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16. Abstract

Durability is a serious issue for managers of the U.S. transportation infrastructure. Work remains to be done to improve the service life, life-cycle durability, and both direct and indirect life-cycle costs of reinforced concrete, steel, and other structural materials in all environments throughout the state of Texas. For this project, researchers performed a feasibility study for the development of a marine exposure test site on the Texas gulf coast. The goals of the site are to increase the service life, reduce the capital and maintenance costs, and improve the quality, performance, and safety of transportation infrastructure in Texas through real-exposure research, experimentation, and testing of construction materials and processes.

A literature survey reviews economic studies of durability problems and associated costs, including the costs nationwide and in Texas of deterioration, degradation, and corrosion, and the tangible benefits of improved durability. The project researchers visited and evaluated existing exposure test sites in the U.S. to identify site requirements and the critical success factors for a Texas marine exposure test site. A quantitative cost-benefit analysis was performed considering costs and future benefits in the short-term and long-term. The results demonstrate that the development of a Texas marine test site would be economically feasible and cost-beneficial to Texas.

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FEASIBILITY STUDY FOR DEVELOPMENT OF MARINE EXPOSURE TEST SITE: TECHNICAL REPORT

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The researcher in charge was Kenneth Reinschmidt.

The United States Government and the state of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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EXECUTIVE SUMMARY

Deterioration and corrosion of transportation infrastructure cost billions of dollars per year in the U.S. and in Texas. Based on a number of studies of the costs of deterioration and corrosion over a period of years, this project resulted in an estimate of the total annual direct costs to TxDOT of $2 billion per year, and indirect costs of $12 billion per year. These substantial costs are attributable to the reduction of service lives; costs of replacement, rehabilitation, and repair; and increased construction costs to prevent or delay deterioration. In addition to these large direct costs, there are substantial indirect costs to the traveling public due to restrictions placed on deteriorated facilities. Moreover, the rehabilitation and repair of deteriorated facilities are dangerous to workers and travelers, as these activities must be carried out while the facilities are still in use.

The costs related to lack of durability are still high and increasing, as this report shows. Budget issues may make it more difficult to find the funds to replace deteriorated facilities in the future, so that deterioration and subsequent replacement of deteriorated facilities will not be a viable strategy. Therefore, much work remains to be done to improve the life-cycle durability of reinforced concrete, steel, and other structural materials, particularly in the coastal environment.

The project researchers performed a feasibility study for the establishment of a marine exposure test site on the Texas gulf coast designed to develop and test improved materials, methods, and systems in order to increase the service life, reduce the capital and maintenance costs, and improve the quality, performance, and safety of transportation infrastructure in Texas. These goals would be accomplished through real-exposure research, experimentation, and testing of construction materials and processes leading to reduced degradation, deterioration, and corrosion. The proposed marine exposure test site should bring positive benefits to the state and the people of Texas.

In this project, researchers performed the following major tasks:

- A search of the literature concerning estimates of the magnitude of degradation, deterioration, and corrosion in the U.S. and in Texas; assessments of the annual costs of these conditions; and estimates of the benefits of mitigating these conditions.
- Identification of the overall condition of Texas transportation facilities and review of economic studies of durability problems and corrosion and deterioration costs, as

well as the financial benefits of reduced deterioration and extended service life of infrastructure.

- Collection and synthesis of information on the existing exposure test sites in the U.S., identifying the advantages and limitations of these sites and the critical success factors for a marine exposure test site on the Texas gulf coast.
- Identification of potential locations on the Texas gulf shoreline for a Texas marine exposure test site, identification of key site infrastructure needs and site requirements, and development of a systematic method to evaluate potential locations.
- Quantification of potential costs and benefits associated with the marine exposure test site and performance of a cost-benefit analysis, considering relevant future effects from a long-term perspective.
- Development of a management plan for constructing and operating a site, including a preliminary business plan, organization plan, and operations/maintenance plan, with financial projections through the life-cycle of a marine exposure test site to estimate funding needs.

As a result of the completion of these tasks, researchers obtained the critical findings discussed below.

The development of a marine exposure test site in Texas should bring significant benefits. These benefits include tangible benefits (savings in overall construction, replacement, rehabilitation, and repair costs as well as better condition of transportation facilities through extended service life) and intangible benefits (savings in traffic delay costs and improvement of safety). In the long-term, the proposed marine test site should recover its costs many times over.

Of course, one cannot expect results overnight. Improved and tested new materials and processes would lead to longer service lives for infrastructure facilities, but new materials can only be implemented in new structures. Thus, there is some lead time before the accrued benefits exceed the costs. Materials and processes for retrofits, rehabilitation, and repairs, aimed at increasing the time between repairs, would have shorter lead times to reach their break-even points. However, in all cases the benefits over time become greater than the costs, as shown by the cost models developed in this research project. Clearly a long-term commitment by TxDOT for support of the site and for the experimental program is necessary for success.

However, it is possible that materials testing programs being conducted by other states, as well as commercial developers, would desire to use the facilities of the proposed Texas marine test site, which would generate some revenues to offset the costs of establishing and operating the Texas facility. The Texas facility might thus provide testing services for a number of states on the gulf coast without their own test sites, or even for inland states.

Summary of Findings

This report, by direction of TxDOT, makes no recommendation concerning whether or not a marine exposure test site should or should not be developed. The report presents only findings concerning cost-benefits of the proposed facility, which are summarized here for convenience.

The project team, based on the information obtained in this research and the studies performed as described herein, finds that:

The proposed Texas marine exposure test site would reduce the future costs of deterioration and corrosion for the Texas transportation infrastructure, and would have a high ratio of benefits to costs. Although these benefits are difficult to quantify, the benefits would be both direct, to TxDOT, and indirect, to the users of the Texas transportation system. Additional benefits might be obtained beyond those considered here by the sale of services to material suppliers, contractors, and transportation agencies outside Texas.

In order to be able to make a decision regarding the development of a Texas marine exposure test site, as outlined herein, it would be necessary for TxDOT to make the following decisions:

- Decide on a single best site for this facility. Some alternative sites are described in this report
- Decide on the scope of the facility. Various possibilities, including cooperation with other marine exposure test sites outside Texas, are described herein.
- Prepare an engineering cost estimate for the scope of the facility, considering the:
  - determined scope,
  - selected site, and
  - necessary support facilities, depending on the site selected.

- Decide on a research plan for the investigation, development, and deployment of the improved materials and processes to reduce deterioration and corrosion in Texas transportation facilities.
- Decide whether to operate and manage such a facility directly by TxDOT or to contract with some other entity for the establishment, operation, and maintenance of the Texas marine exposure test site.
- If it is decided by TxDOT to select a contractor to establish, operate, and maintain this site, said contractor would provide the following to TxDOT:
    - definitive research plan,
    - definitive management plan,
    - definitive marketing plan, and
    - plan for technology development, and deployment and implementation of the materials and processes developed at the marine exposure test site.

CHAPTER 1. INTRODUCTION

Corrosion and deterioration of materials have serious economic impacts on our society and are therefore serious issues for managers of the U.S. transportation infrastructure. Serious material durability problems include the corrosion of structural and reinforcing steel, alkali-silica reaction (ASR), delayed ettringite formation (DEF), external sulfate attack (ESA), freezing and thawing, and many other factors. These problems definitely affect the state of Texas, which is one of the largest users of concrete for transportation systems.

Deterioration and corrosion of transportation infrastructure cost billions of dollars per year in the U.S. and in Texas. These costs are attributable to:

- the reduction of facility service lives,
- costs of replacement, rehabilitation, and repair, and
- increased construction costs to prevent or delay deterioration.

In addition to these large direct costs, there are substantial indirect costs to the traveling public due to restrictions placed on deteriorated facilities. Moreover, the rehabilitation and repair of deteriorated facilities are dangerous to workers and travelers, as these activities must be carried out while the facilities are still in use.

Prevention and reduction of deterioration and corrosion in transportation structures are challenging because the exposure conditions can be quite severe and are difficult to replicate in laboratory experiments. A method to fill this gap between controlled laboratory experiments and uncontrolled in-service behavior observations is the development of a marine exposure test site to test materials in the actual marine environment.

A marine exposure test site is a location along a coastline where specimens made of different materials or made by different processes are exposed to the natural marine environment. The objective is to determine how long these various materials or systems last until deterioration, corrosion, or other processes make them unserviceable. Because these tests are experiments, they are often constructed over a wide range of parameters in order to develop models of material or structural behavior. An example is the water-cement ratio in concrete: in laboratory experiments or in experiments tested at a marine exposure test site, the water-cement ratio can be varied over a much greater range than could be done in an actual constructed facility.

The environmental conditions at a marine exposure test site differ greatly from a similar exposure test site far from the shore. The high chloride content, the high humidity, and the presence of other air and waterborne contaminants produce much different effects on test specimens than would an inland exposure test site. In the continental United States there are three noteworthy marine exposure test sites. These sites are as follows:

- NASA Kennedy Space Center (KSC) Corrosion Technology Laboratory Site (CTLS), Cape Canaveral, Florida (KSC CTLS);
- U.S. Army Natural Weathering Exposure Station, Treat Island, Maine (Army NWES); and
- U. S. Navy Advanced Waterfront Technology Test Site, Port Hueneme, California (Navy AWTTS).

The research team visited these sites as part of this research program.

It is expected that significant benefits, such as the development of new technologies for deterioration and corrosion prevention to enhance the service life of structures, could result from the establishment of a marine exposure test site in Texas. By performing tests of various materials over a period of time at a natural marine exposure test site, beneficial knowledge on deterioration and corrosion could be developed for field structures and could be the basis for improvements in the durability of the transportation infrastructure.

However, there are costs associated with developing and operating a marine exposure test site. The state would procure, maintain, and operate the site and facilities must be procured, maintained, and operated continuously over an extended period of time to achieve these benefits. As a state facility, the marine exposure test site would result in positive benefits to the state of Texas and the taxpayers of Texas. This project examines the feasibility of the development of a marine exposure test site in the state of Texas, considering relevant costs and the expected benefits from development of the site.

OBJECTIVES

The objective of this project is to assess the feasibility for development of a marine exposure test site in the state of Texas. This assessment has been done by determining the long-term value of a marine exposure test site considering recurring expenditures for site operation and maintenance, as well as initial start-up costs, compared to the benefits the state would realize over an extended period of time.

The project has addressed the following sub-objectives:

- Identification of the need for and uses of a marine exposure test site and the tangible benefits to the Texas Department of Transportation (TxDOT) of having a devoted marine exposure test site. This analysis especially focused on durability issues affecting reinforced and prestressed concrete, but also addresses the durability of other materials.
- Review of economic studies of durability problems and deterioration costs, as well as the financial benefits of reduced deterioration and extended service life of the infrastructure.
- Review and synthesis of information on other marine exposure test sites that have been constructed in the United States, identifying successes and limitations of these sites and critical success factors for a marine exposure test site, compared to the objectives for a Texas marine exposure test site.
- Identification of potential locations for a Texas marine exposure test site, identification of key site infrastructure needs, and development of a systematic method to evaluate and compare potential locations.
- Quantification of potential costs and benefits associated with the marine exposure test site.
- Performance of a cost-benefit analysis, considering operations and maintenance costs, initial development costs, and tangible/intangible benefits, based on present worth analyses of future costs and benefits.
- Development of a management plan for constructing and operating a site, including a preliminary business plan, organization plan, and operations and maintenance plan, with financial projections through the life-cycle of a marine exposure test site to estimate funding needs for economic options available to TxDOT.

SCOPE AND APPROACH

The marine exposure test site, as a designated location for performing various tests to prevent durability problems, is aimed at accumulating relevant data and developing a better knowledge about infrastructure durability issues, especially in the marine environment. This knowledge will lead to the development and use of new and advanced technologies (i.e., better specifications, methods, materials, prevention techniques, etc.), that would improve the durability of transportation facilities when implementing them in real construction projects. The current project limits its scope to the durability problems and improvements in durability of the transportation system in the state of Texas.

The marine exposure test site, as a state facility, should provide benefits to the state of Texas and the taxpayers of Texas. To determine the feasibility of the development of a marine exposure test site, the current project performs a cost-benefit analysis that addresses various costs and benefits that will result from the development of a marine exposure test site. These costs and benefits include initial development costs, recurring site operation and maintenance costs, costs of implementation of new technologies/materials, and tangible and intangible benefits. These costs and benefits will occur or be realized over a long period of time, thus they have long-term effects over a wide range of transportation facilities in Texas (e.g., 49,829 highway bridges (*1*) and 192,113 lane miles of highways as of 2006 (*2*)). To take into account overall future effects, the current project takes a long-term perspective on the analysis, considering the life-cycle of the marine exposure test site.

