chapter 3. An example bridge was used here to study the sensitivity of the Perpetual Present Value Cost to variables that may have a significant impact on the PPVC. It is noted here that the example was not very realistic in terms of maintenance and rehabilitation that actually occurs on the nation's bridges. However, it develops considerations and concepts that will be applied to the PennDOT bridge database. The Life Cycle Cost analyses in Chapter 4 will examine different bridge types for the variables discussed in the sensitivity study as much as is possible for the bridge database developed in Chapter 3.

3 - The PennDOT Database

3.1 PennDOT Database Criteria

The database is developed from files supplied by the PennDOT Bridge Division. Inventory files, PennDOT performed department maintenance files, and external contractor maintenance and rehabilitation files were combined to develop the final database to use in the Life Cycle Cost study. Initial and maintenance costs considered include total project costs as represented in PennDOT records. Therefore, non-superstructure costs are included even though the study pertains to the superstructure only. It is assumed that the non-superstructure costs even out over the large database so the relative comparisons between bridge types is not affected. The following describes the development of the final LCC database. The final LCC database used for this Life Cycle Cost study was limited to the following criteria:

- Modern typical bridge structures
  - Precast I-Beam, Box Adjacent, and Box Spread bridges
  - Steel Rolled Shape and Welded Plate Girder bridges
- Bridges built between 1960 and 2010
- Bridges with complete and accurate department maintenance records
  - Known dates
  - Known costs
  - Consider any maintenance cost that is equal to or greater than $\$0.25/\text{ft}^2$
- Bridges with known initial costs
- Bridges with complete and accurate external contractor maintenance and rehabilitation records
  - Known dates
  - Known costs
- Initial cost limitation to bridges with initial cost less than $\$500/\text{ft}^2$ and greater than $\$100/\text{ft}^2$

For a bridge to be included in the final LCC database, all of the above criteria must be satisfied. If any one of the criterion are not, the bridge is not included in the LCC study. Although care was exercised in developing the database, errors may be present due to inaccurate or missing data in the PennDOT inventory and maintenance files. Individual bridge information was not reviewed by PennDOT state or district personnel for accuracy. It is assumed that any errors cancel out over the database so relative comparisons between bridge types is not affected. The following demonstrates the application of the criteria to develop the final LCC database.

3.2 Initial Database

The PennDOT inventory database includes 25,403 structures of which there are 8466 classified as Precast Box Beam – Spread, Precast Box Beam – Adjacent, Precast I Beam, Steel I Beam – Rolled Shape, and Steel I Welded Girder – Plate Girder bridges. All other types of bridge structures were not considered in this work. The Life Cycle Cost study examined the modern era of bridge construction defined as bridges built from 1960 to the present. The study is also limited to bridges built up to 2010. Table 2 shows the total number of bridges in each category in the PennDOT inventory file and also the number of bridges in each category built between 1960 and 2010. This initial database was the starting point in the process to develop the final database for the LCC study.

Table 2: PennDOT Bridge Inventory Initial Database

Bridge Type	Total Number of Bridges	Number of Bridges 1960 - 2010
Steel I Beam	1347	550
Steel I Girder	1112	1017
P/S Box - Adjacent	1814	1440
P/S Box - Spread	2648	2196
P/S I Beam	1545	1384
Total	8466	6587

3.2.1 Department Performed Maintenance Criterion

The initial bridge database was compared to PennDOT's department performed maintenance files. The criteria are that the maintenance performed must have valid dates and costs for all maintenance performed and that the maintenance costs are equal to or greater than $0.25/ft^2. This removes a great portion of bridges in each category since there are many examples of maintenance that was performed that did not have accurate records. For example, a bridge may have 3 valid maintenance records, but one that did not have a valid date. This bridge would not be included in the final LCC database. One caveat to the acceptance is that any maintenance performed in 2015 was considered a valid date, but the date of that maintenance event was defined to be December of 2014. This is because the LCC study is based on the year 2014 (due to the Construction Cost Indices used) and any error in the time value of money conversions would be miniscule. There are also many bridges that did not have any department maintenance that are included in the intermediate database. The remaining bridges in this intermediate database are shown in Table 3.

Table 3: Intermediate Database with Valid Department Maintenance Records

Bridge Type	Number of Bridges with Valid Maintenance	Number of Bridges with No Maintenance	Intermediate Database Totals
Steel I Beam	99	362	461
Steel I Girder	131	574	705
P/S Box - Adjacent	151	1177	1328
P/S Box - Spread	381	1684	2065
P/S I Beam	204	937	1141
Total	966	4734	5700

There were 1853 bridges that had documented department maintenance that exceeded \$0.25/ft^2 performed. Of those, 966 had maintenance records that had known dates and known costs associated with the maintenance efforts. This means that 887 bridges were removed from the database due to incomplete department maintenance information. These are bridges that would certainly have an impact on the Life Cycle Cost analysis averages. Lower percentages of bridges with valid maintenance records would tend to decrease LCC averages over the database. However, the impact on the averages will be relatively small since future discounted maintenance costs are small compared to initial costs as will be demonstrated in the LCC analyses. Table 4 illustrates the number of bridges with documented department maintenance and those that had valid maintenance information.

Table 4: Department Maintenance Bridge Database Numbers

Bridge Type	Number of Bridges with Maintenance	Number of Bridges with Valid Maintenance	Percentage of Bridges with Valid Maintenance
Steel I Beam	188	99	52.7%
Steel I Girder	443	131	29.6%
P/S Box - Adjacent	263	151	57.4%
P/S Box - Spread	512	381	74.41%
P/S I Beam	447	204	45.6%
Total	1853	966	52.1%

There were also 4734 bridges that had no documented department maintenance that exceeded \$0.25/ft^2. This results in 83% (4734/5700) of the bridge database will be bridges where only the initial cost will be used in the LCC analyses. Higher percentages of no maintenance bridges will tend to lower Life Cycle Cost averages across the database. However, the impact on the averages will be relatively small since future discounted maintenance costs are small compared to initial costs as will be demonstrated in the LCC analyses. Table 5 presents the number of bridges with no documented department maintenance and the percentage of the total intermediate database.

Table 5: No Department Maintenance Bridge Database Numbers

Bridge Type	Bridges in Intermediate Database	Number of Bridges with No Maintenance	Percentage of No Maintenance Bridges in Database
Steel I Beam	461	362	78.5%
Steel I Girder	705	574	81.4%
P/S Box - Adjacent	1328	1177	88.6%
P/S Box - Spread	2065	1684	81.6%
P/S I Beam	1141	937	82.1%
Total	5700	4734	83.1%

The bridges considered in the database were built between 1960 and 2010. The department maintenance performed considered was any maintenance exceeding \$0.25/ft^2 up to the year 2014 (with a few in early 2015 back-dated to end of 2014). Any maintenance that may be performed on a bridge in the future, while a certainty, is not considered in the LCC analyses. This means that each bridge is assumed to have no additional future maintenance until its end-of-life. The impact of this will be a lowering of LCC cost averages across the database. However, each bridge type would have a similar impact as long as the average year built is similar (newer bridges would tend to have no early maintenance). It will be shown in the final LCC database that the average year built is similar for the different types of bridges.

3.2.2 Initial Cost Criterion

PennDOT records were searched to determine if the initial cost for the bridges in this intermediate database were available. This criterion also removed additional bridges from the database since there were many examples where initial costs could not be determined. Table 6 presents the number of bridges in the intermediate database that did have initial cost records that results in a new intermediate database.

