

Life Cycle Cost of Bridges

- Part 1: Whole Life Cycle Cost for Chicago-Type Bascule Bridges
Part 2: Life Cycle Cost Analysis of Bridges and Tunnels

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WHOLE LIFE CYCLE COST FOR CHICAGO-TYPE BASCULE BRIDGES

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ABSTRACT

The whole life cost of a bridge consists of the total investment throughout the life of the bridge. This investment includes the initial construction cost, repair and rehabilitation costs, and all maintenance costs. An ability to determine the whole life cost of a bridge will help agencies evaluate the asset value of existing bridges, make better decisions on the design and construction of new bridges, and choose methods and approaches for rehabilitating existing structures such that the lowest life cycle cost is achieved rather than the lowest initial cost. Toward this end the whole life costs of Chicago trunnion bascule bridges are analyzed and found to be less than five times the initial costs for life spans exceeding 100 years. It was also shown that timely maintenance, repair, and rehabilitation can lower the life cycle cost of a bridge.

1. INTRODUCTION

1.1 Background

In the United States there are about 590,000 bridges, of which 27% are considered to be structurally deficient or functionally obsolete (FHWA, 2003). Ever present budget constraints have motivated the development and implementation of enhanced bridge management systems for maintaining and improving existing bridge networks. After two decades of effort, the optimization algorithm for bridge management used in PONTIS (AASHTO, 2003) and the economic analytical tool used in BLCCA (NCHRP, 2003) have emerged as the most commonly used developments for this purpose, but their implementation requires background data on the costs for various maintenance, repair, and rehabilitation (MRR) actions and the probability of a condition changing from one status to another. These data are presently obtained primarily from random expert elicitation or engineering judgment, rather than from a systematic study. This type of data is critical to bridge life cycle asset management. When building a new bridge or preserving and improving an existing bridge, it is necessary to estimate how long the bridge will last and how much it will cost initially and over time. If we defer MRR, how much more might the bridge cost eventually? This study is aimed toward answering these fundamental questions, as well as supplying background data to support the implementation of existing bridge management systems and economic analyses for investment decision-making.

1.2 Chicago Movable Bridges

Chicago has more movable bridges than any other city in the world. Evolved from earlier types of movable bridges, including swing bridges and rolling lift bridges, the double-leaf trunnion bascule bridge best satisfied the governing criteria and therefore became the most popular type of bridge. Among the 63 original movable bridges, are 39 bascules; of these, 32 are single-deck double-leaf trunnion bascules, four are single-deck single-leaf trunnion bascules, and three are double-deck double-leaf trunnion bascules. Based on popularity, bridge age, and availability of historical cost information, this study concentrates on 21 single-deck double-leaf trunnion bascule bridges built between 1902 and 1936.

2. CLASSIFICATION OF CHICAGO-TYPE BASCULES

Chicago-type trunnion bascule bridges have been classified into four generations (Hopson, 1994) which, as described below, are characterized by the evolution of their design and construction. In the description of these bridges the deck widths given are current values which may be different than those of the original bridges due to reconstructions.

2.1 First Generation

The first generation Chicago-type bascule bridges were built between 1900 and 1910 and have tall through-trusses braced over the roadway. The operating machinery and counterweights are below the deck, and each leaf is turned by the action of fixed pinions that rotate and mesh with curved racks on the tail-ends of the three trusses arching above the roadway. Originally, these bridges had simple, wood frame operator houses and were operated manually. Table 1 lists the first generation bascules included in this study. Among them, the Cortland Street Bridge, built in 1902, is actually the first Chicago-type bascule.

Table 1. First Generation Chicago-Type Bascules Included in This Study

No.	Bridge	Year Built	Structural Length (feet)	Deck Width (feet)	Initial Cost ¹ (\$)
1-1	Cortland St. Bridge	1902	217	36	152,911
1-2	E Division St. Bridge	1904	242	39	194,150
1-3	W Division St. Bridge	1904	260	40	256,321
1-4	North Ave. Bridge	1907	273	40	196,964
1-5	N Halsted St. Bridge ²	1908	302	43	247,983

¹ Initial construction cost for superstructure and substructure before adjustment for inflation

² Over canal

2.2 Second Generation

In 1910 the newly appointed Chicago Plan Commission and its consulting architect, Edward H. Bennett, began to work with engineers to improve the artistic quality of Chicago bridges. In 1911 Alexander Von Babo, a city bridge engineer, patented the internal rack and by placing the rack below the bridge deck, the need for through-trusses was eliminated. These efforts resulted in extensive revisions to the shape of the trusses, the configuration and façade of the operator houses

and pit walls, and the ornamental detailing of sidewalk railings, light fixtures and other decorative metal elements. This new design was heavily influenced by Parisian architecture, which, at the time, was considered to be the model of urban design. These innovations defined the second generation Chicago-type bascule bridges, which were those built between 1910 and 1930. Table 2 lists the second generation Chicago-type bascules included in this study. Among them, the Washington Street Bridge is the first trunnion bascule bridge that reflects the new aesthetics.