The scope of this research and contract specifically addresses only the question of whether or not the development of a marine exposure test site is economically and technically feasible and cost-beneficial, not what overall research strategy TxDOT should or should not pursue. The scope of the work and this report is, accordingly, only concerned with evaluating and comparing the case with a marine exposure test site to the case without a marine exposure test site. Obviously, whether or not the proposed marine exposure test site should be developed depends on its position in the spectrum of the long-range TxDOT-supported research program. The scope of the current project did not address the possible combinations and permutation of research conducted in TxDOT-supported laboratories or field exposure test sites. This report makes no recommendation regarding whether TxDOT should or should not develop the proposed marine exposure test site and no recommendations concerning the overall strategy of TxDOT research.

CHAPTER 2. DURABILITY CHALLENGES IN TEXAS

Durability of structures has become one of the most critical issues to most state highway agencies (SHAs). The expenditure for repair and rehabilitation of existing structures is now larger than that of new construction in many states. The amount of effort expended to repair and rehabilitate transportation facilities has increased throughout the United States and the state of Texas is no exception. The following sections describe some of the major durability problems facing the state of Texas, with particular emphasis on those problems that have been most widespread.

DURABILITY CHALLENGES

Durability related problems include corrosion of reinforcing steel, ASR, DEF, external sulfate attack, freezing and thawing, corrosion of structural steel, and possible acid and microbe attack. These issues have been the subject of many research projects in Texas. The following discussions provide descriptions of the basics of each distress mechanism and explain how marine exposure conditions can exacerbate the durability problems.

Alkali-Silica Reaction

In the past ten years or so, ASR has been implicated in the deterioration of a range of TxDOT structures. These structures include bridge footings, bent caps, columns, precast girders, and pavements. Prior to these recent problems, the state of Texas was unaware that ASR was or would ever be an issue in the state.

ASR is an internal chemical reaction between the alkalies and hydroxyl ions in the pore water solution and the reactive siliceous phases in certain aggregates. For ASR to occur in concrete, the following three conditions must be met:

- The pH must be higher than around 13.2.
- There must be reactive silica in the aggregates (most aggregates in Texas contain reactive silica).
- Sufficient moisture must be available to drive the reaction.

Eliminating any of the three necessary conditions for ASR can effectively prevent or minimize expansion and subsequent damage.

ASR can cause distress in a wide range of structures, including structures in marine environments. The marine environment is unique and can exacerbate ASR in several ways. Seawater (and brackish water, as well) are typically composed of high concentrations of Na^+ usually in the range of 11,000 parts per million (ppm). Seawater is also typically quite high in $[Cl^-]$ (20,000 ppm), Mg^{2+} (1,400 ppm), and SO_4^{2-} (*3*). Of these ions, it is the presence of Na^+ ions that has the most direct impact on ASR. Specifically, when Na^+ penetrates into concrete, if the anions entering along with Na^+, specifically Cl^- or SO_4^{2-}, are bound or complexed, an excess of Na^+ results, which then has to be balanced by additional OH^-. During this process, the pH inside the concrete increases, exacerbating the attack on siliceous aggregates, and the excess Na^+ ions are then available to form the expansive gel. It is common to observe this process in marine concrete and it must be considered that this environment can exacerbate ASR. Figure 1 shows examples of ASR-induced damage.

Also, the wetting and drying cycles that concrete undergoes in the tidal zone can also result in concentrations of salts being formed, and these cycles can also result in shrinkage-induced cracks, all of which can further exacerbate ASR. This complex environment is very difficult or impossible to exactly mimic in the laboratory. A warm-water site in Texas would complement existing marine exposure test sites in colder environments such as at the Treat Island site and, more importantly, would allow for the evaluation of Texas materials in a native environment.

Figure 1. Examples of ASR-Induced Damage.

Delayed Ettringite Formation

Delayed ettringite formation is a relatively new type of distress in Texas, and worldwide. It has only been in the past 10 to 15 years that DEF-induced damage has been observed and only in the last few years that a better understanding of the in-depth mechanisms has been gained.

DEF can only occur in concrete if the following three conditions are met:

- the early curing temperatures exceed a threshold value of approximately 158 °F,
- a DEF-susceptible concrete mixture is used, and
- sufficient moisture is present to drive and sustain the reaction.

The basic chain of events for deterioration is as follows. High temperatures, in excess of the threshold value, may inhibit the normal formation of ettringite ($C_4AS_3H_{32}$) and accelerate the formation of calcium silicate hydrate (C-S-H) during cement hydration. The sulfates and aluminates that would usually form ettringite at normal temperatures are instead absorbed by the rapidly forming C-S-H. Later, under long-term, moist conditions, the sulfates and aluminates absorbed by the C-S-H are released into the pore solution of the hardened cement paste and form ettringite. This ettringite tends to grow in small, confined spaces, and as it expands, it leads to very significant pressures that cause the concrete to expand and crack. The presence of moisture tends to promote this process as water tends to leach away the alkalies from the pore solution, lowering the pore solution pH and accelerating the release of sulfate and aluminate ions from the concrete. This process can accelerate even further when ASR first occurs – when the alkalies in the pore solution are absorbed by the ASR gel, lowering the pore solution pH and triggering DEF.

Damage caused by DEF can be quite dramatic. Crack widths can be extremely large. Figure 2 shows an example of DEF-induced damage in Texas. The concern with DEF in a marine environment is based on the availability of an abundance of water, which is needed for expansive ettringite, and the fact that such large crack widths form direct paths for chlorides to reach reinforcing steel, resulting in corrosion of the steel. Again, subjecting reinforced concrete test specimens to true marine conditions cannot be done realistically in the laboratory but could certainly be accomplished in a devoted, long-term marine exposure test site under Texas environmental conditions. Given that DEF has now been confirmed in San Antonio, Houston, and elsewhere, it is likely only a matter of time before cases are observed in marine conditions.

Data gathered and knowledge gained from a marine site would help to provide tools for better dealing with problems as they emerge.

Figure 2. Examples of DEF-Induced Damage in Texas.

External Sulfate Attack

The deterioration of concrete caused by an external source of sulfates is a common type of distress. In Texas, external sulfate attack has not been as widespread as ASR or DEF, but there are potential cases of damage now being investigated, and research on this topic is being performed at The University of Texas at Austin under TxDOT Project 0-4889. Figure 3 shows potential cases of external sulfate attack.

Sulfate attack is an extremely complex process because various sulfate salts, including sodium sulfate, magnesium sulfate, and calcium sulfate can trigger it, and the damage can manifest itself chemically by attacking and decomposing certain hydrates in concrete or physically by salts crystallizing in concrete and degrading concrete without modifying the hydration products.

Equation 1 shows one of the more common ingredients of chemical sulfate attack related to the formation of ettringite:

$$\underset{\textit{Calcium}}{6Ca^{2+}} + \underset{\textit{Sulfate}}{3SO_4^{2-}} + \underset{\textit{Aluminate}}{Al_2O_6^{6-}} + \underset{\textit{Water}}{32H_2O} \rightarrow \underset{\textit{Ettringite}}{3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O} \quad \text{(Eq. 1)}$$

The calcium and sulfate ions could have different sources, internal or external. The formation of ettringite often involves an external sulfate source reacting with monosulfate or gypsum. When considering external sulfate sources, the most common types would be sodium sulfate, calcium sulfate (gypsum), and magnesium sulfate. From a chemical perspective, researchers generally consider magnesium sulfate to be more aggressive than sodium sulfate, which is more aggressive than calcium sulfate. In addition to the formation of ettringite (Eq. 1), another potential reaction associated with sulfate attack could include the formation of gypsum (through the reaction of external sulfates with calcium hydroxide, for instance). When Mg^{2+} is present in the environment, the formation of brucite and the decomposition of C-S-H can also occur.

Physical salt attack has been recognized as one of the most significant causes of damage to concrete structures. This concern with physical salt attack is likely to be relevant in a marine environment and confirms the need for low water-cementitious material ratio (w/cm) concrete, with supplementary cementing materials. However, more work is needed to better understand the influence of specific environmental conditions on this attack. A Texas coastal marine exposure test site would provide ideal conditions for actual exposure tests under gulf coast environmental conditions.

Figure 3. Potential Cases of External Sulfate Attack.

Corrosion of Reinforcing Steel

The initiation and propagation of corrosion of steel in concrete is a significant problem in Texas. Infrastructure systems north of the freeze line exhibit accelerated corrosion due to applications of de-icing and anti-icing chemicals. Infrastructure systems on the coast are exposed to aggressive saltwater. This corrosion is a function of many parameters, many of which are a function of the field environment.

In general, the environment plays a major role in the kinetics of corrosion (i.e., the rate of these reactions). Laboratory investigations can provide comparative studies of the rates of corrosion for different systems. However, the rate that actually occurs under field conditions is unknown. This rate is critical for predicting the long-term performance and service life of reinforced, prestressed, and post-tensioned structures. Key parameters necessary to evaluate the corrosion performance of steel embedded in cementitious materials are the apparent diffusion coefficient, the critical chloride concentration required to initiate active corrosion (also referred to as the critical chloride threshold), and the rate of corrosion after initiation. It is common in concrete technology to evaluate the service life of a reinforced concrete structure exposed to chlorides as two separate phases:

- the first phase being the amount of time for chloride ions to reach the steel-concrete interface in sufficient quantities to initiate active corrosion and
- the second phase being the time required to cause sufficient cracking or spalling of the concrete cover such that the structure is no longer serviceable.

This damage is significant in Texas and threatens the safety of structures. Figures 4 to 6 provide examples of corrosion. Figure 4 shows corrosion-induced delamination and spalling. Figure 5 shows spalling and strand corrosion. Figure 6 is a close-up view of the corrosion damage shown in Figure 5.

The initiation phase of the service life depends on the rate of chloride transport through the cementitious material and the corrosion resistance characteristics of the reinforcement in the cementitious environment. Because temperature and exposure conditions have a significant influence on the rate of chloride transport it is necessary to generate data and develop models from specimens exposed to actual field conditions. The propagation phase is mainly dependent on the rate of corrosion of the reinforcement. Many variables can affect the duration of the initiation and propagation phases and the environment plays a significant role. Both phases of the corrosion process are critical in determining longer-term performance and service life of infrastructure systems. To reliably estimate the performance of these systems, actual exposure at a marine site would provide significant value to TxDOT engineers and the taxpayers of Texas.

Figure 4. Corrosion of Reinforced Concrete Bent.

Figure 5. Spalling and Strand Corrosion.

Figure 6. A Close-up View of Corrosion of Reinforced Concrete.

Corrosion of Structural Steel

Many structures in Texas consist of structural steel elements. These elements are often exposed to environments that can result in the corrosion. Alloying of these metals (i.e., weathering steel) and coatings are often used in these structures with varying degrees of success. Clearly, a field exposure test site could provide significant information on the performance of different steel alloys and coating types. As would be expected these materials are best assessed when exposed to field conditions. NASA KSC research has led to significant findings of in situ deterioration rates and approaches to preventing corrosion damage. Figure 7 provides an example of corrosion of structural steel in Texas. Significant corrosion is found at the bottom of the steel structure.

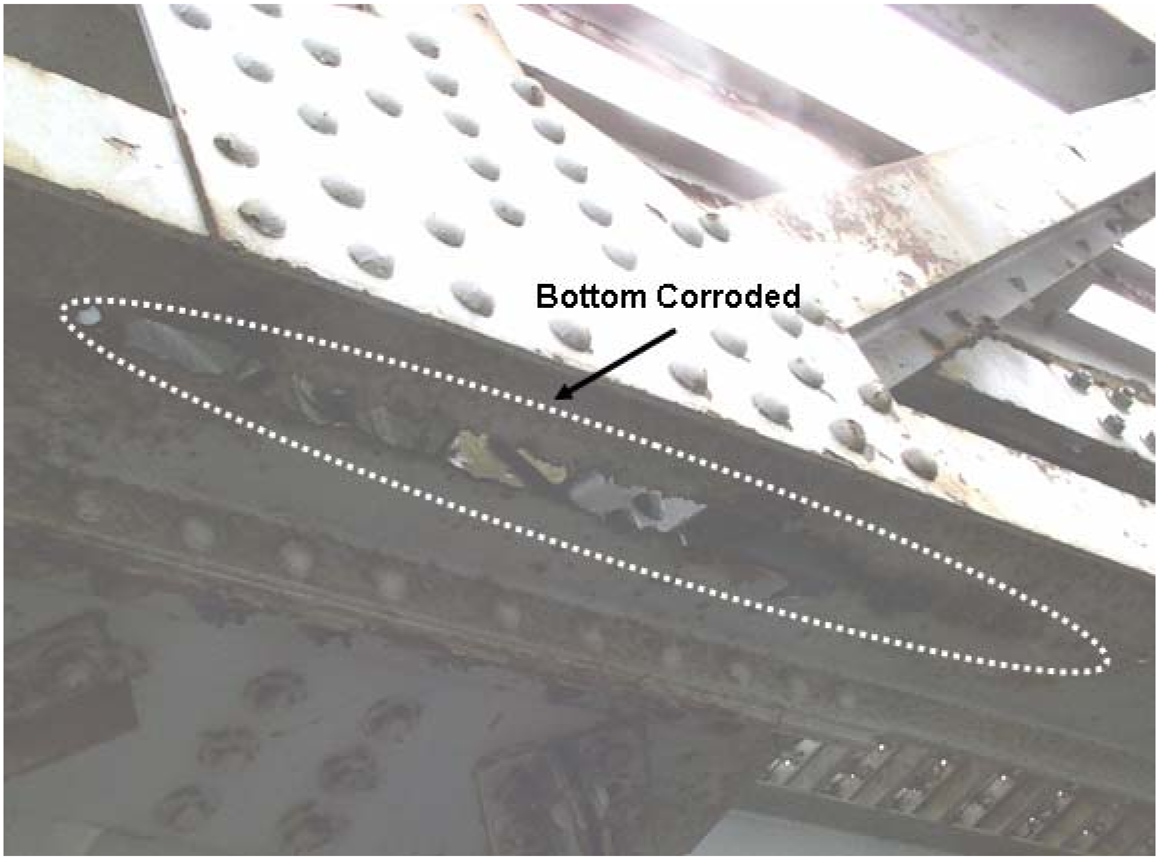


Figure 7. Corrosion of Structural Steel (Bottom Corroded).