Table 6: Intermediate Database with Valid initial Costs

Bridge Type	Number of Bridges with Valid Maintenance and Initial Costs	Number of Bridges with No Maintenance and Initial Costs	Number of Bridges with Valid Maintenance and Initial Costs
Steel I Beam	27	139	166
Steel I Girder	89	367	456
P/S Box - Adjacent	56	431	487
P/S Box - Spread	151	617	768
P/S I Beam	101	447	548
Total	424	2001	2425

The intermediate database has 5700 bridges with valid department maintenance records or bridges with no department maintenance. Of these 5700 bridges, the initial bridge cost for 2425 (42.5%) could be determined. As would be expected, many of the older bridges had incomplete records and were removed from the database. The removed bridges included a representative number from each bridge type. Therefore, the average year built was not affected and the impact of the reduction should be similar for all bridge types.

3.2.3 External Contract Maintenance and Rehabilitation Criterion

In terms of the Life Cycle Cost Analyses, there is no difference between department performed maintenance and external contract maintenance and rehabilitation. In the PennDOT records, the two types of efforts are located in different databases. The development of the final LCC database applied them separately as shown herein. To be included in the final LCC database, the criteria is that the external contract records must have valid dates and costs. The intermediate database that includes bridges with valid or no department maintenance and valid initial costs includes 2425 bridges (Table 6). There were 603 instances of bridges in the intermediate database that had external contracts performed. Of these 603, there were only 26 that had known dates and known costs associated with the work. This means that 565 of the 2425 had to be removed from the database resulting in a final eligible database of 1860 bridges. Table 7 presents the database number of bridges for each category.

Table 7: Intermediate Database that Meets External Contract Criteria

Bridge Type	**Number of Bridges with Valid Maintenance and Initial Costs**	**Number of Bridges Removed due to Missing External Contract Information**	**Number of Bridges with Valid Maintenance, Initial Costs, and Contracts**
Steel I Beam	166	81	85
Steel I Girder	456	192	264
P/S Box - Adjacent	487	63	424
P/S Box - Spread	768	149	619
P/S I Beam	548	80	468
Total	2425	565	1860

The impact of the removal of bridges with documented contracts, but not valid dates and costs, would be similar to the impact from bridges with invalid department maintenance. Also, the same rule that any future contracts that may be performed on a bridge is not considered. With department maintenance, as discussed above, the discounted future costs are usually small compared to the initial costs. For external contracts that involve major rehabilitation, this is not as prevalent and the discounted future rehabilitation costs may be significant. This would result in the average Life Cycle Costs would increase since many of these bridges have been removed from the database. However, there is no manner to predict major rehabilitation dates or costs for the database bridges. Therefore, it is assumed that the different types of bridges would be impacted similarly.

3.2.4 Initial Cost Limitation Criterion

There are bridges built that have unrealistic initial costs due to project specific characteristics. A bridge may have unreasonably high costs due to extremely complicated site characteristics or lower than normal costs due to existing abutments or other atypical beneficial characteristics. To consider typical bridges of the different types, it was decided to remove bridges from the database that had initial costs exceeding \$500/ft^2 and those with costs less than \$100/ft^2. The limits were selected in consultation with the PennDOT Bridge Engineer where the remaining bridges were considered “typical” in his estimation. The criteria removed 155 bridges from the database

3.3 Final LCC Bridge Database

Table 8 presents the final LCC database that will be used for the Life Cycle Cost analyses and the percentage compared to the total number of bridges built from 1960 to 2010 from Table 2.

Table 8: Final LCC Database that Meets All Criteria

Bridge Type	Number of Bridges that Meet All criteria	Percentage of 1960 – 2010 database
Steel I Beam	82	14.9%
Steel I Girder	230	22.6%
P/S Box - Adjacent	400	27.8%
P/S Box - Spread	581	26.5%
P/S I Beam	412	29.8%
Total	1705	25.9%

There were 6587 Precast Box Beam – Spread, Precast Box Beam – Adjacent, Precast I Beam, Steel I Beam – Rolled Shape, and Steel I Welded Girder – Plate Girder eligible bridges identified as being built between 1960 and 2010. Of those, 1705 were found to meet the criteria for the final LCC database. This represents 25.9% of the eligible bridges, a decent percentage of the total. However, the database must be considered only a snapshot of the total PennDOT bridge inventory for the bridge types. The criteria removed nearly 75% of the eligible bridges built between 1960 and 2010, mostly due to incomplete initial cost, maintenance records and external contract records. If these records were complete, the database would be much larger and the resulting Life Cycle Cost analyses would more accurately represent the PennDOT bridge inventory.

3.4 End Of Life Prediction

In the Life Cycle Cost Analyses, the end of life of the bridge (when the bridge needs replacement) defines the life cycle of the bridge. Since the bridges in the final LCC database are all currently in service, it was necessary to estimate an end of life date for each bridge. This was accomplished through the use of average deterioration rates based on the Condition Ratings of the superstructure. This study is interested in the Life Cycle Costs of the superstructure only, so the condition ratings of the deck and substructure were not considered.

3.4.1 Deterioration Rates

To model the deterioration rate, it was assumed that the condition rating decreased linearly over time and the bridge is assumed to be replaced when the condition rating reached 3.0. Also it is assumed that the condition rating is 9.0 when the structure was built. Thus, for a given bridge in the year 2014, the deterioration rate is:

$$Deterioration\ Rate = \frac{(2014\ Condition\ Rating) - 9}{2014 - (Year\ Built)}$$

This has many drawbacks such as deterioration rates are not necessarily linear, rehabilitations tend to raise condition ratings, there is no consideration of average daily traffic, and preservation (maintenance) efforts are not represented.

All 6587 of the bridges built between 1960 and 2010 were used to determine the average deterioration rates for the different types of bridges. Table 9 presents the average deterioration rates and the coefficient of variation of the data within each bridge type.

Table 9: Average Deterioration Rates

Bridge Type	Number of Bridges 1960 - 2010	Deterioration Rate (Condition Rating Loss/Year)	Coefficient of Variation (Mean/St. Deviation)
Steel I Beam	550	-0.07114	54.7%
Steel I Girder	1017	-0.08144	57.4%
P/S Box - Adjacent	1440	-0.08125	50.9%
P/S Box - Spread	2196	-0.07988	70.9%
P/S I Beam	1384	-0.08383	63.3%

It is clear that the variation of the deterioration rate is very high. This is somewhat expected given the variation of bridge characteristics and environments. Other models were considered for deterioration rates. PennDOT assumes certain remaining life based on a non-linear deterioration rate and a Business Plan Network. These were considered for this study, but were found to be difficult to apply and draw conclusions given the limited database of bridges. However, a side-study (not shown here) showed that the differences were small for the averages in Table 9 and the PennDOT method for the bridges in a Business Plan Network of 1. Therefore, given little alternative, the average deterioration rates in Table 9 were used to estimate the remaining life of each bridge in the final LCC database.

3.4.2 Remaining Life and Bridge Life

To estimate the remaining life for each bridge, it is assumed that the bridge will be replaced when the superstructure condition rating reaches 3.0 for the deterioration rates from Table 9:

$$Remaining\ Life = \frac{3 - \ (2014\ Condition\ Rating)}{(Average\ Deterioration\ Rate)}$$

The bridge life becomes:

$$Bridge\ Life = 2014 - (Year\ Built) + Remaining\ Life$$

Table 10 presents the average year built and the average bridge life for the different bridge types in the final LCC database.