Table 2. Second Generation Chicago-Type Bascules Included in This Study

No.	Bridge	Year Built	Structural Length (feet)	Deck Width (feet)	Initial Cost ¹ (\$)
2-1	Washington St. Bridge	1913	263	36	238,288
2-2	Grand Ave. Bridge	1913	270	60	195,141
2-3	Chicago Ave. Bridge	1914	291	37	255,583
2-4	Webster Ave. Bridge	1916	287	38	245,721
2-5	Monroe St. Bridge	1919	271	38	420,875
2-6	Franklin-Orleans St. Bridge	1920	320	38	827,487
2-7	Madison St. Bridge	1922	283	40	1,186,569
2-8	Adams St. Bridge	1926	250	64	1,065,644
2-9	100 th St. Bridge	1926	326	40	930,948
2-10	106 th St. Bridge	1928	349	38	907,144
2-11	LaSalle St. Bridge	1928	347	57	1,318,801
2-12	Clark St. Bridge	1929	346	38.5	1,331,020
2-13	Roosevelt Rd. Bridge	1929	257.5	90	1,195,449
2-14	Wabash Ave. Bridge	1930	345	60	1,568,499

¹ Initial construction cost for superstructure and substructure before adjustment for inflation

2.3 Third Generation and Fourth Generation

From an architectural point of view, the period between the great depression and World War II (1930-1945) encompasses the third generation in Chicago bascule bridge design. After the consulting architect, Edward Bennett, was dismissed in 1930, design engineers wanted to project a more contemporary image and the state of the economy encouraged streamlining. Hence, the third generation bridges built during the 1930s followed established structural and architectural models, but had simpler ornamental details. Table 3 lists the two third generation bridges which are included in this study. Several bridges built after 1945 are classified as fourth generation Chicago-type trunnion bascules. They are somewhat sleeker and technically more sophisticated than their predecessors. However, since this study concentrates on older bridges built before 1940, no fourth generation bridges are included.

Table 3. Third Generation Chicago-Type Bascules Included in This Study

No.	Bridge	Year Built	Structural Length (feet)	Deck Width (feet)	Initial Cost ¹ (\$)
3-1	S Halsted St. Bridge	1933	316	57	626,857
3-2	S Ashland Ave. Bridge	1936	312	60	951,259

¹ Initial construction cost for superstructure and substructure before adjustment for inflation

3. WHOLE LIFE COST ANALYSIS

The whole life cost of a bridge is the total investment, which consists of the initial construction cost, repair and rehabilitation costs, and all maintenance costs throughout the life of the bridge. According to Novick (1991), the design and rehabilitation of bridges based on life cycle cost considerations has the potential to save hundreds of millions of dollars in future construction costs.

3.1 Data Base

All available cost data for each bridge from the time of its construction until 2002 was collected from the Chicago Transportation Department and the Chicago Public Library. Except for a few years, the MRR costs for the years from 1900 to 1978 were found to be quite complete. For years after 1978, the repair and rehabilitation costs were collected from capital improvement program reports and maintenance costs were given as a lump sum for all city bridges (which number about 250); since detailed maintenance costs for individual bridges were not available, reasonable estimates were deduced from assumptions based on history and engineering judgment. To account for inflation the Engineering News Record Building Cost Index was used to convert actual costs to 2002 dollars.

3.2 Relationship between Structure Size and Initial Construction Cost

These historical cost data provide an opportunity to determine the relationships illustrated in Figure 1 between structure size and initial construction cost for Chicago-type bascule bridges. Such relationships are helpful for developing conceptual estimates for new bridges. In this study the structure size is defined as the bridge length times the deck width, and the initial construction cost includes the cost of the superstructure and substructure only. As can be seen, the best-fit (least squares) relationships for the first and second generation bridges are essentially parallel. However, the scatter in the second generation data is sufficiently large that it can be considered to encompass the data for the first and third generation bridges.

3.3 Achievable Useful Life

There are various definitions for the useful life of a bridge. In this study the useful life is defined as the period from initial construction to the point where the reconstruction cost is greater than the initial cost. Most of the Chicago bridges studied have never been reconstructed and have had a useful life greater than 75 years, which is a commonly assumed bridge design life. The first Chicago-type bascule, the Cortland Street Bridge, is currently more than 102 years old.

3.4 Cost Distribution over Time

After these movable bridges were built, they required annual maintenance, and three or four decades later they usually needed major repair or rehabilitation. Although annual costs fluctuated, the accumulated costs followed a common trend over time. One example of this trend is shown in Figure 2 for the Cortland Street Bridge.

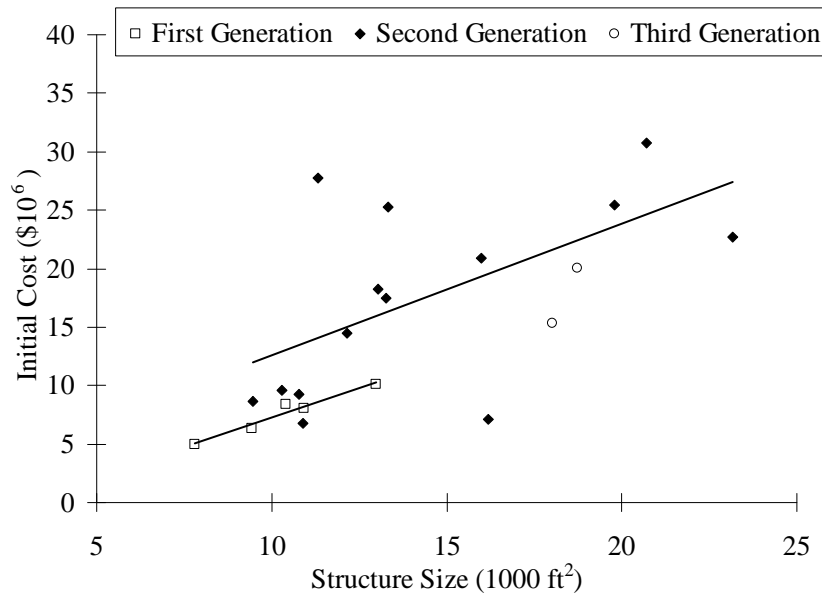


Fig. 1. Initial Construction Cost as a Function of Size for Chicago-Type Bascule Bridges