Deterioration of Other Materials

Other materials also deteriorate. The objective of the exposure test site is to provide information on the field performance of materials and/or structural components such that researchers can assess and resolve issues related to deterioration. The above discussion focused on deterioration of concrete and steel materials, simply because these materials are so heavily used in transportation facilities and so there are significant needs to do this. However, there will be a need to assess the performance of other material types such as paints, composites, coating materials, and other products used in the infrastructure system. These materials could also be assessed at a Texas marine exposure test site.

CONDITION OF TRANSPORTATION FACILITIES IN TEXAS

According to *TxDOT: Meeting the Challenge* (*4*), "By 2030, Texas' population is expected to rise to 35 million, an increase of 12 million people. During that same period, road use will increase by 214 percent and highway freight traffic will jump by 77 percent." Managing and maintaining this growing transportation infrastructure system will be a challenging task for TxDOT, especially with limited funds. New construction of infrastructure facilities means increases in maintenance and repair costs in the future. These facilities are exposed to the natural environment, and thus they can suffer from durability problems. This section describes the conditions of transportation facilities in the state of Texas, especially highway bridges and highway pavements because they constitute a large part of TxDOT assets and are major concerns in deterioration challenges. This section identifies the needs for improvements in corrosion, deterioration prevention, and extension of service life.

Highway Bridges in Texas

Highway bridges have received significant interest regarding durability problems. A significant amount of funds has been spent for the maintenance and rehabilitation of highway bridges, because highway bridges are susceptible to deterioration and have very important functions in the state transportation system. Structural failure of bridges due to deterioration can be very costly and, in addition, there exist large amounts of user costs (e.g., traffic delay costs) caused by the replacement and rehabilitation activities which interrupt or stop bridge traffic.

TxDOT published the *Report on Texas Bridges* annually from year 2002 to 2004. After 2004, the report has been published biannually. Therefore, the available data from these reports cover years 2002, 2003, 2004, and 2006. The report provides descriptions of Texas bridges and their condition based on information in the Bridge Inspection Database, the Unified Transportation Program (UTP) planning document, and the Design and Construction Information System (DCIS) (*5, 6, 7, and 8*). In the reports, TxDOT classifies bridges by their condition as described below.

Classifications of Texas Bridges

Administrative Classification. Bridges can be classified by location for administrative purposes, as shown below:

- on-system bridges: Located on the designated state highway system and administered by TxDOT.
- off-system bridges: Not part of the designated state highway and under the direct jurisdiction of local governments.

Classification by Condition. Highway bridges are classified based on the Federal Highway Administration classification method into two major groups, based on their condition:

- sufficient bridges and
- deficient bridges.

Also, deficient bridges are sub-classified into three categories:

- structurally deficient bridges,
- functionally obsolete bridges, and
- substandard-for-load-only bridges.

TxDOT manages and maintains these classified bridges through necessary treatments (repair/replacement/rehabilitation) which are determined by their condition. Table 1 provides descriptions of the classifications and criteria based on *Report on Texas Bridges* (*5, 6, 7, and 8*). The term deterioration relates to the condition structurally deficient.

Table 2 provides the statistics on the number of Texas on-system bridges classified by condition. Unfortunately, as explained above the data available for the current project cover only four years: 2002, 2003, 2004, and 2006.

Table 1. Classification of Texas Bridges by Condition.

Condition	Criteria
Structurally Deficient*	If a structure meets any of the following criteria: – an extreme restriction on its load-carrying capacity – deterioration severe enough to reduce its load-carrying capacity beneath its original as-built capacity – closed – frequently over-topped during flooding, creating severe traffic delays
Functionally Obsolete	If it fails to meet any of the following criteria: – deck geometry – load-carrying capacity – vertical or horizontal clearances – approach roadway alignment
Substandard-for-Load-Only	Not structurally deficient or functionally obsolete but original as-built capacity was not designed to carry current legal loads.
Sufficient	Not structurally deficient, functionally obsolete, or substandard-for-load-only.

*If a structure is structurally deficient as well as functionally obsolete, it is classified as structurally deficient.

Table 2. Current Condition of on-System Bridges in Texas.

on-System Bridges	2002		2003		2004		2006	
	No.	**Percent**	**No.**	**Percent**	**No.**	**Percent**	**No.**	**Percent**
Total	32,010	100.0	32,206	100.0	32,287	100.0	32,674	100.0
Sufficient	27,431	85.7	27,665	85.9	27,660	85.7	28,135	86.1
Structurally Deficient	688	2.1	645	2.0	565	1.7	483	1.5
Functionally Obsolete	3,661	11.4	3,701	11.5	3,888	12.0	3,951	12.1
Substandard-for-Load-Only	204	0.6	184	0.6	151	0.5	105	0.3
Not Classified	No Info	No Info	11	0.0	23	0.1	No Info	No Info

In Table 2, the total number of on-system bridges has been increasing, from 32,010 in FY 2002 to 32,674 in FY 2006. This increase includes construction of bridges at new locations. As of FY 2006, the percentages of sufficient and deficient (non-sufficient) bridges were approximately 86 and 14 percent, respectively. The percentages of structurally deficient bridges and functionally obsolete bridges were about 1.5 and 12 percent, respectively. The structurally deficient bridges suffer from deterioration and they eventually need to be rehabilitated because there can be safety issues with this classification of bridges. The functionally obsolete bridges are not directly related to the degree of deterioration. However, they are also under consideration for rehabilitation.

For the transportation facilities in Texas, TxDOT performs significant rehabilitation activities as well as preventive maintenance and spends a significant amount of funds to perform these activities. In FY 2007 TxDOT spent about 38 percent of its total highway fund disbursements for the maintenance of facilities and the majority of these expenditures were for highway bridges and highways. This information is based on the TxDOT website. Figure 8 is copied from http://www.dot.state.tx.us/services/finance/total_receipts.htm (9) and Figure 9 is copied from http://www.dot.state.tx.us/services/finance/disbursements.htm (*10*).

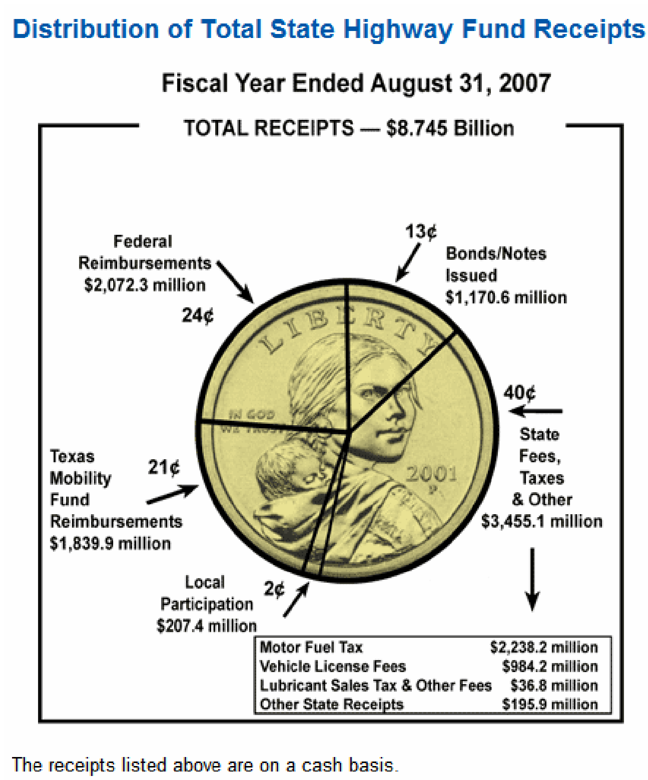


Figure 8. TxDOT Highway Fund Receipts.

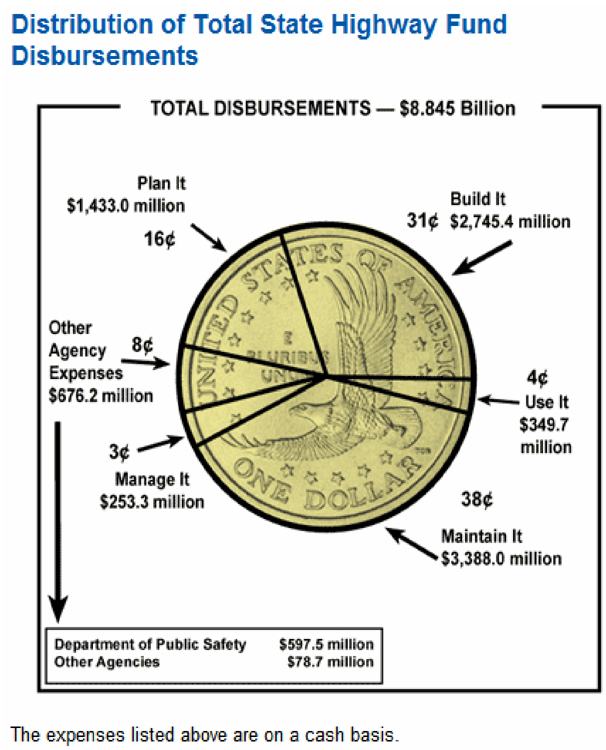


Figure 9. TxDOT Highway Fund Disbursements

Maintenance activities include repair, replacement, rehabilitation, preventive maintenance, and routine maintenance. This percentage represents a large amount of expenditures considering that TxDOT's total state highway fund disbursements were $8.845 billion in FY 2007, so that disbursements for maintenance in that year were $3,388 million (see Figure 9). Throughout this report, estimates of the costs of deterioration are based on data taken from publications by TxDOT and publications by the Federal Highway Administration and other agencies, not on original research.

The details on expenditures for replacement/rehabilitation of Texas highway bridges and Texas highways are shown in Appendix I and Appendix II, respectively. As found in Appendices I and II, about $500 million and more than $1,400 million (as of FY 2006) were spent for replacement and rehabilitation of highway bridges and highways, respectively (these amounts do not include preventive maintenance and routine maintenance.) Figure 10 is taken from page 31 of the *Report on Texas Bridges* (as of September 2006) *(8)* which was published by TxDOT in 2007. It shows that TxDOT spent $489.1M for on-system bridge replacement/rehabilitation. Also, page 33 of this report says that TxDOT spent $55.4M for off-system bridge replacement/rehabilitation. Thus, the total replacement/rehabilitation costs are \$489.1M + \$55.4M = \$544.5M or about \$500M. Consequently, the development of materials and method to reduce replacement and rehabilitation costs are areas of potential high payback.