Table 10: Final LCC Database that Meets All Criteria

Bridge Type	Number of Bridges in Final LCC Database	Average Year Built	Average Bridge Life (years)
Steel I Beam	82	1981	81.3
Steel I Girder	230	1977	79.2
P/S Box - Adjacent	400	1985	74.0
P/S Box - Spread	581	1984	79.9
P/S I Beam	412	1984	74.5

3.4.3 End of Life Year

The life cycle starts at the year the bridge is built and goes through the year it is replaced (end of life year). The Life Cycle Cost Analyses for each bridge in the final LCC database requires discounting future costs to current value. This means that the year for the bridge replacement (end of life) is necessary for the analyses. Given the remaining life, the end of life year becomes:

$$End\ of\ Life\ Year = 2014 + Remaining\ Life$$

3.5 Summary

Table 11 presents a summary of the final LCC bridge database to be used in Life Cycle Costs studies in the next chapter.

Table 11: Final LCC Bridge Database Summary

Bridge Type	Number of Bridges in Final LCC Database	Percentage of 1960 – 2010 database	Average Year Built	Average Bridge Life (years)
Steel I Beam	82	14.9%	1981	81.3
Steel I Girder	230	22.6%	1977	79.2
P/S Box - Adjacent	400	27.8%	1985	74.0
P/S Box - Spread	581	26.5%	1984	79.9
P/S I Beam	412	29.8%	1984	74.5
Total	1705	25.9%		

Appendix A lists the bridges in the database used for the Life Cycle Cost Analyses. Not all of the 1705 bridges in Table 11 were included in the LCC database as explained in the next section. In the appendix, there are three tables for each type of bridge type. The first lists the general information for each bridge. For the steel bridges, the first table also lists the rebar, geometry, and material characteristics since this study examined variations within steel bridge types. The second table lists the initial cost for the bridge, maintenance costs, year from year built, and type of maintenance, and external contract work. All costs are reduced to dollars/ft^2 of surface deck area. The monetary values are all in constant 2014 dollars as will be explained in the next chapter. The third table presents the Life Cycle Cost results for each bridge. It presents the Perpetual Life Cycle costs, initial costs, maintenance plus external contract costs, along with the basic bridge characteristics. The third table also presents the averages and standard deviations for the bridge data.

4 - PennDOT Database Life Cycle Cost Analyses

4.1 Database Life Cycle Costs

The final LCC bridge database is analyzed for Life Cycle Costs according to the procedures previously demonstrated in Chapter 2. However, the Chapter 2 example was generic with all costs associated with the bridge known. The bridge database, of course, is missing some of the variables used in the example. For instance, there was no data on demolition costs or salvage costs. Also, there is no attempt to add routine maintenance and inspection costs. The database includes the initial cost for the structure, valid maintenance costs, and valid external contract costs. These costs are listed in the second table in Appendix A for each bridge type in constant 2014 dollars. The Life Cycle Cost analyses conducted in this study use constant 2014 dollars.

4.2 Constant 2014 Dollars

The database presented in Appendix A was developed from the criteria previously discussed. The valid initial costs, maintenance costs and external contract costs collected were actual dollars spent at the time of the cost. Therefore, they must be inflated to an equivalent amount in 2014. The dollars at the time expended are transformed into constant 2014 dollars using the Construction Cost Indices (CCI) provided by Engineering News Record publications. Given an expenditure in a past year 19XX, the equivalent 2014 dollars can be determined by:

$$2014\ Dollars = \frac{CCI\ 2014}{CCI\ 19XX} 19XX\ Dollars$$

Table 12 Shows the Historical Construction Cost Indices from 1960 to 2014.

As an example, if a bridge’s initial cost is $330,000 and it is built in 1994, the equivalent 2014 initial cost for the bridge is:

$$2014\ Bridge\ Initial\ Cost = \frac{9806}{5408} \$330{,}000 = 1.813(330{,}000) = \$598{,}370$$

In terms of inflation, this means a bridge built in 2014 costs 81.3% more than a bridge built in 1994.

The cost data for all the bridges in Appendix A are in constant 2014 dollars. Therefore, the study assumes that all of the bridges are built in 2014 for the Life Cycle Cost analyses. The constant 2014 dollars is necessary to (1) account for inflation to transform past built bridges to 2014 using the Construction Cost Index and (2) the discount rate for all future costs considers future inflation and discounting future costs with the discount rate is applied to constant 2014 dollars.

Table 12: Historical Construction Cost Indices from 1960 to 2014 (Engineering News Record)

Year	CCI	Year	CCI	Year	CCI
2014	9806	1995	5471	1976	2401
2013	9547	1994	5408	1975	2212
2012	9308	1993	5210	1974	2020
2011	9070	1992	4985	1973	1895
2010	8799	1991	4835	1972	1753
2009	8570	1990	4732	1971	1581
2008	8310	1989	4615	1970	1381
2007	7966	1988	4519	1969	1269
2006	7751	1987	4406	1968	1155
2005	7446	1986	4295	1967	1074
2004	7115	1985	4195	1966	1019
2003	6694	1984	4146	1965	971
2002	6538	1983	4066	1964	936
2001	6343	1982	3825	1963	901
2000	6221	1981	3535	1962	872
1999	6059	1980	3237	1961	847
1998	5920	1979	3003	1960	824
1997	5826	1978	2776		
1996	5620	1977	2576		

4.3 Life Cycle Cost Example PennDOT Bridge 30570

The Life Cycle Cost analysis will be demonstrated using Precast Box Beam – Spread PennDOT Bridge 30570. The results are shown in Appendix A.

BrKey:	30570
Bridge Type:	P/S, Box Beam (Spread)
County:	Shuylkill
Location:	0.75 mi. N of Exit 107(33)
Year Built:	1969
Spans:	3
Length:	176 ft
Deck Area:	7621 ft^2
Super Cond Rating:	5

Using the average Precast Box Beam – Spread bridge deterioration rate of -0.07988 from Table 9, with a superstructure condition rating of 5, the remaining life is:

$$Remaining\ Life = \frac{(3-5)}{-0.07988} = 25\ years$$

The bridge life is estimated to be:

$$Bridge\ Life = 2014 + 25 - 1969 = 70\ years$$

There were two incidents of department maintenance and one external contract. For this example, total costs and costs/ft^2 of deck area are shown. The remainder of this report will use costs/ft^2 for direct comparisons. The costs at the time of the work and year of the work are:

Initial Cost:	Year = 1969	Cost = \$141475 (\$18.56/ft^2)	Work: Bridge Construction
External Contract:	Year = 1988	Cost = \$58401 (\$7.66/ft^2)	Work: Latex Overlay
Maintenance 1:	Year = 2009	Cost = \$1891 (\$0.25/ft^2)	Work: Repair Concrete Deck
Maintenance 2:	Year = 2013	Cost = \$2510 (\$0.33/ft^2)	Work: Repair Concrete Deck

To transform the costs to constant 2014 dollars, the Construction Cost Indices are applied. To set the time frame for the Life Cycle Cost analysis, the date of maintenance from the built date is determined. The inputs for the LCC analysis are:

Initial Cost:	Year = 0	Cost = \$18.56/ft^2(9806/1269)	= \$143.45/ft^2
External Contract:	Year = 19	Cost = \$7.66/ft^2(9806/4519)	= \$ 16.63/ft^2
Maintenance 1:	Year = 40	Cost = \$0.25/ft^2(9806/8570)	= \$ 0.28/ft^2
Maintenance 2:	Year = 44	Cost = \$0.33/ft^2(9806/9547)	= \$ 0.34/ft^2

The bridge life timeline is shown in Figure 8.