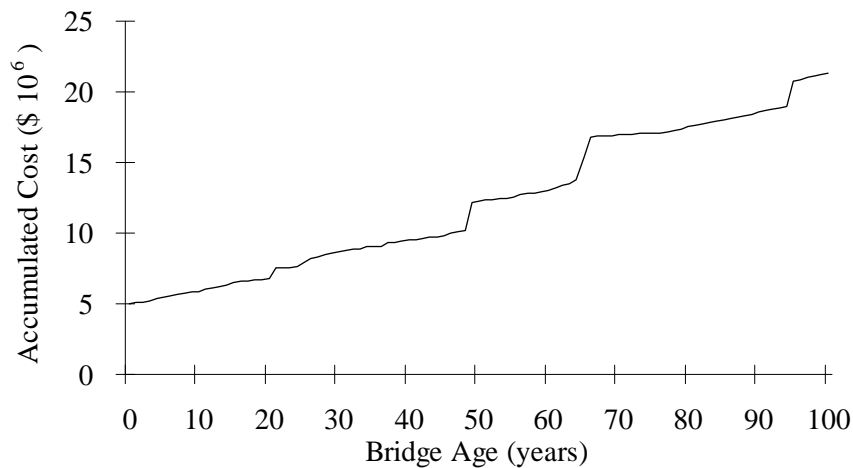


Fig. 2. General Pattern for Accumulated Costs over Time

3.5 Relationship between Whole Life Cost and Bridge Age

Studied here are the relationships between the whole life cost of these movable bridges and traffic volume (ADT and ADT growth rate), bridge opening/closing operations, and bridge age. The total life cycle cost (TLCC) is normalized with respect to the initial cost (IC) for each bridge. No obvious relationships were found between the TLCC/IC ratio and the traffic volume or between the TLCC/IC ratio and the bridge openings, but there was a strong relationship between the bridge age and the TLCC/IC ratio, as shown in Figure 3. In general, older bridges have higher TLCC/IC ratios, which is as expected. For these Chicago-type bascules, the total cost is about four times the initial cost for the first generation bridges, which are around 100 years old and have not been reconstructed.

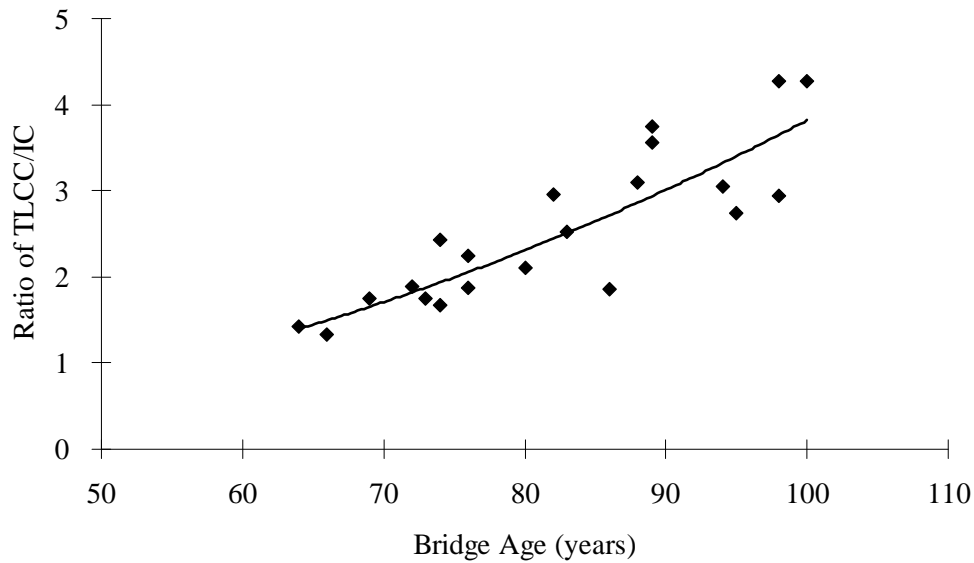


Fig. 3. Relationship between Whole Life Cost and Bridge Age

3.6 MRR Impact on Whole Life Cost

Although the total life cycle cost of a bridge is strongly related to bridge age, as illustrated in Figure 3, these same data show that bridges of the same age may have different TLCC/IC ratios, which means that their whole life costs are different. In practice, the bridge engineer always needs to make the decision when and how to rehabilitate a deteriorated bridge; for example, should it be rehabilitated now or later, should the effort involve extensive rehabilitation or minor repair, and so forth. This study helps to determine the impact of MRR practice on whole life cost. Table 4 summarizes the major capital improvement history for two bridges with identical design and built at almost the same time. Bridge 1-5 was rehabilitated in 1931 and bridge 1-4 experienced two major repairs in 1955 and 1966. By 2001 the TLCC/IC ratio for bridge 1-5 was lower than that for bridge 1-4, and bridge 1-5 was in better condition, as determined by its Sufficiency Rating (common index used nationally to rate the condition of bridges; ranges from 0 to 100, with 100 being the best and a rating of 50 or less suggesting the need for reconstruction). In 2002 there were plans to replace bridge 1-4 at a cost of about double its initial cost, while bridge 1-5 was rehabilitated at a cost of about 80% of its initial cost. Figure 5 shows that, although the TLCC/IC ratio for bridge 1-5 was higher than that for bridge 1-4 after the former was rehabilitated in 1931, 22 years later the ratio was lower than that for bridge 1-4. Up to reconstruction, the total cost savings for bridge 1-5 was 4.64 million dollars, as determined by the difference in the TLCC/IC ratios in 2001 times the initial construction cost expressed in 2002 dollars. Alternatively, a comparable rationale suggests that the delayed rehabilitation of bridge 1-4 cost 3.69 million dollars more than it would have if the work were performed earlier; however, it is fully appreciated that there may be valid reasons for the delayed rehabilitation. Similar analyses on other Chicago bridges also show that timely and comprehensive repair and rehabilitation may reduce life cycle costs.