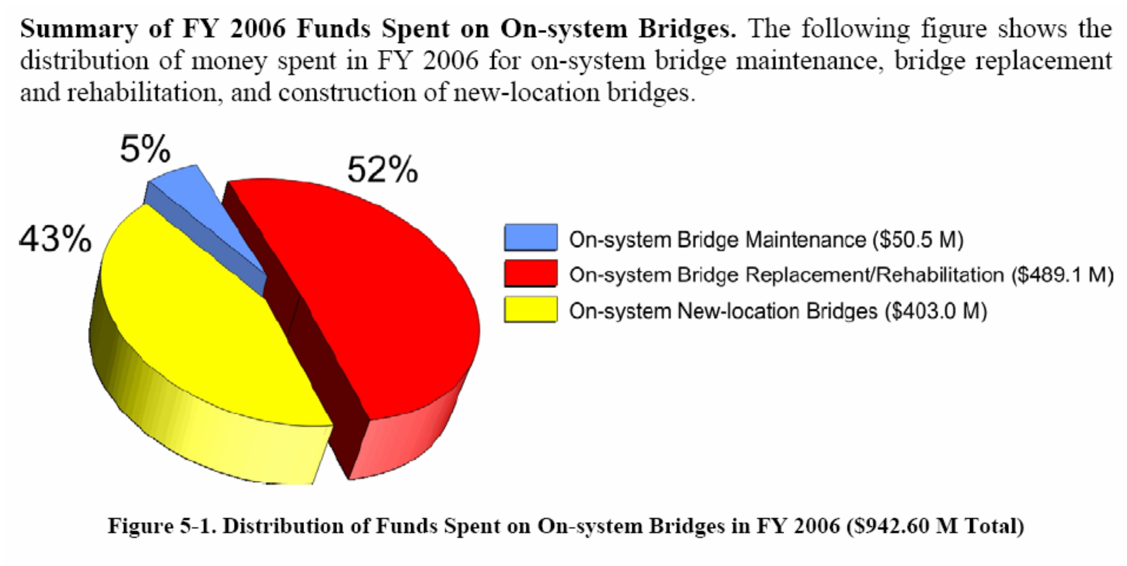

Summary of FY 2006 Funds Spent on On-system Bridges. The following figure shows the distribution of money spent in FY 2006 for on-system bridge maintenance, bridge replacement and rehabilitation, and construction of new-location bridges.

Figure 5-1. Distribution of Funds Spent on On-system Bridges in FY 2006 ($942.60 M Total)

Figure 10. FY 2006 Funds Spent.

As to the rehabilitation costs of highways, TxDOT's *Annual Financial Report,* for the Fiscal Year ended August 31, 2006 (*11*) says on page 53 that the actual maintenance costs for interstate highways were about \$434M and the actual maintenance costs for other highways were about \$1,750M. Total costs are about \$2.1B (= \$434M + \$1,750M). The report *Condition of Texas Pavements* (*12*) published by TxDOT says on page 188 that \$1,706M is needed to repair Texas pavements in FY 2006. This \$1,706M is for total pavement needs. On the same page, it is stated that among these costs, \$295M is for preventive maintenance.

Table 3 shows the funds spent on on-system bridges for maintenance, replacement, and rehabilitation. As mentioned earlier, on-system bridges are bridges located on the designated state highway system and administered by TxDOT. Table 4 provides the numbers of on-system bridges replaced or rehabilitated by bridge condition (*1, 5, 6, and 7*). There are variances in the amount of funds spent in different years. In 2004 and 2006, the average total amount of funds spent on replacement and rehabilitation of the on-system bridges was about \$500 million.

Report on Texas Bridges (as of September 2006) (*8*) became available on the TxDOT website after the analysis was carried out using the model to obtain the results. For the analysis, the research team used 2006 data from *Bridge Facts* (*1*). It provides summary information and no discrepancy was found in the data compared to *Report on Texas Bridges* (as of September 2006) (*8*).

Table 3. Funds Spent on on-System Bridges.

Year	2002	2003	2004	2006
Maintenance (incl. preventive maintenance)	$57.2M	$78.8M	$58.8M	No Info
Replacement/Rehabilitation	$237.4M	$619.7M	$446.7M	$489.1M
Total Sum	$294.6M	$698.5M	$505.5M	No Info

Table 4. Number of on-System Bridges Rehabilitated.

Condition of on-System Bridges in Replacement/Rehabilitation Projects Let to Contract	2002	2003	2004
Structurally Deficient	66	47	47
Functionally Obsolete	51	62	41
Not Structurally Deficient or Functionally Obsolete	148	232	202
Total Sum	265	341	290

TxDOT's 2011 Goal

"In 2001, TxDOT set its goal to make at least 80 percent of Texas bridges good or better by September 2011 and to accelerate the upgrade of all structurally deficient on-system bridges, prioritizing critically deficient bridges, to eliminate all structurally deficient on-system bridges in the State of Texas (*5, 6, 7, and 8*)." Currently 79.5 percent of Texas bridges are classified as sufficient bridges including both on-system and off-system bridges. In general, on-system bridges are in better condition than off-system bridges. Off-system bridges have higher percentages than on-system bridges in deficient (non-sufficient: structurally deficient, functionally obsolete, and substandard-for-load-only) classifications. In Table 2, the percentage of sufficient on-system bridges is approximately 86 percent as of 2006. To see the condition of off-system bridges and total bridges, refer to Appendix I.

There has been a decreasing trend in the percentage of structurally deficient bridges. The percentages are 2.1, 2.0, 1.7, and 1.5 percent from years 2002, 2003, 2004, and 2006, respectively, so they appear to be decreasing uniformly. However, the decreasing trend is not sufficient to attain TxDOT's 2011 goal. Based on the information above, it is expected that the rehabilitation and maintenance of bridges, especially structurally deficient bridges, will continue costing the state taxpayers a significant amount of money in the future unless better materials and methods are developed.

Highways in Texas

TxDOT published a report, *Condition of Texas Pavements* (*12*) based on analysis of the Pavement Management Information System (PMIS). The report describes the major highway systems by pavement type as well as by condition. It also provides information about maintenance level of service and estimates of preventive maintenance and rehabilitation needs. Tables in this section are based on the report, *Condition of Texas Pavements*. This report covers from year 2003 to 2006. The research team did not use the previous year's data because there were significant adjustments in the data from 2002 to 2003.

Classification of Highways

According to *Condition of Texas Pavements*, highways can be classified by system (interstate highways, state highways, business, and so on), pavement type, and condition. The following sections provide classifications by pavement type and condition.

Classification by Pavement Type. Highways are classified by pavement type as:

- flexible or asphalt concrete pavement (ACP),
- continuous reinforced concrete pavement (CRCP), and
- jointed concrete pavement (JCP).

The report *Condition of Texas Pavements* (*12*) reveals the following facts:

- On page 193, "Flexible pavements make up 92.34 percent of TxDOT-maintained lane mileage, but only require *60.50 percent* of the total pavement needs. $1,032 million is needed to repair flexible pavements in FY 2006."
- On page 194, "CRCP pavements make up only 5.35 percent of TxDOT-maintained lane mileage, but require *25.22 percent* of the total pavement needs. $430 million is needed to repair CRCP lane miles in FY 2006."
- On page 195, "JCP pavements make up only 2.31 percent of TxDOT-maintained lane mileage, but require *14.28 percent* of the total pavement needs. $244 million is needed to repair CRCP lane miles in FY 2006"

These facts are summarized in Table 5 showing the percentages of each classified group in total lane miles, capacity, and maintenance needs. Although CRCP and JCP have small percentages of lane mileages, their percentages of travel capacity and maintenance needs are not negligible. If we can assume that only CRCP pavements are related to corrosion and deterioration problems, the total corrosion related costs for highways would be about $430 million, as shown above.

Table 5. Highways by Pavement Type.

	Percent of the TxDOT-maintained lane mileage	**Percent of the capacity of the vehicle miles traveled**	**Percent of total maintenance needs (funds)**
Flexible or Asphalt Concrete Pavement	92.3	72.6	60.50
Continuously Reinforced Concrete Pavement	5.4	22.0	25.22
Jointed Concrete Pavement	2.3	5.4	14.28

Classification by Condition. PMIS evaluates the condition of highways in the following three different scoring systems:

- distress describes visible surface deterioration;
- ride quality is calculated from pavement roughness measured by calibrated electronic equipment; and
- (overall) condition is the combined score of these two measures, adjusted for traffic and speed.

The overall condition score has five classes:

- 90~100 (very good),
- 70~89 (good),
- 50~69 (fair),
- 35~49 (poor), and
- 1~34 (very poor).

As a combined score, the number represents the overall condition of highways with a single number.

Similar to the highway bridges, TxDOT set another goal for highway pavements. "In August 2001, the Texas Transportation Commission set a goal to have 90 percent of Texas pavement lane miles in good or better condition within the next ten years (that is, by FY 2012) (*5, 6, 7, and 8*)." In the PMIS, good or better was defined as a condition score of 70 or above. Table 6 shows the percentage of lane miles above the condition score goal (i.e., ≥ 70) for the last five years. About 95 percent of total lane miles were rated each year.

In Table 6, the percentages of highways above the targeted score have varied a little over recent years and there is no clear increasing trend (the percentages for 2006 are slightly below those for 2005). In addition, CRCP and JCP have lower percentages than ACP. Note that corrosion and deterioration processes are more related to CRCP and JCP than ACP. Achieving TxDOT's 2012 target for highway pavements will be challenging, considering the past and current status of the highways. Detailed data can be found in Appendix II.

Table 6. Percentage of Lane Miles above Condition Score Goal.

Fiscal Year	2002	2003	2004	2005	2006
Statewide	84.2%	85.3%	87.0%	87.3%	86.7%
Flexible or Asphalt Concrete Pavement	No Info	No Info	No Info	88.7%	88.0%
Continuously Reinforced Concrete Pavement	No Info	No Info	No Info	84.1%	83.1%
Jointed Concrete Pavement	No Info	No Info	No Info	58.3%	56.6%

Pavement Needs

The Needs Estimate program in the PMIS categorizes the pavement system by types of repair treatments using predetermined criteria, which include not only distress and ride scores, but also other factors such as traffic, number of lanes, and functional classification.

The treatments are classified as follows:

- Needs Nothing (no treatment);
- Preventive Maintenance (PM, such as a seal coat or crack seal);
- Light Rehabilitation (LRhb, such as a thin hot-mix overlay);
- Medium Rehabilitation (MRhb, such as slab repair or thick hot-mix overlay); and
- Heavy Rehabilitation (HRhb, such as a new flexible or rigid pavement).

Table 7 shows, by treatment, the amount of funds needed, their percentages in total, and their percentages in lane miles. These estimates only cover pavement-related expenses. They do not cover right-of-way, bridge repair, capacity, safety, traffic control, or other roadside improvement costs. Total lengths of lane (including all main miles and frontage roads) in 2005 and in 2006 were 191,415 and 192,113 lane miles, respectively. Table 8 provides the estimates of pavement needs for other previous years.

Table 7. PMIS Estimated Pavement Needs for FY 2005 and 2006.

	FY 2005			FY 2006		
	Funds Needed	Percent in Fund Needs	Percent in Total Lane Miles	Fund Needs	Percent in Fund Needs	Percent in Total Lane Miles
Preventive Maintenance	$329M	20.7	27	$295M	17.3	24
Light Rehab.	$256M	16.1	6	$271M	15.9	6
Medium Rehab.	$496M	31.2	4	$555M	32.5	5
Heavy Rehab.	$511M	32.1	1	$585M	34.3	1
Total	$1,592M	100.0	38	$1,706M	100.0	36

Table 8. PMIS Estimated Pavement Needs for FY 2002 – 2004.

	FY 2002	FY 2003	FY 2004
Preventive Maintenance	$306M	$325M	$356M
Rehabilitation	$1,256M	$1,377M	$1,517M
Total	$1,562M	$1,702M	$1,873M