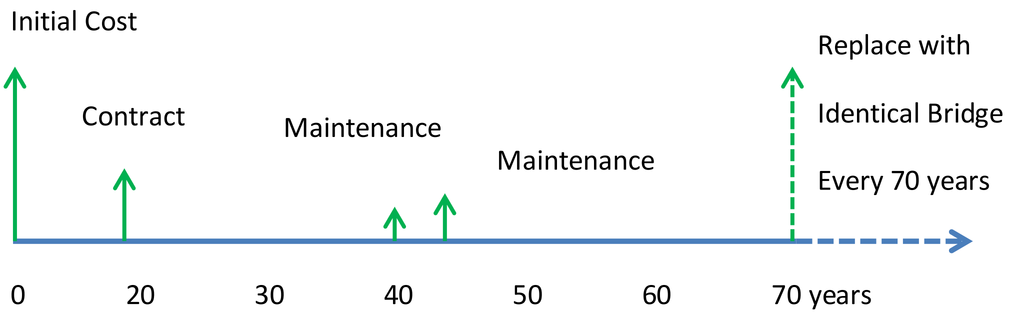


Figure 8: PennDOT Bridge 30750 Life Cycle Cost Timeline

To determine the Present Value Cost, the future costs are discounted to year 0 with a discount rate of 2.3% and added to the initial cost:

$$PVC = \$143.45 + \$16.63(1.023)^{-19} + \$0.28(1.023)^{-40} + \$0.34(1.023)^{-44} = \$154.49/ft^2$$

The Present Value Cost of only the future costs (maintenance and contracts) is:

$$Maintenance\ PVC = 16.63(1.023)^{-19} + 0.28(1.023)^{-40} + 0.34(1.023)^{-44} = \ \$11.04/ft^2$$

Finally, to compare this bridge with others in the PennDOT database, the Perpetual Present Value Cost for Bridge 30570 is:

$$PPVC = \$154.49\left[\frac{(1+0.023)^{70}}{(1+0.023)^{70}-1}\right] = 1.256(\$154.49) = \$193.97/ft^2$$

4.4 Removal of Non-Typical Bridges

There are 1705 bridges in Table 11 that met the database selection criteria. However, there are only 1186 that are used for the Life Cycle Cost comparisons. For the Life Cycle Cost analyses, bridges were removed based on Perpetual Present Value Costs that were considered non-typical. The idea is to compare typical bridges based on the bridge type averages. Therefore, working with the PennDOT Bridge Engineer, a removal criterion was set to be bridges that have a Perpetual Present Value Costs exceeding plus or minus one standard deviation from the mean of the entire bridge type group. This removes bridges that have either unreasonably high or low PPVC due to complicated or simple projects and keeps what is considered typical bridges. Table 13 shows the original number of bridges in the Table 11 database and the number of bridges used for the Life Cycle Cost study.

Table 13: Final Life Cycle Cost Database

Bridge Type	Number of Bridges in Table 11 Database	Number of Bridges in LCC Study Database	Percentage Removed with "Typical Bridge" Criterion
Steel I Beam	82	54	34%
Steel I Girder	230	144	37%
P/S Box - Adjacent	400	282	30%
P/S Box - Spread	581	397	32%
P/S I Beam	412	309	25%
	1705	1186	30%

From Table 13, the percentage of bridges removed with the "Typical Bridge" criterion is fairly consistent over the bridge types. The opinion is that the final Life Cycle Cost database represents typical bridges for the different bridge types and that the averages can be used for comparison. Appendix A contains the 1186 individual bridge results for each bridge type for the final Life Cycle Cost database.

4.5 Life Cycle Cost Results

For each bridge type, the third table in Appendix A lists the PPVC, Initial and present value of all future maintenance costs. Each bridge can be compared to any other within a bridge type or over different bridge types using the PPVC. The third table also lists year built, bridge life, length and number of spans. At the top of the third table are averages and standard deviations for all of these quantities.

Table 14 presents the results of the Life Cycle Cost study for the averages over the database. The PPVC is the quantity to equally compare over different bridge types. The least expensive alternative is the P/S I Beam, followed by the Steel I Beam. Another important consideration for bridge owners is bridge life. Both of the steel bridge types (rolled and girder) have the longest average bridge life. However, since the standard deviations, average length, average number of spans, and average life all vary considerably between the bridge types, it is worth studying these variables a little closer.

Table 14: Life Cycle Cost Results Using Total Database

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Length	Avg # Spans	Avg Year Built	Avg Life
Steel I Beam	54	$232.78	$194.78	$0.42	166	2.19	1980	82
Steel I Girder	144	$273.71	$226.10	$0.21	406	4.07	1976	80
P/S Box - Adjacent	282	$278.30	$223.74	$0.96	89	1.31	1987	74
P/S Box - Spread	397	$256.11	$210.65	$2.06	89	1.56	1986	79
P/S I Beam	309	$217.50	$174.10	$0.20	212	2.43	1985	73

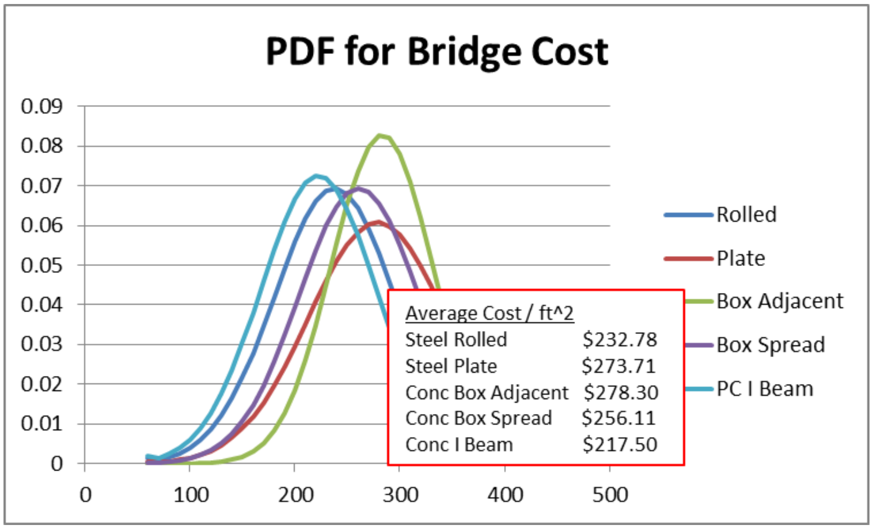
4.5.1 Variability in Perpetual Present Value Cost

Table 15 repeats the averages for PPVC for the different bridge types, but it also presents the standard deviation in the PPVC.