Table 4. Major Capital Improvement Practice Comparison

No.	Year Built	Capital Improvement Year	Cost ¹ (\$ 10 ⁶)	TLCC/IC ²	Sufficiency Rating in 2001	Reconstruction Year	Cost (\$ 10 ⁶)
1-4	1907	1955	1.32	2.82	15.0	2002	17.13
		1966	1.20				
1-5	1908	1931	2.88	2.36	45.3	2002	7.90

¹ Real cost adjusted to year 2002

² Not including cost for reconstruction in 2002

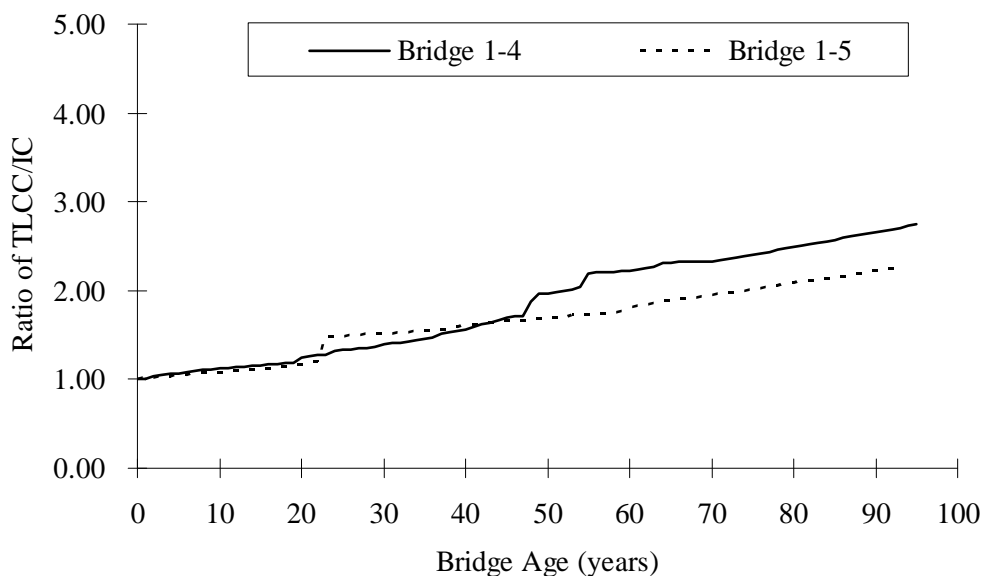


Fig. 4. Impact of MRR on Bridge Whole Life Cost

3.7 Annual Maintenance Cost

Another goal of this study is to determine the maintenance cost and its distribution among major items. Movable bridges usually need routine maintenance to support their operation, and maintenance costs for movable bridges are typically greater than those for fixed bridges. Table 5 gives the average distribution of costs for Chicago-type trunnion bascule bridges based on their historical maintenance cost records from 1929 to 1966, a period when itemized maintenance cost information was available. On average, annual maintenance costs for these bridges were about 1% of their initial costs.

Table 5. Maintenance Costs and Distribution among Major Items

Bridge	Average Maintenance (\$ 10 ³)	Deck and Structure (%)	Mechanical System (%)	Electrical System (%)	Painting Glazing (%)	Traffic Control (%)
First Generation	182	27	21	20	8	13
Second Generation	127	22	17	26	9	15

¹ Real cost adjusted to year 2002

4. CONCLUSION

The results of this brief study show that (a) the achievable useful life of a bascule bridge can be more than 100 years, (b) the total life cycle cost for a 100-year-old bascule bridge can be less than five times its initial cost, and (c) timely MRR actions can lower the total life cycle cost of a bridge.

ACKNOWLEDGEMENTS

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LIFE CYCLE COST ANALYSIS OF BRIDGES AND TUNNELS

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ABSTRACT

This paper presents an analysis of life cycle costs for four bridges and two tunnels constructed and operated by the Port Authority of New York and New Jersey. Cost components include the initial cost, repair and rehabilitation costs, and annual maintenance costs. Results show that the maintenance and rehabilitation costs, as a percentage of the initial cost, are reasonably similar for both bridges and tunnels for perhaps the first 65 years of their service life, after which these costs increase significantly for bridges. However, based on cost per square foot and cost per traffic lane, the opposite is clearly true. Only time and detailed cost records for ensuing years will reveal how the two types of structure compare over their entire service lives.

KEY WORDS

Life cycle cost, bridges, tunnels, initial cost, rehabilitation cost, maintenance cost.