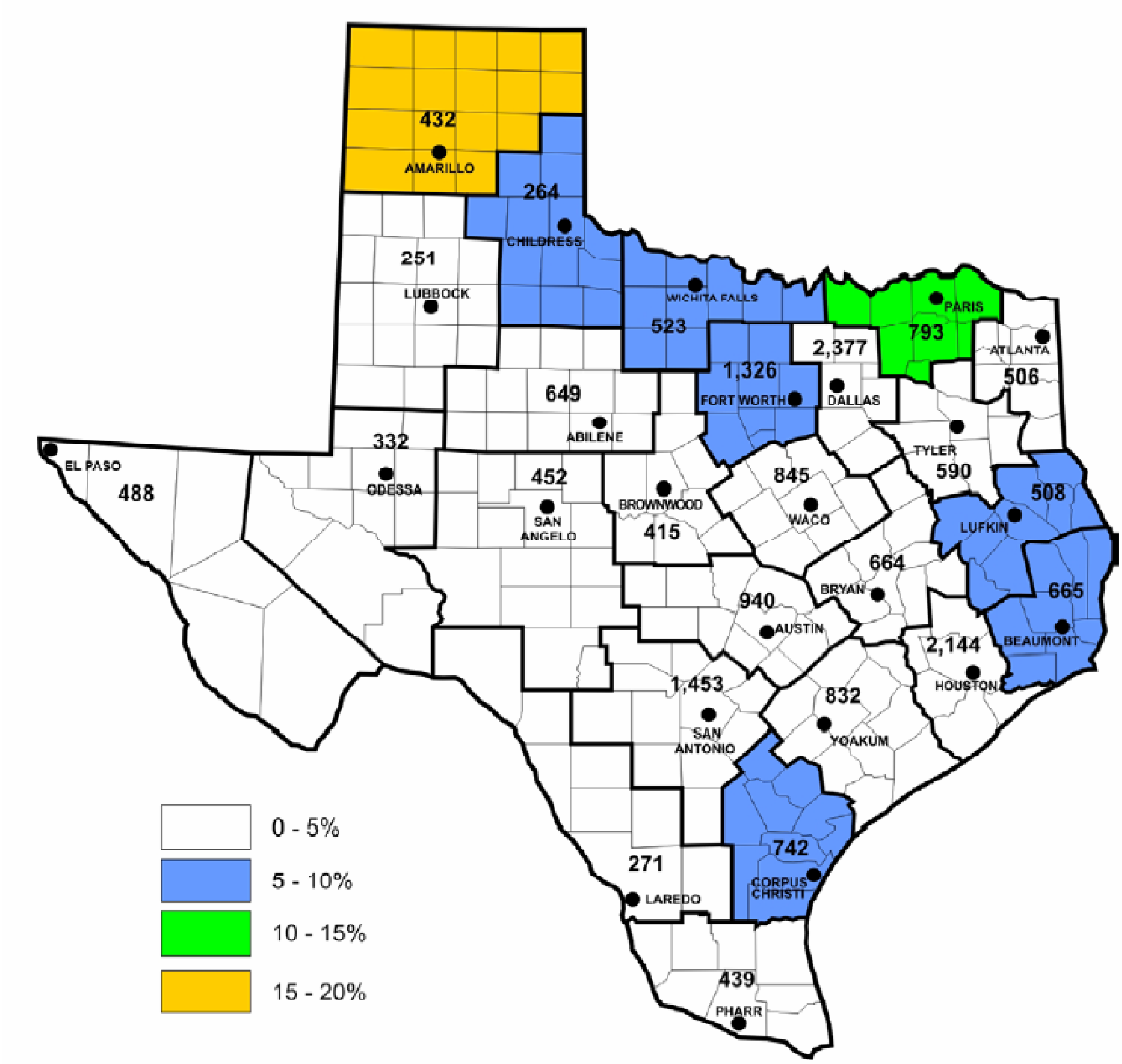
Over the past five years, the average total maintenance expenditure for Texas highway systems was about $1.6 billion. As in the case of bridges, the need for maintenance activities for the highway system will not likely decrease in the future unless new innovative maintenance materials or methods are developed and implemented, or the durability of pavements is improved.

Structural Deficiency of Texas Highway Bridges

Although the proposed facility, the marine exposure test site, would obviously be constructed on the Texas coast, if it were to be constructed at all, one should not make the mistake of assuming that, from its name, it would offer no benefits outside the Texas coastal zone. Although corrosion and deterioration issues are more obvious in the coastal zone, transportation facilities far form the coastal zone also suffer from these conditions, The maps below graphically illustrate that the problems with deterioration and corrosion occur all across Texas, including the north, and are not limited to locations with marine exposure. These locations would benefit as well from improved materials, methods, and processes developed by the proposed marine exposure test site.

The following figures show the distribution of structurally deficient bridges in Texas. The figures were obtained from *Report on Texas Bridges* *(5, 6, and 7).* The 2006 report does not provide such figures. The *Report on Texas Bridges* begins from fiscal year 2002. After 2004, this report was published biannually. There is no publication of *Report on Texas Bridges* for year 2005. The research team assumed that data officially published by TxDOT are authoritative.

Figures 11, 12, and 13 are for structurally deficient on-system bridges. Figures 14, 15, and 16 are for structurally deficient off-system bridges. From these figures, it can be concluded that deterioration problems are severe in all areas of Texas as well as in the coastal area. Therefore, although the proposed marine exposure test site would be on the gulf coast, the beneficiaries of the research done there would extend across the state to all Texans.

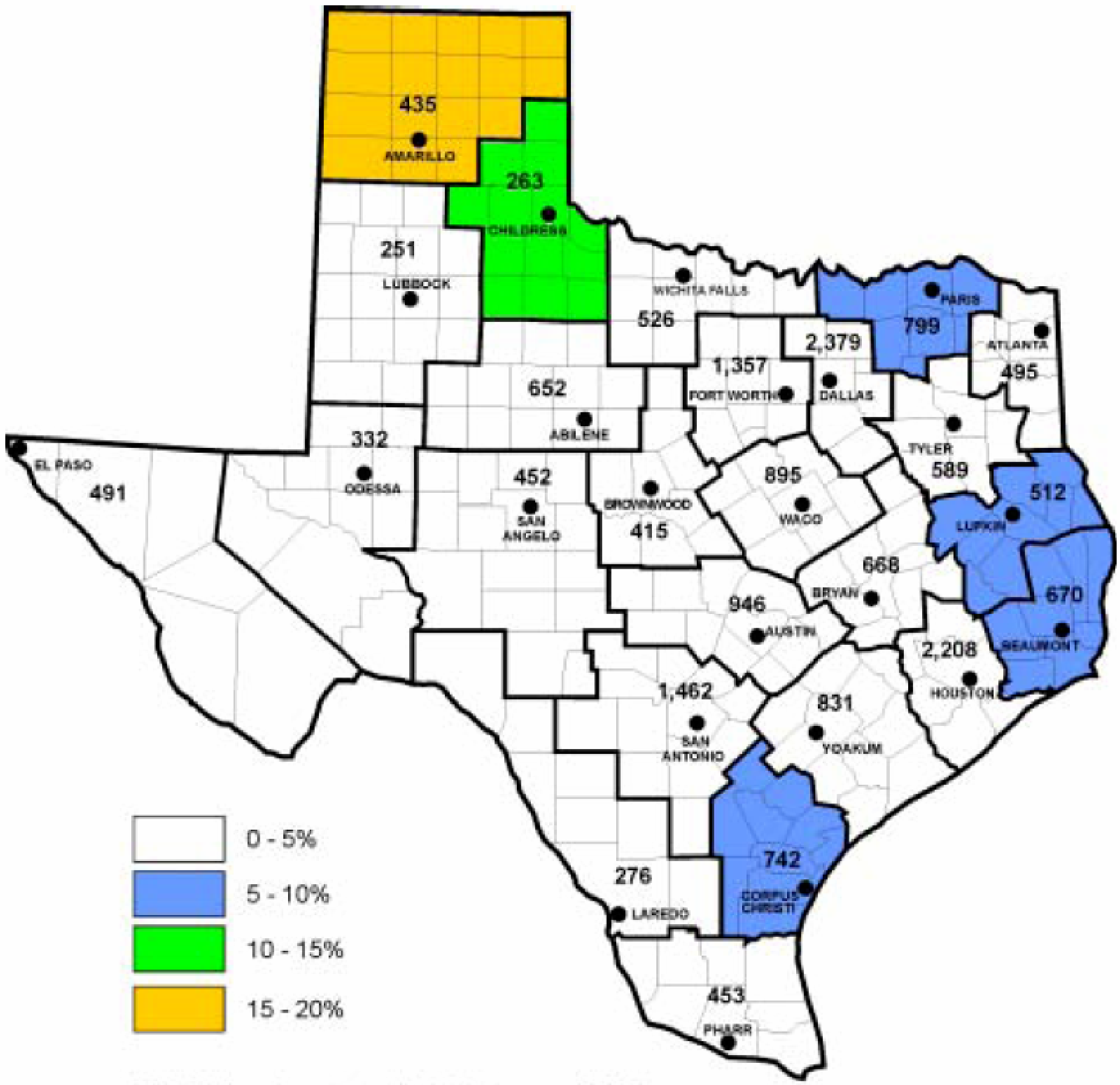


NOTE: Colors show structurally deficient range of 0-20%.

Numbers show total count of on-system span-type bridges in each district. (Discrepancies exist between FY 2001 and FY 2002 numbers, a result in part of refined database queries.)

Figure 4-9. Percent of Structurally Deficient On-system Span-type Bridge Deck Area in September 2002 by District

Figure 11. Structurally Deficient on-System Bridges, 2002.

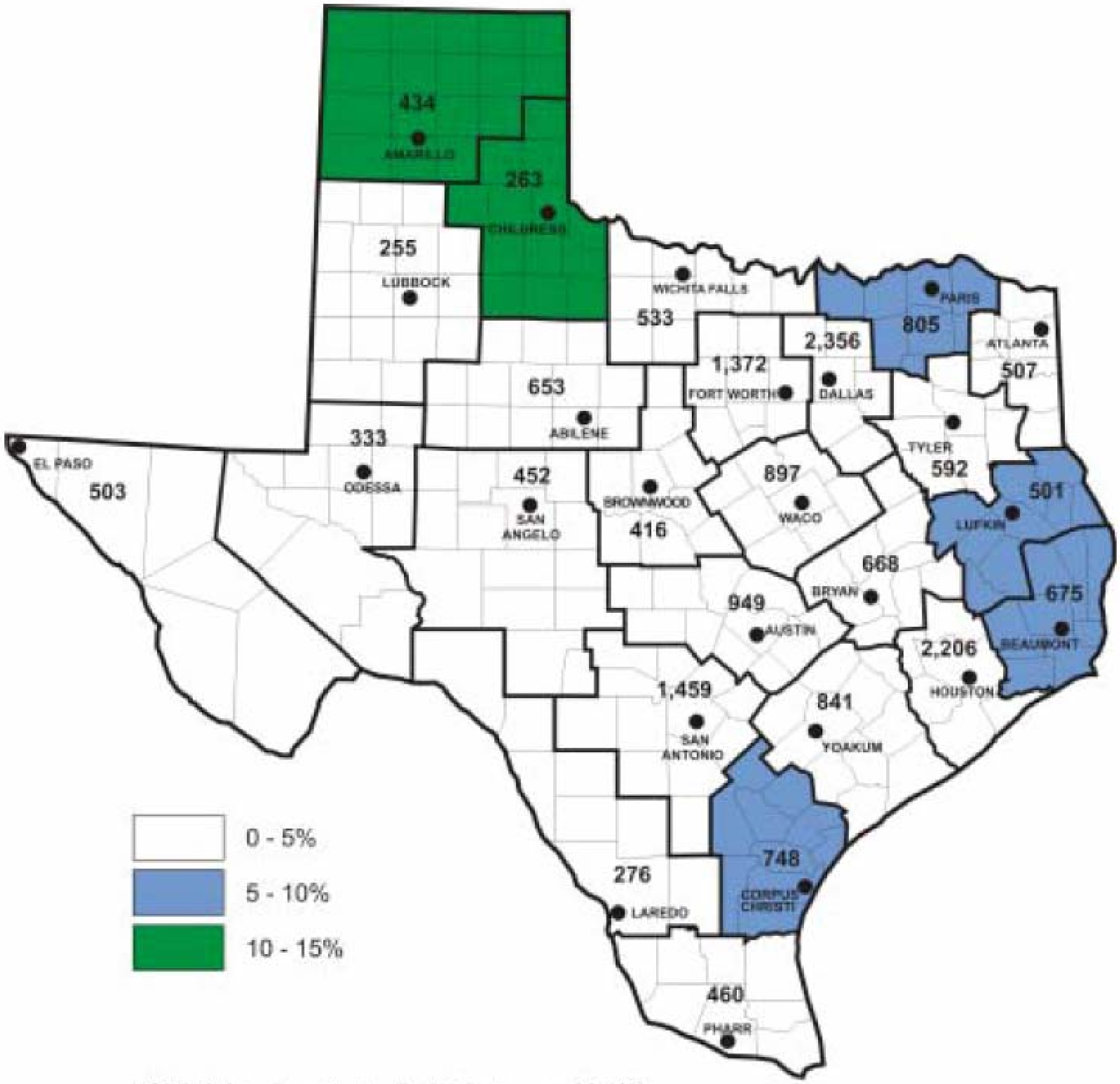


NOTE: Colors show structurally deficient range of 0-20%.

Numbers show total count of on-system span-type bridges in each district.

Figure 4-9. Percent of Structurally Deficient On-system Span-type Bridge Deck Area in September 2003 by District

Figure 12. Structurally Deficient on-System Bridges, 2003.



NOTE: Colors show structurally deficient range of 0-15%.

Numbers show total count of on-system span-type bridges in each district.

Figure 4-9. Percent of Structurally Deficient On-system Span-type Bridge Deck Area in September 2004 by District

Figure 13. Structurally Deficient on-System Bridges, 2004.