Table 15: Statistical Characteristics of Perpetual Present Value Cost

	Mean	St. Dev	Pr(PPVC<$300)
Steel I Beam	$232.78	$57.51	87.9%
Steel I Girder	$273.71	$65.60	65.6%
P/S Box - Adjacent	$278.30	$48.02	67.4%
P/S Box - Spread	$256.11	$53.51	79.4%
P/S I Beam	$217.50	$54.85	93.4%

Assuming that the behavior follows a Normal distribution, Figure 9 demonstrates the Probability Density Function (PDF) PPVC behavior of the different bridge types. The PDF shows the mean and the standard deviation characteristics. All of the bridge types are similar in both mean and standard deviation. There is no one type of bridge that is clearly less expensive or more uncertain in the cost than another. This is especially true given the limited database that is used in the Life Cycle Cost study.



Average Cost / ft^2	
Steel Rolled	$232.78
Steel Plate	$273.71
Conc Box Adjacent	$278.30
Conc Box Spread	$256.11
Conc I Beam	$217.50

Figure 9: Probability Density Function for Perpetual Present Value Cost

A useful way to use such data is to ask the question, what is the probability that the PPVC is less than $300/ft^2 for the different bridge types? Still assuming the probability distribution is Normal, any statistics textbook can determine that the probability (shown in Table 15) is:

$$Probability(PPVC < \$300/ft^2) = \Phi\left(\frac{300 - Mean}{St.\,Deviation}\right)$$

This analysis is demonstrated in Figure 10 where the Cumulative Density Function (CDF) is plotted for the different bridge types. There is a 93% probability (confidence for bridge owners) that a Precast I Beam bridge, and an 88% probability that a Steel I Shape Beam bridge, will have a Perpetual Present Value Cost less than $300/ft^2. The probabilities decrease for the other types of bridges.

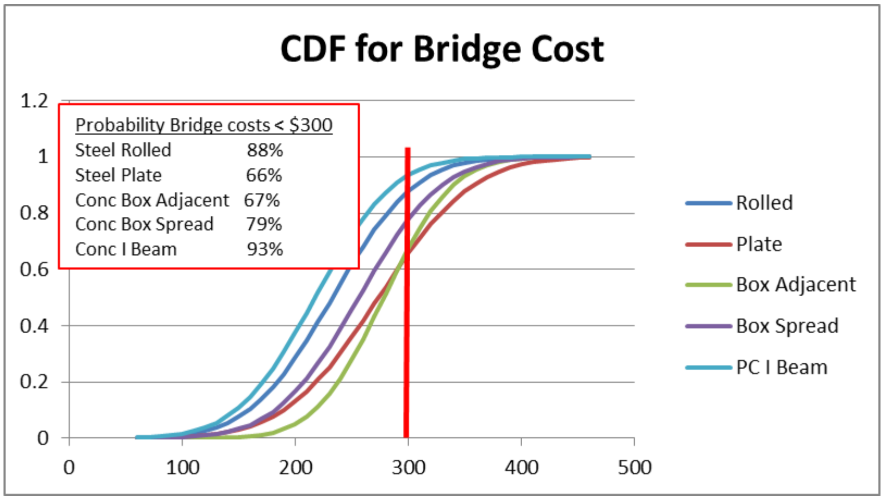


Figure 10: Cumulative Density Function for Perpetual Present Value Cost

4.5.2 Variability in Bridge Life

A similar analysis can be conducted for bridge life. Table 16 repeats the averages for bridge life for the different bridge types, but it also presents the standard deviation in the bridge life.

Table 16: Statistical Characteristics of Bridge Life

	Mean	St. Dev.	Pr(Life>75yrs)
Steel I Beam	82	10.83	73.0%
Steel I Girder	80	15.40	62.7%
P/S Box - Adjacent	74	10.47	45.6%
P/S Box - Spread	79	11.15	65.6%
P/S I Beam	73	11.91	44.3%

Assuming that the behavior follows a Normal distribution, Figure 11 demonstrates the Probability Density Function (PDF) bridge life behavior of the different bridge types. The PDF shows the mean and the standard deviation characteristics. All of the bridge types are similar in mean bridge life and standard deviation (with some differences). There is no one type of bridge that clearly has a significantly longer bridge life (except there is a difference between steel and concrete as a whole) or more uncertain bridge life than another.

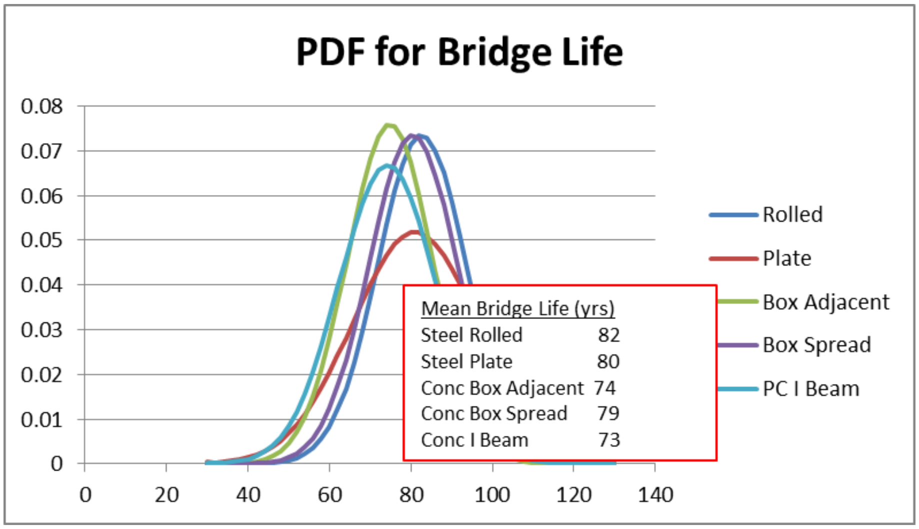


Figure 11: Probability Density Function for Bridge Life

Again, a useful way to use such data is to ask the question, what is the probability that the Bridge Life exceeds 75 years for the different bridge types? Still assuming the probability distribution is Normal, any statistics textbook can determine that the probability (shown in Table 16) is:

$$Probability(Life > 75\ years) = 1 - \Phi\left(\frac{75 - Mean}{St.\,Deviation}\right)$$

This analysis (assuming Normal distribution) is demonstrated in Figure 12 where the Cumulative Density Function (CDF) is plotted for the different bridge types.

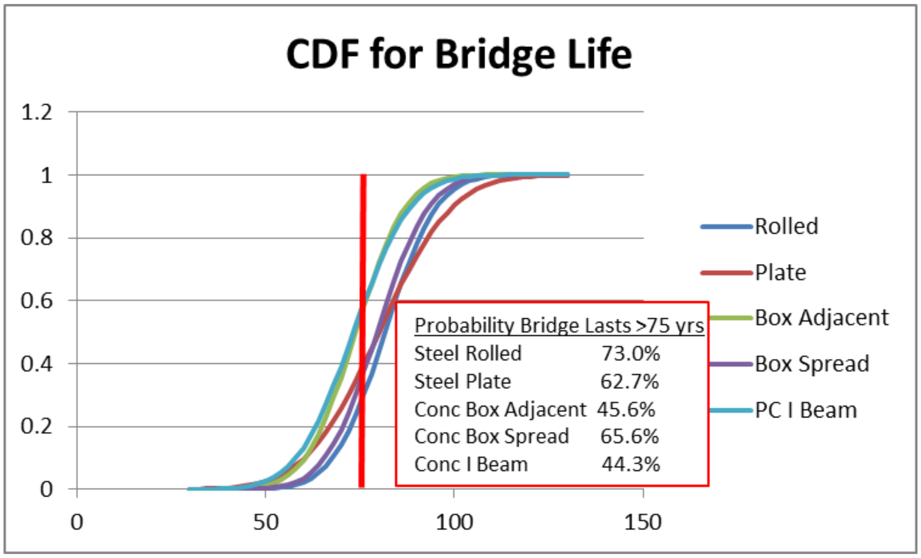


Figure 12: Cumulative Density Function for Bridge Life

There is a 73% probability (confidence for bridge owners) that a Steel I Shape Beam bridge, but only a 44% probability that a Precast I Beam bridge, will have a Bridge Life that exceeds 75 years. The probabilities are between the two for the other types of bridges.