INTRODUCTION

Although tunnels are usually more difficult and more expensive to build than bridges, many engineers feel that tunnels cost less than bridges to maintain and will be cost effective in the long term. In addition, recent advances in tunneling technology and, in some cases, the reduced disturbance to the environment and community suggest that a tunnel must be accorded serious consideration as an alternative to a bridge, especially in urban areas. To facilitate a meaningful comparative analysis for these two types of structure, it is necessary to have reasonably accurate long-term cost data, including the initial construction cost and all maintenance and rehabilitation costs. The ultimate objective of this overall effort is to develop a comprehensive life cycle cost analysis model for both bridges and tunnels over the entire service life of each. In addition to the foregoing cost data, this model would include operating costs (such as ventilation and fire protection, but not toll collection facilities) and user costs (cost to the user due to lane closures when a structure is undergoing maintenance or rehabilitation). As an initial step, analyzed in this paper are the initial construction costs,

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major rehabilitation costs, and annual maintenance costs for six structures (four bridges and two tunnels) over approximately a 70-year period.

STRUCTURES ANALYZED

The historical cost data for the four bridges and two tunnels included in this study have been obtained from the Port Authority of New York and New Jersey. Most of these structures were built around the same time and have been in use for about 70 years, so analyses of their life cycle costs are well suited for comparison. Table 1 gives the basic descriptive information for each structure. The George Washington Bridge, the Holland Tunnel, and the Lincoln Tunnel cross the Hudson River in the Manhattan area; the other three bridges (the Outerbridge Crossing, the Goethals Bridge, and the Bayonne Bridge), called the Staten Island bridges, connect Staten Island with the coast of New Jersey. Except for the Bayonne Bridge, these structures accommodated an average traffic volume of about 20,000 vehicles per day per lane in 2003; the Bayonne Bridge handled only about one-quarter of this volume.

Table 1: Basic Descriptive Information for Bridges and Tunnels

Facility Name		Year Built	Structural Type	Total Length (feet)	Width ¹ (feet)	Number of Traffic Lanes	Average Daily Traffic per Lane ²
Outerbridge Crossing		1928	Truss	8,800	62	4	20,926
Goethals Bridge		1928	Truss	7,100	62	4	19,511
Bayonne Bridge		1931	Steel Arch	5,780	85	6	5,049
George Washington Bridge	Upper level	1931	Suspension	4,760	119	6+2	20,732
	Lower level	1962				6	
Holland Tunnel	North tube	1927	Tunnel	8,558	29.6	2	22,693
	South tube			8,371		2	
Lincoln Tunnel	North tube	1945	Tunnel	7,482	31	2	19,249
	Center tube	1937		8,216		2	
	South tube	1957		8,006		2	

¹ External diameter for the tunnels

² Based on two-way traffic volume in 2003

COST ADJUSTMENTS AND ASSUMPTIONS

Of major significance, all annual cost data provided by the Port Authority were adjusted for inflation by using the Building Cost Index compiled by Engineering News Record to convert all costs to 2002 dollars. As with any study of this type, accurate historical data for each individual structure are difficult, if not impossible, to obtain. In many cases, especially prior to 1973, the data gleaned from the Port Authority combined the maintenance costs for several structures and sometimes included operating costs (such as toll collection) and the cost of ancillary structures (such as a bus station).

To further complicate the analysis, the Bayonne Bridge and the George Washington Bridge were constructed initially with an “extra structural capacity” to add more traffic lanes in the future, thus increasing the initial construction costs beyond what they would have been without this provision. The Bayonne Bridge was constructed with the provision to add two additional traffic lanes; although these lanes were never built, it is estimated that they could have been added for about 10% the cost of the bridge. Accordingly, the adjusted initial construction cost of the bridge taken to be 110% of the actual initial cost and the bridge is considered to have six traffic lanes for this analysis. The George Washington Bridge was initially built with a single deck consisting of six traffic lanes with a provision for two more that were added in 1946. The current lower level with six traffic lanes was anticipated in the initial design, but it was not constructed until 1962 (some 30 years later), and all costs associated with this lower level are excluded from this analysis to the extent possible to separate costs. Hence, the “adjusted” initial construction cost for the eight-lane upper level of the George Washington Bridge used for this study was determined by taking eight-fourteenths of the sum of the construction costs for the original bridge in 1931 plus the added two lanes in 1946 plus the six-lane lower level in 1962, each converted to 2002 dollars. Since the lower level is 31 years younger than the upper level, it is assumed that 10% of the post-1962 rehabilitation costs and 20% of the post-1962 maintenance costs are attributable to the lower level and these costs are subtracted from the Port Authority cost data for the entire bridge.

Similarly, the Lincoln Tunnel consists of three tubes, built one at a time. Although most of the structural work for the north tube was actually finished about the same time as the center tube, its opening was delayed by World War II; the cost data for these two tubes are included in this analysis and their age is considered to date from 1937. The south tube was built 20 years later, and all costs for the south tube are excluded from this study. In addition, 15% of the post-1957 rehabilitation costs and 25% of the post-1957 maintenance costs are attributed to the south tunnel and therefore excluded from this analysis. As there are no cost records for the first four years (1927-1930) that the Holland Tunnel was in operation, the annual maintenance costs for these years are assumed to be the same as those for the succeeding four years (1931-1934).

The annual maintenance costs for the three Staten Island bridges for the years before 1973 were combined; since no individual cost information was available, the combined maintenance costs for these three bridges were arbitrarily allocated in proportion to their initial costs. For all of these structures, it is assumed that 25% of the reported annual expenditures were for maintenance and the remaining 75% were operating costs, and the latter are excluded from this analysis (this distribution was suggested by personnel at the Port Authority).