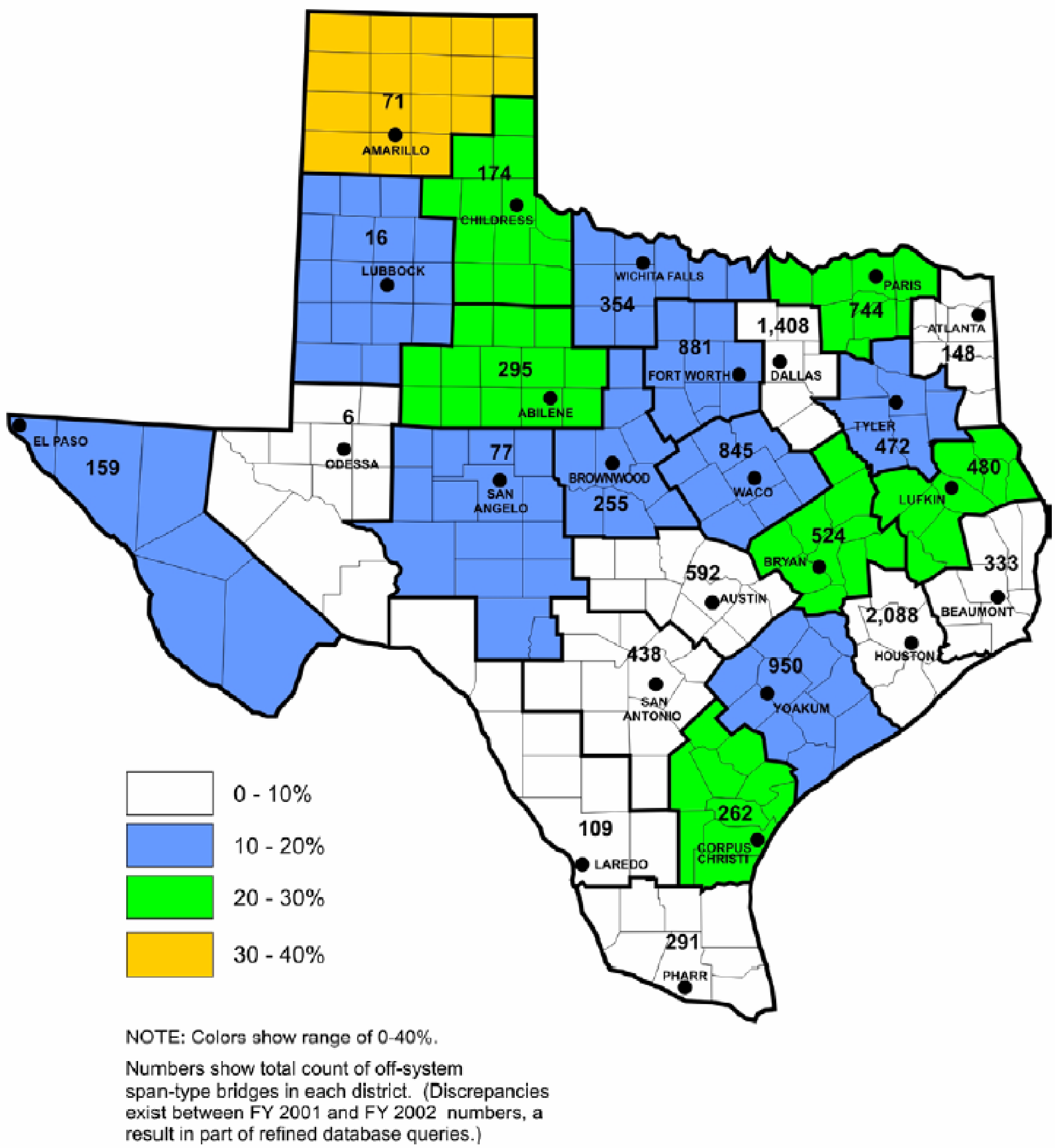


Figure 4-10. Percent of Structurally Deficient Off-system Span-type Bridge Deck Area in September 2002 by District

Figure 14. Structurally Deficient off-System Bridges, 2002.

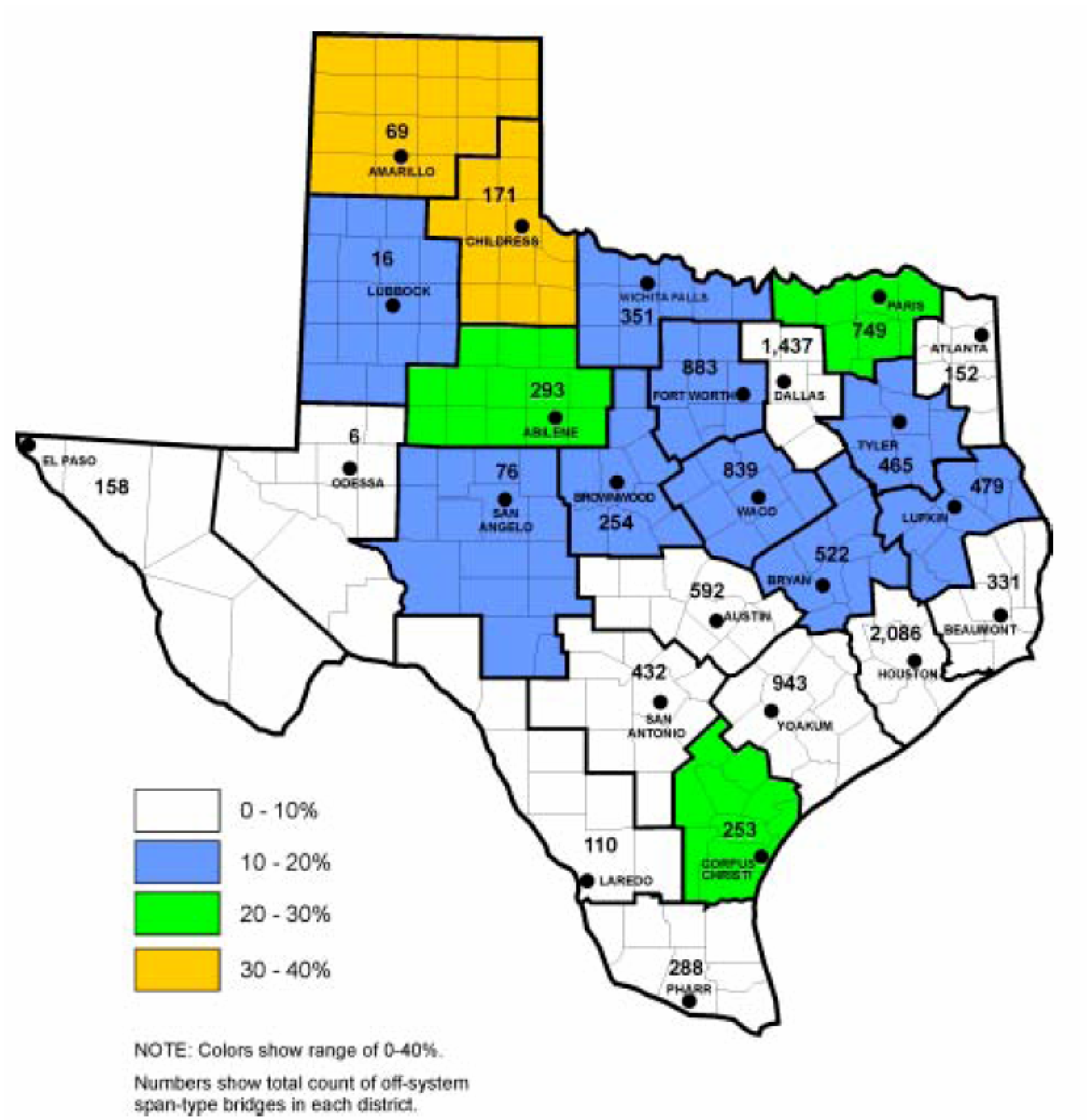


Figure 4-10. Percent of Structurally Deficient Off-system Span-type Bridge Deck Area in September 2003 by District

Figure 15. Structurally Deficient off-System Bridges, 2003.

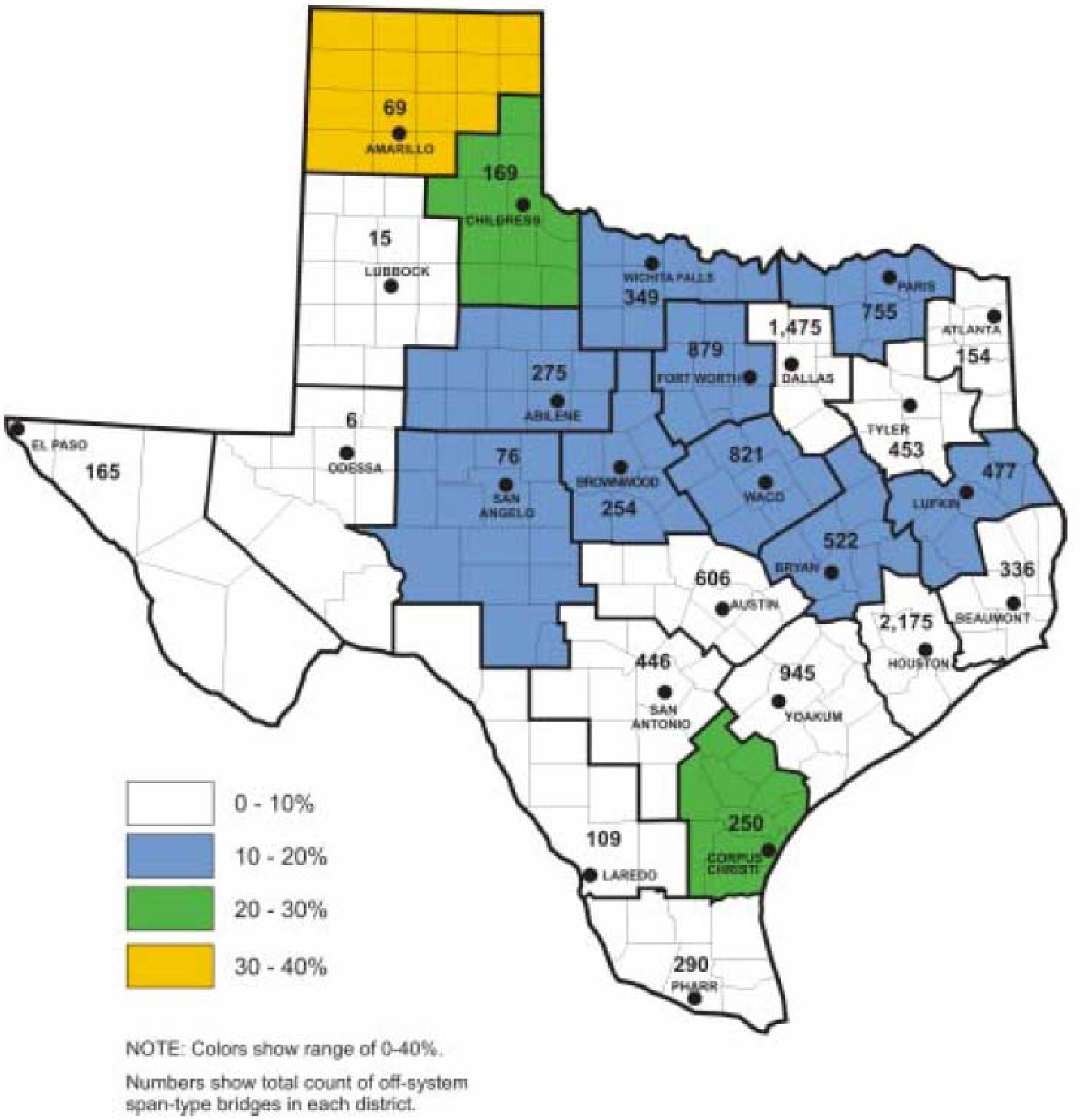


Figure 4-10. Percent of Structurally Deficient Off-system Span-type Bridge Deck Area in September 2004 by District

Figure 16. Structurally Deficient off-System Bridges, 2004.

SUMMARY

In this chapter, durability problems and current condition of transportation facilities in Texas have been discussed. Durability issues are plaguing every SHA and these issues include ASR, DEF, external sulfate attack, corrosion of reinforcing steel and structural steel, and other deterioration mechanisms. States such as Texas with saltwater coastlines have more challenges with durability of their infrastructure system.

Considering that expenditures for the maintenance of existing transportation facilities have continuously grown beyond construction costs of new facilities in many states, SHAs need to take innovative actions to improve overall efficiency and safety of the infrastructure system.

It is quite clear that field research is needed to increase the durability and longevity of concrete, steel, and other structural materials exposed to severe environments. To reduce the impact of the durability problems described above, control of deterioration processes is needed. Having a field marine exposure test site could provide the state of Texas with an important tool to test and evaluate new methods and materials to reduce or prevent deterioration. A natural marine exposure test site can provide the environment for critical exposure conditions that are difficult or impossible to replicate in laboratory experiments.

CHAPTER 3. LITERATURE REVIEW

Durability problems cause significant economic burdens in constructing and maintaining transportation facilities. As part of this project's effort to identify costs caused by durability problems and benefits of prevention efforts, previous economic studies on corrosion were reviewed. Only a limited number of studies and resulting reports are available on the cost of deterioration other than corrosion in concrete and other materials. Thus, this project used corrosion costs to estimate all deterioration costs.