4.5.3 Variability in Average Number of Spans

There is a significant difference in average number of spans between the bridge types. The following examines sub-groups of the bridge types for various numbers of spans. Table 17 shows the results for simple-span bridges. There are 608 simple span bridges that meet the criteria and the re-application of the "Typical Bridge" PPVC criterion.

Table 17: Life Cycle Cost Results for Simple Span Bridges

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Length	Avg # Spans	Avg Year Built	Avg Life
Steel I Beam	22	$302.38	$253.90	$0.13	90	1.00	1981	84
Steel I Girder	21	$318.73	$263.02	$0.25	128	1.00	1979	81
P/S Box - Adjacent	215	$300.74	$241.81	$1.00	65	1.00	1987	74
P/S Box - Spread	245	$294.67	$245.40	$1.06	54	1.00	1988	81
P/S I Beam	105	$287.24	$234.67	$0.04	108	1.00	1989	76

For all the bridge types, the PPVC increases compared to the entire database results. This is expected since most of the time simple-span bridges have higher cost per ft^2. The ranking also changes some with the three concrete bridge types being the least expensive. However, all the bridge types are fairly competitive as they were for the entire database.

Table 18 presents the results for 2-span bridges. There are 184 two-span bridges that meet the criteria and the re-application of the "Typical Bridge" PPVC criterion. For 2-span bridges, some of the PPVC increase and some decrease compared to the overall results. Steel I Girder bridges have the least PPVC, followed by Precast Box Beam – Spread bridges. However, like in previous examples, all of the bridge types are competitive.

Table 18: Life Cycle Cost Results for 2-Span Bridges

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Length	Avg # Spans	Avg Year Built	Avg Life
Steel I Beam	16	$234.04	$193.99	$0.05	198	2.00	1988	81
Steel I Girder	24	$210.49	$175.04	$0.24	243	2.00	1976	81
P/S Box - Adjacent	32	$242.74	$191.74	$1.53	155	2.00	1987	72
P/S Box - Spread	59	$226.78	$183.55	$0.08	127	2.00	1989	74
P/S I Beam	53	$230.78	$183.02	$0.18	209	2.00	1985	71

To consider any bridge that exceeds a simple span, Table 19 has the results for all the bridges that have a number of spans that exceed one (all multi-span bridges). There are 614 multi-span bridges that meet the criteria and the re-application of the "Typical Bridge" PPVC criterion.

Table 19: Life Cycle Cost Results for All Multi-Span Bridges (Number of Spans > 1)

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Length	Avg # Spans	Avg Year Built	Avg Life
Steel I Beam	35	$213.82	$177.00	$0.62	213	2.80	1980	80
Steel I Girder	123	$262.12	$217.78	$0.19	460	4.66	1976	80
P/S Box - Adjacent	70	$214.90	$170.96	$1.21	181	2.63	1983	73
P/S Box - Spread	170	$190.13	$152.34	$3.29	158	2.82	1980	77
P/S I Beam	216	$193.38	$153.66	$0.21	260	3.15	1983	73

All of the different bridge type average PPVC decreases compared to the overall database for multi-span bridges. Here Precast Box Beam – Spread bridges have the least PPVC, but, again, all of the bridge types are competitive with Steel I Girder (high average number of spans) bridges on the high end of PPVC.

4.5.4 Variability in Average Bridge Length

The Steel Marketing Development Institute, through the Short Span Steel Bridge Alliance, defines short span bridges as those with a length of 140 ft or less. To consider short span bridge behavior, Table 20 presents the results for all bridges that have a maximum span of 140 ft. There are 708 multi-span bridges (most of them precast concrete boxes) that meet the criteria and the re-application of the "Typical Bridge" PPVC criterion. Here the Steel I Beam bridges are the least expensive with Precast Box Beam – Spread next. All of the average PPVC are greater than those of the entire database.

Table 20: Life Cycle Cost Results for Bridge Length Maximum = 140 ft

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Length	Avg # Spans	Avg Year Built	Avg Life
Steel I Beam	27	$266.24	$222.08	$0.16	84	1.26	1978	82
Steel I Girder	18	$311.26	$257.19	$0.29	119	1.00	1977	81
P/S Box - Adjacent	240	$292.38	$235.03	$0.95	69	1.09	1987	74
P/S Box - Spread	325	$272.20	$225.14	$2.16	64	1.23	1986	81
P/S I Beam	98	$281.64	$231.20	$0.05	104	1.08	1987	77

For bridges that have bridge length greater than 140 ft, Table 21 presents the results. There are 479 multi-span bridges (most of them precast concrete boxes) that meet the criteria and the re-application of the "Typical Bridge" PPVC criterion. The three concrete bridge types have the least average PPVC.

Table 21: Life Cycle Cost Results for Bridge Length > 140 ft

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Length	Avg # Spans	Avg Year Built	Avg Life
Steel I Beam	28	$216.25	$180.08	$0.69	234	2.86	1982	80
Steel I Girder	96	$256.79	$213.34	$0.19	281	3.02	1975	80
P/S Box - Adjacent	48	$214.14	$170.45	$1.41	213	2.77	1983	73
P/S Box - Spread	75	$191.14	$153.59	$0.90	206	3.16	1981	74
P/S I Beam	232	$195.38	$154.71	$0.25	258	3.05	1984	72

4.5.5 Summary of PPVC Comparisons

Drawing absolute Life Cycle Cost conclusions between different bridge types is difficult given the PennDOT database used in the analyses. The database comprises bridges that met all of the criteria, including known dates and costs for all maintenance performed, known dates and costs for all external contracts performed, and known initial costs. There were many bridges that had maintenance and external contracts, but without known dates or costs. These bridges were removed from the database. There were many bridges with most of the information known, but one item missing. These bridges were removed from the database. Therefore, the database is biased towards bridges that did not have maintenance or external contracts since these would not have been removed as long as they had initial costs. The results do not include a large number of bridges that have maintenance. So, consideration of the specific numbers must be taken in context that the numbers represent the bridges that made it into the database, and the database is not as comprehensive as one would like.

However, a conclusion that can be drawn is that all the types of bridges are fairly competitive in both Initial Costs and Perpetual Present Value Costs. With the dispersion of costs (standard deviation) any of the bridge types may be least expensive for a given project.

4.5.6 Future Costs

The benefit in considering Life Cycle Costs in bridge project decisions is that a LCC analysis considers future costs and bridge life. Both are important aspects for bridge management. Bridge life was addressed above with the steel bridge types having a slight advantage over the concrete types. One indicator of how much future maintenance costs and bridge life impact Life Cycle Costs would be the ratio of PPVC and Initial Cost. The ratio would contain an influence from bridge life since the PPVC assumes the bridge is replaced into perpetuity. Table 22 presents the average PPVC, Initial Cost, the present value cost of all future maintenance costs, bridge life, and the ratio of PPVC and Initial Cost. The average Future Cost is the sum of all maintenance and external contract work for each bridge type divided by the number of bridges for that bridge type.