INITIAL COSTS

To place these six structures in perspective, the initial costs and three unit costs (cost per square foot, cost per linear foot, and cost per lane) are summarized in Table 2. The cost per square foot is the total initial cost divided by the area (total length times the width for bridges and total length times the external diameter for tunnels). The cost per linear foot is the total initial cost divided by the total length. And the cost per lane is the total initial cost divided

by the number of traffic lanes; this is a measure of the cost to provide the same traffic capacity. As seen from the results in Table 2, the total initial costs for the three facilities crossing Hudson River are of the same order, but much larger than those for the Staten Island bridges. The cost per square foot for the two tunnels is 2.5 to 3 times that for the bridge, and the cost per lane for the two tunnels is 2.2 to 2.7 times that for the bridge. However, the tunnels are about 70% longer than the bridge and this is reflected in the fact that the cost per linear foot for the tunnels is about 70% that for the bridge. For the three Staten Island bridges, the total initial cost, cost per square foot, cost per linear foot, and cost per lane for the Goethals Bridge and the Outerbridge Crossing Bridge are about 50%, 50%, 40%, and 80% those for the Bayonne Bridge, respectively.

Table 2: Initial Costs of Structures

Facility	Total Initial Cost (\$10 ⁶)	Cost per Square Foot (\$/ft ²)	Cost per Linear Foot (\$10 ³ /ft)	Cost per Lane (\$10 ⁶ /lane)
Outerbridge Crossing	185	339	21	46
Goethals Bridge	139	316	20	35
Bayonne Bridge	308	627	53	51
George Washington Bridge	973	1,717	204	121
Holland Tunnel	1,089	4,347	129	272
Lincoln Tunnel	1,288	5,293	164	322

MAJOR REPAIRS AND REHABILITATIONS

Except during World War II, all of these bridges and tunnels received annual capital investments for major repairs and rehabilitations. In general, these structures needed major rehabilitation soon after they reached an age of about 50 years. Table 3 gives the timing and nature, as well as the cost as a percentage of the initial cost, of major completed or ongoing work on these structures after 1984, the first year from which detailed records of contract work are available. A study of these results suggests the following noteworthy points:

- The superstructure of all the three Staten Island Bridges underwent major rehabilitation around age 70, but the intensity was much higher for the two truss bridges than for the steel arch bridge.
- For the structures crossing the Hudson River, the George Washington Bridge required more frequent structural rehabilitation than the tunnels.
- The tunnels required rehabilitation of their tubes or ceilings soon after age 50 and their ventilation and fire protection systems at around age 75.
- Compared to their initial cost, rehabilitation costs were generally lower for the tunnels than for the bridges; in particular, the rehabilitation costs for the two truss bridges were extremely high.
- Deck rehabilitation and repainting steel are major cost items for bridges.

Table 3: Major Rehabilitations after 1984

Facility Name	Rehab-1			Rehab-2			Rehab-3		
	at Age	Activity	Cost /IC	at Age	Activity	Cost /IC	at Age	Activity	Cost /IC
Outerbridge Crossing	57	Roadway and deck	9%	66	Concrete slab	11%	72	Deck; structural steel; sidewalk	29%
Goethals Bridge	73	Repaint and steel truss	14%	75	Deck; structural steel; sidewalk	46%			
Bayonne Bridge	70	Main span structure	2%	71	New Jersey abutment	10%			
George Washington Bridge	57	Replace soffit slab	2%	66	Repaint upper level; structural steel	4%	70	Repaint two towers	6%
Holland Tunnel	58	Install ceiling	8%	75	Replace fire standpipe	2%	76	Ventilation system	6%
Lincoln Tunnel	53	North tube structure	3%	58	Center tube structure	3%			

ANNUAL MAINTENANCE COSTS

Historical annual maintenance costs per lane up to year 2001 (the latest year that such data were available) are plotted in Figure 1 for all six structures. These plots show that the annual maintenance cost per lane for the tunnels is considerably higher than that for the bridge crossing the same waterway and annual maintenance costs began to accelerate around age 50 for both bridges and tunnels.

TOTAL LIFE CYCLE COSTS

The total life cycle costs at some point in time are the cumulative value of initial costs, repair and rehabilitation costs, and annual maintenance costs up to that point. Figures 2 and 3 show the life cycle costs per traffic lane up to 2009 for the Staten Island Bridges and the three facilities crossing the Hudson River, respectively. The annual repair and rehabilitation costs for years 2002 to 2009 are based on the latest capital plan provided by the Port Authority; the annual maintenance costs for this period are assumed to be the average of those for the previous five years (1997-2001). Current plans call for replacement of the Goethals Bridge sometime after 2008, thus terminating its life cycle with about 80 years of service life. Although each bridge and tunnel took about three years to build, the construction costs are

shown in these figures as a “vertical jump” for simplicity and the age of the structure is measured from this point. As mentioned in the assumptions, the annual costs for the Staten Island bridges until 1973 were provided as a “lump sum” and distributed among the three bridges in proportion to their initial costs; accordingly, year 1973 is indicated on each of the curves for these bridges. In 1972, the cumulative maintenance and rehabilitation costs for these three bridges was about 43% of their combined initial Construction cost.