PREVIOUS STUDIES

There have been several previous studies on quantifying corrosion costs at the national level. No comprehensive studies have been performed to evaluate the costs of concrete deterioration (not including corrosion). Starting with the study by Uhlig *(13)*, several studies were performed to estimate corrosion and deterioration costs using different approaches. Their estimates and approaches (as discussed below) differ in detail, but all studies emphasize the great financial significance of economic losses caused by durability problems.

Uhlig's Study

Uhlig's study *(13)* was the earliest effort to estimate the cost of corrosion at a national level. Uhlig estimated corrosion costs for the United States economy by summing the costs of materials and procedures required for corrosion control, which first brought attention to the economic effects of corrosion. The study measured the costs of corroding structures to both the owner/operator (direct cost) and to others (indirect cost). Uhlig estimated the direct cost for year 1949 by summing the costs of corrosion prevention and repair methods and relevant services. As a result, the estimated total annual corrosion costs were \$5.5 billion, which was equivalent to 2.1 percent of the 1949 U.S. Gross National Product (GNP).

Hoar's Study

Hoar (*14*) identified the costs of corrosion by industry sectors, focusing on direct corrosion costs. Direct costs to owner/operators were estimated based on the information from interviewing corrosion experts and surveying expenditures for corrosion protection practices in major economic sectors. The estimated total costs for year 1970 accounted for 3.5 percent of the 1970 United Kingdom GNP.

National Bureau of Standards (NBS) Study

NBS study (*15*) applied an economic input/output analysis using the U.S. input/output matrix that was constructed by the Department of Commerce from the census of manufacturers. It classified the U.S. economy into 130 industrial sectors.

According to the study (*15*), "The input/output model is an equilibrium model of an economy showing the extent to which each sector uses inputs from the other sectors to produce its output. Thus it shows how much each sector sells to other sectors. The study collected data on corrosion-related changes in resources, capital equipment and facilities, and replacement rates for capital stock of the capital items among sectors. The standard input-output matrix is modified based on identified elements of various sectors which represent corrosion expenditures."

In this study, corrosion costs were defined as "the increment of total cost incurred because corrosion exists." Based on this definition, the matrix was adjusted assuming two alternative states: what if corrosion does not exist in the world, and what if it does exist. The study assumed three different worlds:

1) World I: real world of corrosion,
2) World II: hypothetical world without corrosion, and
3) World III: hypothetical world with the economically most effective corrosion prevention.

Using comparisons between the assumed hypothetical worlds, total corrosion costs were classified into avoidable costs and unavoidable costs:

- avoidable cost (able to be reduced by effective prevention), is the difference between the costs in World I and World III and

- unavoidable costs (costs not able to be reduced), are the difference between the costs of World II and World III.

As a result, the total corrosion costs for year 1975 were estimated to be $82 billion or 4.9 percent of the 1975 U.S. GNP. About 40 percent of this cost was estimated to be avoidable.

Battelle Columbus Laboratories (BCL) Study

In 1995, the BCL study *(16)* updated the previous NBS study performed in 1978 *(15)*. The updated estimate of total corrosion costs was $300 billion/year, which was 4.2 percent of the 1995 U.S. GNP. Based on their "judgmental evaluation," the percentage of avoidable corrosion cost of the total was reduced from 40 percent (in 1978) to 35 percent (in 1995), in part due to the broader application of corrosion-resistant practices. Of the $300 billion/year $105 billion/year was estimated to be avoidable costs.

FHWA Study

The FHWA study *(17)* is the most recent study at the national level on corrosion costs. It took two different approaches:

1) Estimating corrosion costs by corrosion control methods and services, and

2) Estimating corrosion costs by specific industry sectors for the purpose of comparison.

This study concluded that the second approach better accounts for the majority of corrosion costs than the first approach because secondary costs are easily missed using the first approach, such as some corrosion management costs and costs of capital loss. The content of this study is also available at http://www.corrosioncost.com/home.html.

The First Approach

The first FHWA approach estimated corrosion costs by corrosion control methods and services. The estimate is based on the costs of corrosion control methods and services, which is similar to Uhlig's approach. Different corrosion control methods were considered: protective coatings, corrosion-resistant alloys, corrosion inhibitors, engineering plastics and polymers, cathodic and anodic protection, and corrosion control services. As a result, the estimate of the total annual direct corrosion cost was $121 billion, which was equivalent to 1.38 percent of the United States Gross Domestic Product (GDP) in 1998 (*17*).

The Second Approach

The second FHWA approach estimated corrosion costs by specific industry sector. Direct corrosion costs for specific industry sectors were individually estimated based on interviews with experts and data collected for the corresponding industry. National level corrosion costs were extrapolated from the estimates for a quarter of total industry (27.54 percent of total GDP) based on Bureau of Economic Analysis (BEA) category and industrial GDP. As a result, the total direct corrosion costs were estimated to be $276 billion per year (about 3.1 percent of the U.S. GDP). However, this estimate was considered to be very conservative (that is, it is low) because it includes only major costs. A comparison of the two approaches reveals that there are significant additional costs other than physical treatment of corrosion problems.

For the indirect costs, the FHWA study (*17*) simply assumed the "total indirect costs over the total U.S. economy can be equal to, if not greater than, the total direct costs." Thus, the total cost (direct cost + indirect cost) was estimated at $552 billion per year in 2001. The majority of the indirect costs included were:

- productivity losses due to outages, delays, and litigation;
- taxes and overhead on the cost of the corrosion portion of goods and services; and
- indirect costs of non-owner/operator activities.

Highway Bridges

In the FHWA study, the infrastructure sector was divided into highway bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads. The following is a summary of the analysis for highway bridges.

- Half of the bridges in the United States were built between 1950 and 1994.
- The annual direct cost of corrosion of highway bridges is $8.3 billion.
- Approximately 15 percent of all bridges in the U.S. are structurally deficient, primarily due to corrosion. The most significant mechanism is chloride-induced

corrosion of steel members, with the chlorides coming from de-icing salts and marine exposure.

- Life-cycle analyses estimated indirect costs to the user due to traffic delays and lost productivity at more than ten times the direct cost of corrosion maintenance, repair, and rehabilitation.

In addition, there is a very important point that needs to be emphasized: the cost of replacing aging bridges increased by 12 percent between 1995 and 1999. "There has been a significant increase in the required maintenance of the aging bridges, since many of the 435,000 steel and conventional reinforced-concrete bridges date back to the 1920s and 1930s. Although the vast majority of the 108,000 prestressed-concrete bridges have been built since 1960, many of them will require maintenance in the next 10 to 30 years. Therefore, significant maintenance, repair, rehabilitation, and replacement activities for the nation's highway bridge infrastructure are expected over the next few decades." (*17*)

ESTIMATION OF CORROSION COSTS IN TEXAS

Using the estimates in the FHWA report (*17*), which is the most recent estimate available, corrosion costs (direct costs) to the state of Texas were estimated as shown below through interpolation based on proportional differences between the U.S. GDP and Texas Gross State Product (GSP) after the U.S. total costs for the year 2005 were estimated considering inflation.

Table 9 shows the estimates made for the state of Texas. In Table 9, the 2006 GDP and GSP data were obtained from the Bureau of Economic Analysis website (*18*) that has been updated for year 2006. But, the 1998 U.S. GDP was based on the FHWA report (*17*) which the original estimate belongs to. Texas direct corrosion costs for year 2006 were obtained using a simple interpolation method and then the estimate for year 2006 was multiplied by inflation rate (1.04) to estimate 2007 Texas direct corrosion costs. The inflation rate 1.04 was obtained using the Bureau of Labor Statistics' inflation calculator (*19*). As a result, direct corrosion costs to Texas are estimated at about $34.8 billion per year.

Table 9. Estimate of Direct Corrosion Costs in Texas.

		Year 1998	Year 2006	Year 2007
U.S. Total	GDP	$8,790.1B	$13,149.0B	No Info
	Direct Corrosion Costs	$275.7B	$412.4B	
	Percent of GDP	3.14%	3.14%	
Texas	GSP	No Info	$1,065.9B	
	Direct Corrosion Costs		$33.4B	$34.8B
	Percent of GSP		3.14%	No Info

As explained earlier, the FHWA report provides separate estimates specifically for highway bridges. Based on the fraction of ownership by the state of Texas in the total number of highway bridges, the direct and indirect costs were estimated using an interpolation method. In the FHWA report, the value of the multiplier to estimate indirect costs for highway bridges is ten. The current project uses the same value for the multiplier.

The current project accepts the authority of the Federal Highway Administration on this subject. It was the intent of the cited FHWA report to inform state highway departments about the appropriate factor for relating indirect costs to direct costs, and it is believed that the FHWA considered this issue thoroughly, based on the information available. The current project did not have the time, funding, or scope to challenge or refute the results published by the FHWA. As indirect costs of deterioration and repair to highway users are largely hidden and unreported, the research team found the factor of ten determined by the FHWA after much study to be reasonable.

As a result, as shown in Table 10, the total direct corrosion cost for Texas highway bridges is estimated to be $689 million and the total indirect corrosion cost is estimated to be $6.9 billion. According to the report, *TxDOT has a Plan: Strategic Plan for 2007-2011* (*20*), "Congestion on roadways costs Texans an average of $6.2 billion each year."

Table 10. Interpolation of Corrosion Costs for Texas Highway Bridges.

<table>
<tr><th></th><th>Corrosion Costs in Highway Bridges</th><th>USA Total</th><th>State of Texas</th></tr>
<tr><td rowspan="2">FHWA Estimates (FHWA 2001)</td><td>Direct corrosion costs</td><td>$8,300M</td><td rowspan="2">No Info</td></tr>
<tr><td>Indirect corrosion costs
(Multiplier applied to direct costs: 10 times)</td><td>$83,000M</td></tr>
<tr><td rowspan="3">Current Project Estimate for Texas</td><td>Fraction of Ownership in Highway Bridges</td><td>100.0%</td><td>8.3%</td></tr>
<tr><td>Direct corrosion costs</td><td rowspan="2">No Info</td><td>$688.9M</td></tr>
<tr><td>Indirect corrosion costs
(Multiplier applied to direct costs: 10 times)</td><td>$6,889M</td></tr>
</table>

COMPARISON OF THE PREVIOUS STUDIES

The reviewed studies provide previous estimates of direct corrosion costs that are equivalent to about 3 to 4 percent of national GDP. Corrosion is one of various durability problems in infrastructure facilities. Considering this fact, the total costs of durability would be greater than corrosion costs. Table 11 shows the various cost estimates for corrosion and Figure 17 provides a graphical comparison of them.

Table 11. Estimates of Corrosion Costs in Previous Studies.

	Uhlig's Study (13)	Hoar's Study (14)	NBS Study (15)	BCL Study (16)	FHWA Study (17)
Annual Corrosion Cost (Current Dollars)	$5.5B	No Info	$70.0B	$300.0B	$276.0B
Percent of GDP/GNP	2.1% of 1949 U.S. GNP	3.5% of 1970 UK GNP	4.2% of 1975 U.S. GNP	4.2% of 1995 U.S. GNP	3.1% of 1998 U.S. GDP

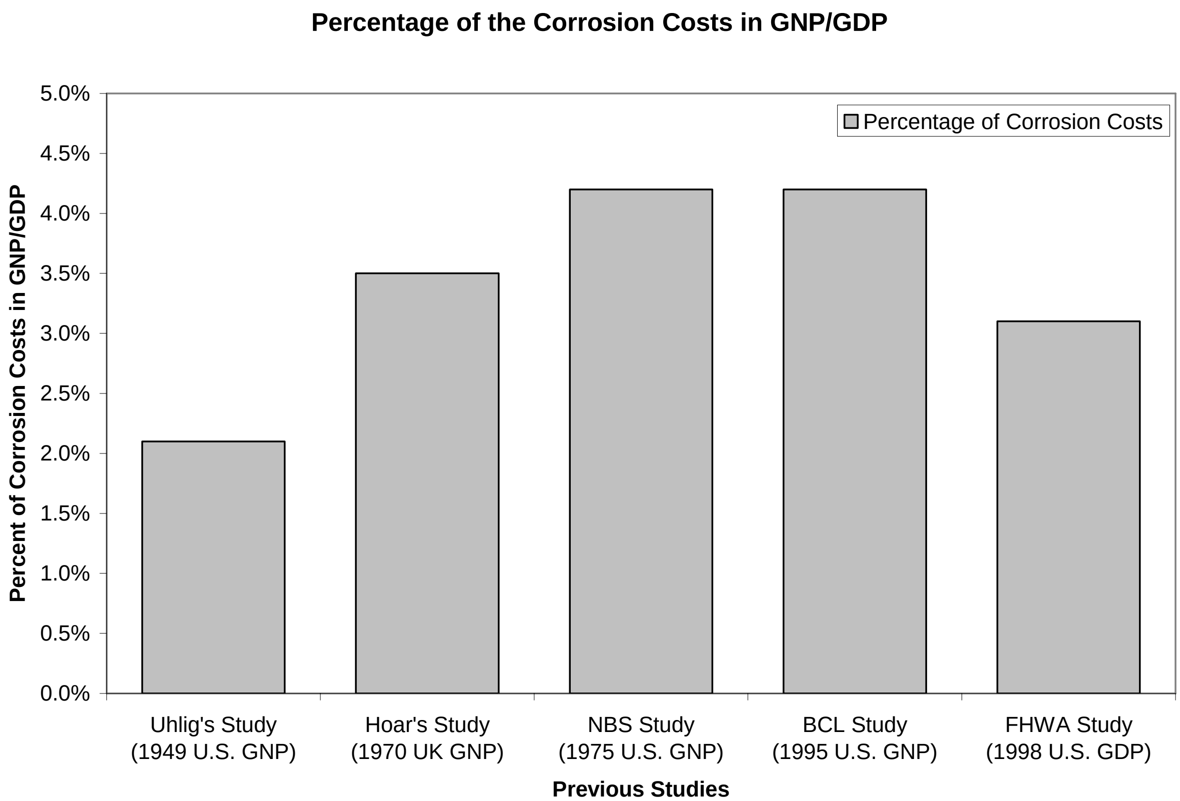


Figure 17. Corrosion Costs as Percent of the GNP/GDP.