Table 22: Life Cycle Costs and PPVC/Initial Cost for Total Database

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Life	PPVC/Initial Cost
Steel I Beam	54	$232.78	$194.78	$0.42	82	1.20
Steel I Girder	144	$273.71	$226.10	$0.21	80	1.21
P/S Box - Adjacent	282	$278.30	$223.74	$0.96	74	1.24
P/S Box - Spread	397	$256.11	$210.65	$2.06	79	1.22
P/S I Beam	309	$217.50	$174.10	$0.20	73	1.25

For instance, for Steel I Beam bridges, the result indicates that, for this database, on average it takes 20% more than the initial cost to take care of all future maintenance costs and replace the bridge into perpetuity. The reason that the above statement states “for this database” is that the database is biased towards bridges with no maintenance costs.

When comparing the bridge types, the steel type bridges have a lower future cost component (1.20 and 1.21 vs. 1.22 – 1.25). This is a combination of future maintenance costs and bridge life. Precast I beam bridges have the lowest Future Cost of $0.20, but an average bridge life of only 73 years, whereas Steel I Beam bridges have a higher Future Cost of $0.42, but the average bridge life is 82 years. The combination of the two variables results in Steel I Beam bridges having a lower PPVC/Initial Cost of 1.20 while the Precast I Beam bridges have a ratio 0f 1.25.

4.5.7 Maintenance and External Contracts

The second table in Appendix A lists the maintenance and external contracts that were performed on each bridge for each bride type in the database. Table 23 lists the types of maintenance that are included in the database.

Table 23: Maintenance Definitions for the Database

Group	PennDOT Designation	Description
1 - Concrete Deck	6-D744303-RPR.CONC.DECK	Concrete Deck (Repair)
2 - Deck Joints	20-D744102-RPR.STL.EXP.DAM	Steel Dams (Repair/Rehab)
	2-A743301-RESEAL DK.JOINT	Reseal Deck Joint
	33-B744102-RPR/RPLCOMPR.SEAL	Compression Seal (Repair/Rehab)
	4-A744101-REPAIR DK.JOINT	Repair/Reseal Deck Joint
3 - Structure Framing	25-A744602-RPR/RPL.STEEL BEAM	Stringer (Repair/Replace) - Steel
	54-D744602-RPR/RPLSTLDIAPHRAM	Diaphragm/Lateral Bracing (Repair/Replace) - Steel
	49-C744602-RPR.STEELGIRDER	Girder (Repair) - Steel
	42-A744603-RPR/RPL.CONC.BEAM	Stringer (Repair/Replace) - Concrete
	69-B744603-RPR/RPLCONC DIAPHRAM	Diaphragm (Repair/Replace) - Concrete
	45-D744503-RPL.BRGPED/SEAT	Pedestal Seat (Reconstruct)
	EXTERNAL CONTRACT WORK	Various Superstructure Work
4 - Painting	57-A743201-SPOT PAINT SUPERSTR	Superstucture Spot Painting
	65-C743201-PAINT SUPERSTRUCTURE	Superstructure Full Painting
5 - Protection	80-A743401-PROT.CTG.TO SUPERSTR	Superstructure Protective Coating

The maintenance work is divided into five groups: Concrete Deck, Deck Joints, Structure Framing, Painting and Protection. Noting that the database has concerns in terms of completeness of information, Tables 24 through 26 present maintenance characteristics for the Concrete Deck, Deck Joints and Structure Framing groups.

Table 24: Maintenance Characteristics for Concrete Deck Repair

	# Bridges	# Occurrences	Avg Age to Repair	Average Cost per ($/ft^2)	% of Bridges Repaired	Avg Cost over all Bridges
Steel Rolled	54	12	42	$0.29	22.22%	$0.06
Steel Plate	144	22	39	$0.89	15.28%	$0.14
Concrete Box Adjacent	282	32	35	$6.95	11.35%	$0.79
Concrete Box Spread	397	82	37	$1.15	20.65%	$0.24
Concrete I-beam	309	78	40	$0.46	25.24%	$0.12

Table 25: Maintenance Characteristics for Deck Joints

	# Bridges	# Occurrences	Avg Age to Repair	Average Cost per ($/ft^2)	% of Bridges Repaired	Avg Cost over all Bridges
Steel Rolled	54	16	37	$0.32	29.63%	$0.09
Steel Plate	144	42	36	$0.64	29.17%	$0.19
Concrete Box Adjacent	282	25	32	$3.43	8.87%	$0.30
Concrete Box Spread	397	51	33	$0.91	12.85%	$0.12
Concrete I-beam	309	51	35	$0.94	16.50%	$0.16

Table 26: Maintenance Characteristics for Structure Framing

	# Bridges	# Occurrences	Avg Age to Repair	Average Cost per ($/ft^2)	% of Bridges Repaired	Avg Cost over all Bridges
Steel Rolled	54	4	38	$9.87	7.41%	$0.73
Steel Plate	144	19	38	$1.08	13.19%	$0.14
Concrete Box Adjacent	282	2	27	$63.81	0.71%	$0.45
Concrete Box Spread	397	18	25	$44.04	4.53%	$2.00
Concrete I-beam	309	6	39	$0.51	1.94%	$0.01

The number of occurrences is the total number of maintenance events that were performed for that bridge type. The average cost per event is the total cost of all occurrences divided by the number of occurrences. The percentage of bridges repaired is the number of occurrences divided by the number of bridges. However, this may have some inaccuracy since the same repair may have been applied to a bridge more than once. The same inaccuracy may be present in the average cost over all bridges in that the average cost of each repair times the number of occurrences is divided by the number of bridges in the database for each bridge type.

The results shown are for the database as developed and the number of maintenance occurrences is fairly low. With the limited number of bridges in the database that have valid maintenance records, it is difficult to draw meaningful conclusions. However, the Concrete Box type bridges, when maintenance is required, have high maintenance costs for deck repair and structure framing. Concrete Box type bridges are configured to where the deck is part of the structure framing, so there is a cross-over when trying to separate the deck from the box.

So, again, consideration of the specific numbers must be taken with the context that the numbers represent the bridges that made it into the database, and the database is not as comprehensive as one would like. However, if the database was comprehensive, such a study could be very beneficial to bridge owners and managers.

4.5.8 PennDOT Steel Bridge Database

Within the steel type bridge database, additional characteristics were examined. For instance, curved steel bridge construction is more complicated than straight bridges. Fracture-critical bridges, having additional scrutiny over non-fracture-critical bridges, may result in additional initial and future costs. Also, coating systems can have an influence on initial and future costs. Table 27 examines these variables. The following discusses the results within the limited steel bridge PennDOT database.