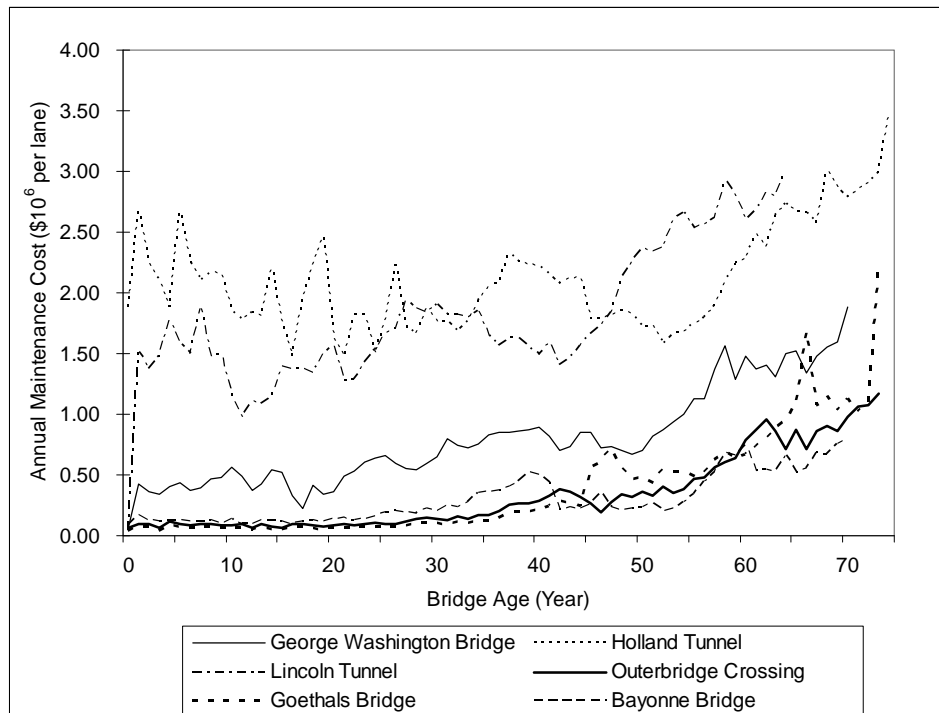


Figure 1: Annual Maintenance Costs per Lane

Figure 2 shows that, following modest maintenance during first three decades or so, the total life cycle costs for these bridges began to increase noticeably. Although the total investment in each of these bridges is different, the rates of increase are quite similar for all three bridges, except for the very rapid increase for the Goethals Bridge around age 75, thus suggesting why it is scheduled to replacement in the next few years. Figure 3 shows that the rate of increase of the total life cycle costs for the Hudson River structures was more-or-less constant for the first 50 years or so, after which a somewhat increased rate began to be manifested. However, after about 60 years the rate for the bridge began to increase somewhat faster than for the tunnels.

Parallel with Table 2 for initial costs, Table 4 presents the total life cycle costs and associated unit costs for these structures at age 70. A comparison of the 70-year unit costs for the structures crossing the Hudson River shows that the ratios of tunnel unit costs to bridge unit costs are each about 80% of the corresponding ratios based on initial costs, thus suggesting that the life cycle cost of the tunnels is approaching that of the bridge. A similar comparison for the Staten Island bridges shows that the total and unit costs of the truss

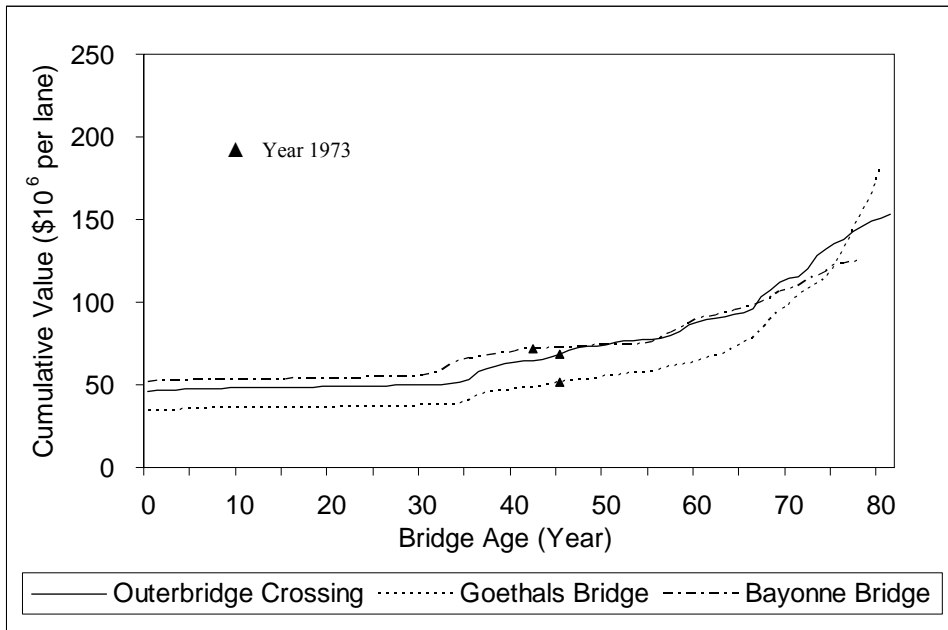


Figure 2: Life Cycle Costs for Staten Island Bridges

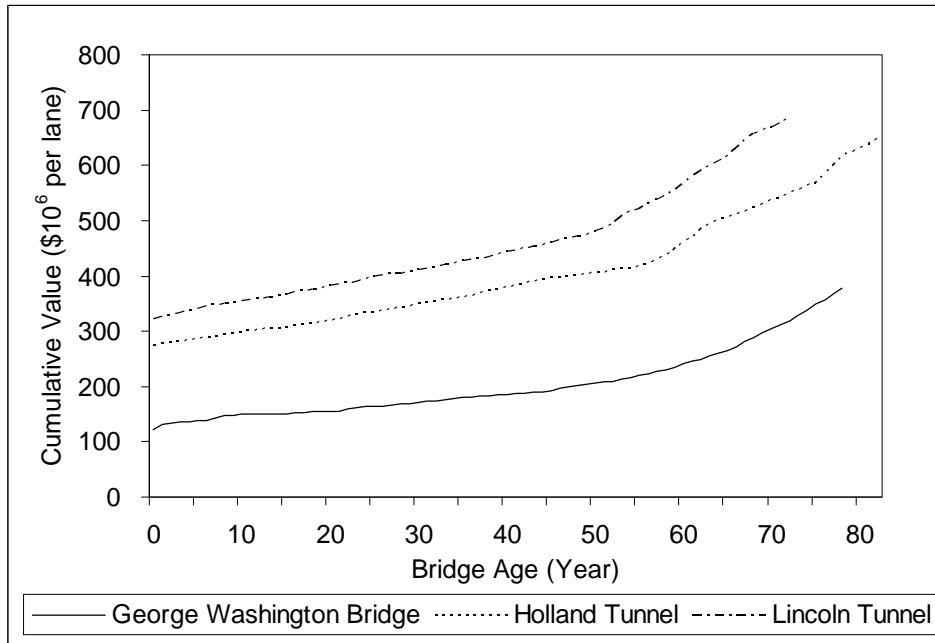


Figure 3: Life Cycle Costs for Structures Crossing the Hudson River

bridges relative to the arch bridge at age 70 are about 25% higher than the corresponding values based on initial costs, thus indicating that the truss bridges are becoming more expensive to maintain and rehabilitate than the arch bridge (relative to their respective initial construction costs). However, this trend is obviously influenced by the fact that the Bayonne

Bridge (arch bridge) is designed more robustly than necessary and carries only about 25% of the traffic volume per lane as the other two bridges.

Table 4: Total Life Cycle Costs at Age 70

Facility	Total Cost (\$10 ⁶)	Cost per Square Foot (\$/ft ²)	Cost per Linear Foot (\$10 ³ /ft)	Cost per Lane (\$10 ⁶ /lane)
Outerbridge Crossing	456	836	52	114
Goethals Bridge	394	895	55	99
Bayonne Bridge	648	1,319	112	108
George Washington Bridge	2,443	4,313	513	305
Holland Tunnel	2,145	8,563	253	536
Lincoln Tunnel	2,704	11,002	341	669

To compare the time-dependent development of total life cycle costs, the ratios of total life cycle cost (TLCC) to initial cost (IC) are given in Table 5 for all six structures at similar ages (some data were obtained from projected work plans to 2009). The TLCC/IC values for all of these structures are around 1.6 at age 50 and around 2.0 at age 65; similar values were obtained at 50 and 65 years for a number of Chicago bridges subjected to a similar analysis currently in progress. This suggests that (a) the accumulated costs for maintenance, repair, and rehabilitation as a percentage of initial construction cost are more-or-less consistent for bridges during the first 65 years of their service life and (b) these costs for tunnels are generally similar to those for bridges. The results suggest that bridges older than 65 years have reached the stage where considerable rehabilitation is needed to ensure and/or enhance their integrity. This can be seen by the large increase in bridge TLCC/IC values at age 70, age 75, and at the future time when all currently planned capital investment will be completed. The two tunnels also show increases in their TLCC/IC values after age 65, but these increases are less than those for bridges. More long-term data are needed to clarify whether or not TLCC/IC values for tunnels do indeed increase more slowly and remain lower than those for bridges.

Table 5: TLCC/IC Values for Structures at Specific Time

Facility	Age 50	Age 60	Age 65	Age 70	Age 75	Completion of Planned Projects
Outerbridge Crossing	1.6	1.9	2	2.5	2.9	3.5
Goethals Bridge	1.6	1.9	2.2	2.8	3.5	5.3
Bayonne Bridge	1.4	1.8	1.9	2.1	2.4	2.6
George Washington Bridge	1.7	2.0	2.2	2.5	2.9	3.6
Holland Tunnel	1.5	1.7	1.9	2.0	2.1	2.5
Lincoln Tunnel	1.5	1.8	1.9	2.1		2.3

CONCLUSIONS

Based on the foregoing analysis of life cycle costs (including initial construction, repair and rehabilitation, and annual maintenance costs) for four bridges and two tunnels in the New York-New Jersey area, the following tentative conclusions can be advanced:

- The total initial costs for the three facilities crossing Hudson River are quite similar and much larger than those for the Staten Island bridges. The cost per square foot for the two tunnels is 2.5 to 3 times that for the bridge, and the cost per lane for the two tunnels is 2.2 to 2.7 times that for the bridge; in contrast, the cost per linear foot for the tunnels is about 70% that for the bridge. A comparison of the three Staten Island bridges shows that the Bayonne Bridge costs more than the other two bridges by all four of the criteria, even though the other bridges are 65% to 80% longer.
- Relative to initial costs, the rehabilitation costs for the tunnels were generally lower than those for each of the bridges, especially after age 65 or so. The two tunnels required rehabilitation of their tubes and/or ceilings around age 55, and the mechanical and electrical equipment in their ventilation system at age 75. In general, however, up to the present time the tunnels have required less rehabilitation than the George Washington Bridge and the two truss bridges.
- The annual maintenance cost per lane for the tunnels is considerably higher than that for the bridge crossing the same waterway; however, the annual maintenance costs for all four bridges and two tunnels began to accelerate around age 50.
- In terms of the cost per square foot and cost per lane at age 70, the tunnels are still more expensive than the bridge crossing the same waterway, but the difference is decreasing with time. This is also true for the comparison between the steel arch Bayonne Bridge and the other two truss bridges.
- The ratios of total life cycle cost to initial cost for all of the structures are about the same up to age 65, after which they tend to increase faster for bridges than for tunnels.

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