Table 27: Steel I Beam and Steel I Girder Bridges

	# Bridges	PPVC	Initial Cost	Future Cost	Avg Length	Avg # Spans	Avg Year Built	Avg Life
Steel Rolled - All	54	$232.78	$194.78	$0.42	166	2.19	1980	82
Steel Rolled - Straight	46	$229.94	$193.19	$0.48	160	2.22	1979	82
Steel Rolled - Weathering	15	$242.75	$203.95	$0.07	164	1.47	1983	83
Steel Girder - All	144	$273.71	$226.10	$0.21	406	4.07	1976	80
Steel Girder - Straight	100	$273.54	$225.58	$0.21	330	3.18	1976	80
Steel Girder - Weathering	11	$254.04	$215.76	$0.03	263	2.45	1974	83
Steel Girder - Non Fract. Crit.	132	$272.53	$225.11	$0.23	359	3.50	1976	80

4.5.8.1 Curved vs. Straight Steel Bridges

When comparing the results for straight bridges and the results for all of the bridges, for both the Steel I Beam and Steel I Girder bridges in the database, there is little difference between curved and straight bridges for PPVC, Initial Costs, Future Costs, or Bridge Life. Although there are not that many curved bridges in the database (8 I beam (15%) and 44 I Girder (30%)), the additional costs associated with curved bridges does not increase the all bridge data significantly (($232.78-$229.94)/$229.94 = 1.2% for I Beam and nearly nothing for I Girder).

4.5.8.2 Fracture-Critical Steel Bridges

There were 12 fracture-critical bridges in the Steel I Girder database. The PPVC for the fracture-critical bridges is actually lower than the PPVC for all I Girder bridges. From this database analysis, it does not appear that fracture-critical designation has a significant impact on Life Cycle Costs.

4.5.8.3 Painted vs. Weathering Steel

The database includes 15 I Beam and 11 I Girder bridges that used weathering steel. The remainder of the bridges are assumed to be painted. When comparing the painted to the weathering steel bridges, the results are mixed. For PPVC, the weathering steel I Beam bridges have a higher (4.3%) PPVC than the overall PPVC, but the I Girder weathering steel bridges have a lower (0.4%) PPVC. However, what is consistent is that future costs are significantly less for weathering steel bridges than for painted bridges. Also, the bridge life increased slightly.

4.5.8.4 Galvanizing

There were no galvanized bridges that made it into the Life Cycle Cost database. This is unfortunate because protective coating systems is an important aspect of steel bridges and galvanizing has become an economical and effective protection system. Recent information shows that Hot Dipped Galvanizing initial costs are approximately equal to or even less than a quality 3-coat paint system. Of course paint systems need maintenance over the bridge life, whereas galvanizing usually does not, or it may require a zinc-rich spot painting at about 60 years. Group 4 in Table 23 shows the painting maintenance for the steel bridges. Table 28 lists the number of paint maintenance events where there were 4 I Beam and 11 I Girder paint maintenance records. The present value of the average future painting costs for these bridges are \$1.44/ft^2 and \$0.21/ft^2, respectively. If galvanizing was an option, these future costs would be eliminated. However, since there were no galvanized bridges in the database, no direct comparisons can be made in this study.

Table 28: Painted Steel I Beam and Steel I Girder Bridges

	# Bridges	# Occurrences	Avg Age to Repair	Average Cost per (\$/ft^2)
Steel Rolled	54	4	34	\$1.44
Steel Plate	144	11	39	\$0.21

4.5.8.5 Summary of PennDOT Steel Bridge Database

The discussion on characteristics of steel bridges, whether it is curved vs. straight, fracture-critical, or painted vs. weathering steel vs. galvanizing, is based on the limited PennDOT database developed herein. Hard conclusions are difficult to discern due to the limitations within the database. However, with a more comprehensive database, these types of studies would be beneficial to bridge owners and managers.

4.6 Summary

This chapter determined the Life Cycle Costs for the Life Cycle Cost bridge database. The initial costs, Life Cycle Costs, and future costs of the 1186 bridges in the database are examined with respect to variability in bridge type, bridge length, number of spans, and bridge life. The steel bridges in the database are also examined with respect to protective coating systems. Drawing hard conclusions from the results is difficult knowing that the database is limited with respect to the PennDOT bridge inventory. Chapter 5 presents a summary of the study and conclusions from the results.

5 - Summary and Conclusions

5.1 Review of Objectives and Life Cycle Cost Database

The objective of this study was to examine historical Life Cycle Costs of typical steel and concrete bridges across the United States. This requires collecting the life histories of bridges, including initial costs, maintenance, rehabilitation and bridge life. Unfortunately, except for the Pennsylvania Department of Transportation, the select number of states and counties contacted for this study were not able to provide the required data on their bridges due to the large amount of time and resources required to collect this data. Therefore the Life Cycle Cost study contained in this report is limited to state bridges in the PennDOT inventory. Even within the PennDOT inventory, only 18% (1186 bridges out of a possible 6587) of the bridges built between 1960 and 2010 had complete historical records and are included in the Life Cycle Cost analyses. The database must be considered only a snapshot of the total PennDOT bridge inventory. The criteria applied removed 82% of the eligible bridges, mostly due to incomplete initial cost, maintenance records and external contract records. If these records were complete, the database would be much larger and the resulting Life Cycle Cost analyses would more accurately represent the PennDOT bridge inventory.

5.2 Interpreting Results and Conclusions

The report examines the initial costs, Life Cycle Costs, and future costs of the bridges in the database with respect to variability in bridge type, bridge length, number of spans, and bridge life. The types of bridges in the database include steel rolled shape beam, steel plate girder, precast box, and precast beam bridges. The steel bridges in the database are also examined with respect to protective coating systems.

Therefore, given the nature of the database used, interpreting the tables and figures showing comparisons of initial costs, Perpetual Present Value Costs, maintenance and future costs, and bridge life is left to the reader. Consideration of the specific numbers and any conclusions must be taken in the context that the results represent the bridges that made it into the database, and the database is not as comprehensive as desirable for drawing conclusions.

A conclusion that can be drawn, however, is that all the types of bridges are fairly competitive in both Initial Costs and Perpetual Present Value Costs. The average initial costs vary from \$174/ft^2 to \$226/ft^2 and the average Perpetual Present Value Costs vary between \$218/ft^2 (Pretressed I Beam) and \$278/ft^2 (Prestressed Adjacent Box). For bridge life, the lowest average life was 73 years (Pretressed I Beam) and the longest was 82 years (Steel I Beam).

The coefficient of variation (standard deviation / mean) of the PPVC was approximately 20%, which is considerably high. With the relatively small differences in the PPVC averages, given the dispersion of the PPVC costs (standard deviation), any of the bridge types may have the least Perpetual Present Value Cost for a given project.

5.3 Future Work

Even though this research was limited to only a subset of PennDOT bridges, the analyses demonstrate the potential benefits of LCC analysis for bridge construction and management. A study of a more comprehensive database of bridges on the initial costs, Life Cycle Costs and future costs of different types of bridges over a diverse set of circumstances would be very useful for bridge owners and managers. With a more comprehensive database, not only would there be a more accurate comparison of bridge types, an accurate comparison of design details, such as jointless decks, rebar coatings, steel protection systems, and other construction details could be completed. The author worked with several states and many counties to try to develop a broad database of bridges across the country. However, these particular states and local owners could not provide the necessary historical data. Although extending this work would take considerable effort, other states and counties could be contacted in an effort to obtain a comprehensive bridge database.

Appendix A - PennDOT Bridge Database

The PennDOT Bridge Database is Divided by Bridge Type:

- **Steel I-Beam**
- **Steel I Welded Girder**
- **Precast Box Beam – Adjacent**
- **Precast Box Beam – Spread**
- **Precast I Beam**

For Each Bridge Type, the Data is Presented as:

- **General Information**
- **Initial Cost, Maintenance and External Contracts**
- **Life Cycle Cost Results**