ESTIMATION OF DETERIORATION COSTS FOR TEXAS TRANSPORTATION FACILITIES

In the previous section, annual direct corrosion costs for Texas highway bridges were estimated to be $689 million based on FHWA estimates. In addition, annual indirect corrosion costs for Texas highway bridges were estimated to be equal to the estimated direct costs, which are $689 million. However, corrosion is one of various durability problems that include ASR, DEF, external sulfate attack, other deterioration processes, etc. Also, highway bridges are one type of infrastructure facilities. Therefore, the total deterioration costs (direct and indirect costs) for Texas transportation facilities would be much greater than the estimates above. The current project attempted to estimate deterioration costs for Texas transportation facilities as follows.

- Annual Direct Deterioration Costs for Texas Highway Bridges

Corrosion of the structure is likely and usually progresses with other deterioration processes. Therefore, costs caused by corrosion are also related to costs caused by other durability problems. And corrosion is one of various durability problems. Based on this idea, it is assumed that direct deterioration costs (including corrosion costs) for Texas highway bridges would be two times the direct corrosion costs for Texas highway bridges. As a result, direct deterioration costs for Texas highway bridges are estimated to be $1.38 billion.

- Annual Direct Deterioration Costs for Texas Transportation Facilities

While bridges are one type of transportation facilities, impacts by durability problems on bridges are most significant compared to other facilities because many bridges are exposed to more severe environments (such as ground water and seawater). On the other hand, in the case of highways, one of the major systems in public transportation, about 92 percent of total lane miles in Texas are made of asphalt (*12*). Based on this idea, total direct deterioration costs for Texas transportation facilities are assumed to be about 1.5 times the direct deterioration cost for Texas highway bridges. As a result, total direct deterioration costs for Texas transportation facilities are estimated to be about $2.06 billion.

- Annual Indirect Deterioration Costs for Texas Transportation Facilities

It is difficult to estimate indirect costs because the scope of indirect costs is very broad. The recent study by FHWA (*17*) estimated the U.S. total indirect corrosion costs to be equal to the U.S. total direct costs. On the other hand, the same study applied the multiplier 10.0 to direct corrosion costs for the U.S. highway bridges to estimate indirect corrosion costs for the U.S. highway bridges. Significance of traffic costs in highway bridges should have been considered. In the case of highway bridges, the traffic costs are very high because it is more difficult to find alternate routes compared with other transportation facilities such as highways. It is assumed that indirect deterioration costs for Texas transportation facilities would be 5.5 times (middle value of the two multipliers = (1 + 10) / 2) the direct deterioration costs, which lead to an estimated, $11.3 billion (= 5.5 × $2.06 billion).

SUMMARY

The studies reviewed provide different estimates of corrosion costs. The estimates of the costs of deterioration and corrosion made in this report are based on publications by the Federal Highway Administration and other agencies, not on original research. These estimates range from 3 to 5 percent of the GNP, which is not a negligible value. Considering all other durability problems in addition to corrosion costs, the total durability costs would far exceed these estimates. Also, there exist indirect costs, which would be estimated to be much greater than the direct costs.

The recent study by FHWA (*17*) estimated the total annual direct corrosion costs for U.S. highway bridges at $8.3B. The FHWA life-cycle analysis estimated indirect costs to the user due to corrosion of highway bridges at 10 times the direct cost of corrosion, which equals $83B (see page 24 of the FHWA report). Therefore, total corrosion costs including both direct and indirect costs for U.S. highway bridges are $91.3B.

The FHWA study estimated the U.S. total direct corrosion costs from all sources at $276B per year. In the FHWA estimate, the U.S. total indirect corrosion costs are estimated to be equal to the U.S. total direct corrosion costs. The FHWA report says, on page xiii, "The U.S. total indirect corrosion costs (i.e., the costs incurred by other than owners and operators as a result of corrosion) are conservatively estimated to be equal to the direct cost; giving a total direct plus indirect cost of $552 billion (= 2 × $276B)." FHWA stated that their estimate of indirect costs is *conservative*. Also, corrosion constitutes only one of various durability problems, as discussed earlier in this report. So, the total costs caused by all durability problems taken together will be greater than the estimated *corrosion costs* alone.

Using the interpolation method based on the inflation rate and the percentage of Texas GSP in the United States GNP, and relying on the FHWA estimates (*17*), the direct corrosion costs of Texas for the year 2007 were estimated to be about $36 billion. In addition, direct corrosion costs for Texas bridges were estimated to be about $689 million and indirect corrosion costs to be $689 million. In addition, deterioration costs (direct and indirect costs) for Texas transportation facilities were estimated. The estimated direct and indirect costs are approximately $2 and $11 billion, respectively.

As emphasized in the FHWA report, there have been increasing trends in the cost of replacement and rehabilitation of transportation facilities, especially highway bridges. With limited budgets, any state highway agency would not be free from difficulties concerning these increasing costs. One of the most critical reasons for replacement and rehabilitation of facilities would be durability problems, which is the domain in which efforts should be concentrated. Considering that magnitude of the costs of deterioration for Texas transportation infrastructure, approximately $2 billion per year, it is apparent that the development of a marine exposure test site would be a cost-effective step to start reducing and resolving the problems.

TxDOT has stated that the costs estimated in this report are "too high." The research team strongly believes that these estimates are low, due to lack of data on deterioration and corrosion causing estimation bias toward the low side. In any case, TxDOT has not provided any other cost estimates to be used.

CHAPTER 4. SITE VISITS

OBJECTIVES

The objective of the site visits was to identify best practices of constructing, operating, and managing a marine exposure test site. Through interviews with site managers using a specifically designed questionnaire for this project, the site visits ascertained the successes and limitations of existing sites and derived critical success factors for a Texas marine exposure test site. Also, there are lessons learned from existing sites regarding site management and operation.

EXISTING MARINE EXPOSURE TEST SITES IN THE USA

The research team visited three marine exposure test sites in the continental United States:

- NASA Kennedy Space Center Corrosion Technology Laboratory Site, Cape Canaveral, Florida;
- U.S. Army Natural Weathering Exposure Station, Treat Island, Maine; and
- U. S. Navy Advanced Waterfront Technology Test Site, Port Hueneme, California.

The research team interviewed representatives from each site to obtain information regarding various aspects of their sites using the questionnaire designed by the research team to elicit the needed information. The questionnaire has four different sections:

1) site characteristics,

2) management,

3) facilities and equipment, and

4) alternatives.

The site characteristics and facility/equipment sections were designed to identify critical site requirements and success factors, while the management and alternatives sections were intended to obtain information about site management, organization, and operation.

The questionnaires were sent to the sites before the arrival of the research team in order to prepare the hosts for the questions and the information sought, and to help the research team identify pertinent information and success factors.

The following sections describe each of the sites and provide summaries of the questionnaire responses. For the detailed verbatim responses to the questionnaire at the various sites, refer to Appendix III. Additional pictures of the existing sites can be found in Appendix IV.

NASA Kennedy Space Center Corrosion Technology Laboratory Site, Cape Canaveral, Florida

The research team visited this site on May 24, 2007. Work on corrosion issues at KSC began in the 1960s with the evaluation of long-term protective coatings for the atmospheric protection of carbon steel. NASA established the KSC CTLS at that time. The site has provided over 40 years of information on the long-term performance of many materials for corrosion protection of NASA, other government agencies, and industry.

The KSC CTLS is located at latitude 28.7° N, longitude 80.6° W. Figure 18 shows the location of and entrance to the site with the Atlantic Ocean behind it. The site has approximately 600 ft of near-beach exposure for atmospheric corrosion specimens. The site can accommodate many types of test samples, including standard size metallic test coupons (4 inch × 6 inch), stress corrosion cracking specimens, and full-scale test articles.

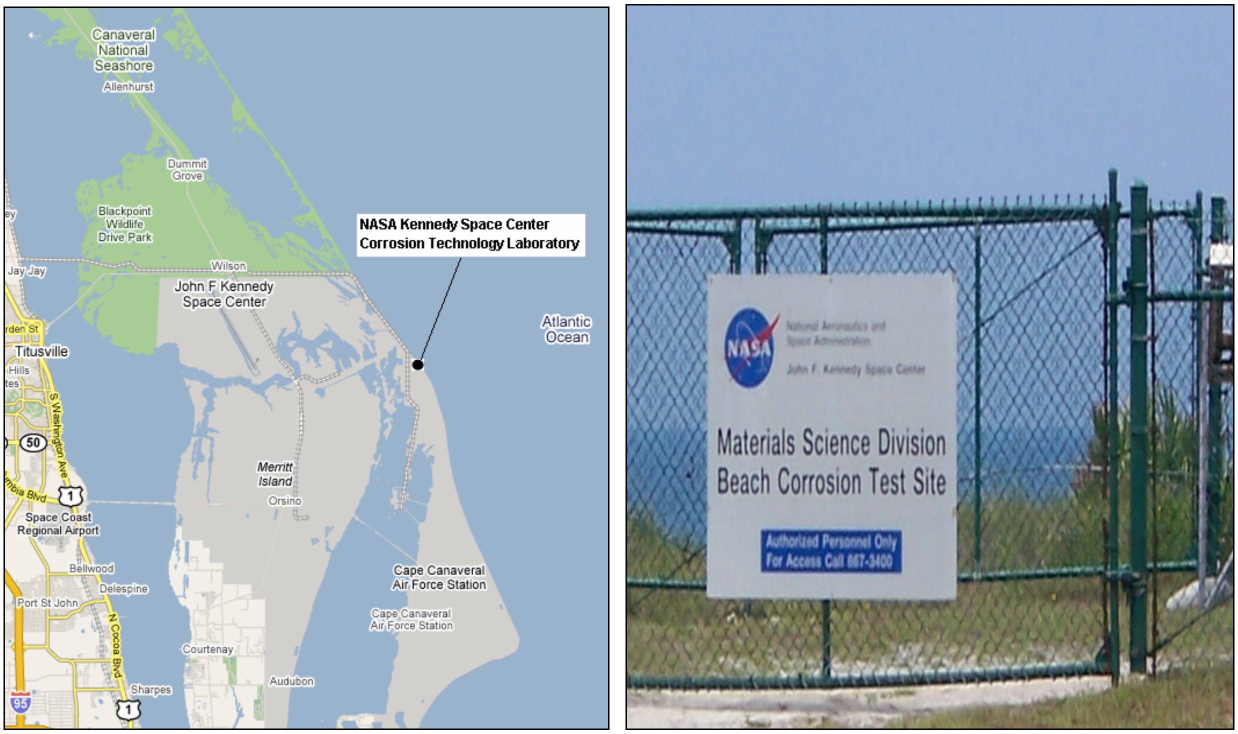


Figure 18. Location of and Entrance to the KSC CTLS.

The site currently has more than 200 stands with racks that hold seventy-five 4 inch × 6 inch test panels contained in a 20,000 sq ft fenced area (Figure 19 and Figure 20). The site also has a fenced seawater immersion test site with two immersion tanks that have a continuous once-through, filtered supply of seawater, directly from the Atlantic Ocean. The site has a plan for the expansion for more beachfront exposure stands. Figure 21 shows their expansion plans obtained from the interviewed personnel.

Figure 19. Stands with Racks that Hold Steel Test Panels.

Figure 20. Test Panels Exhibiting Corrosion.

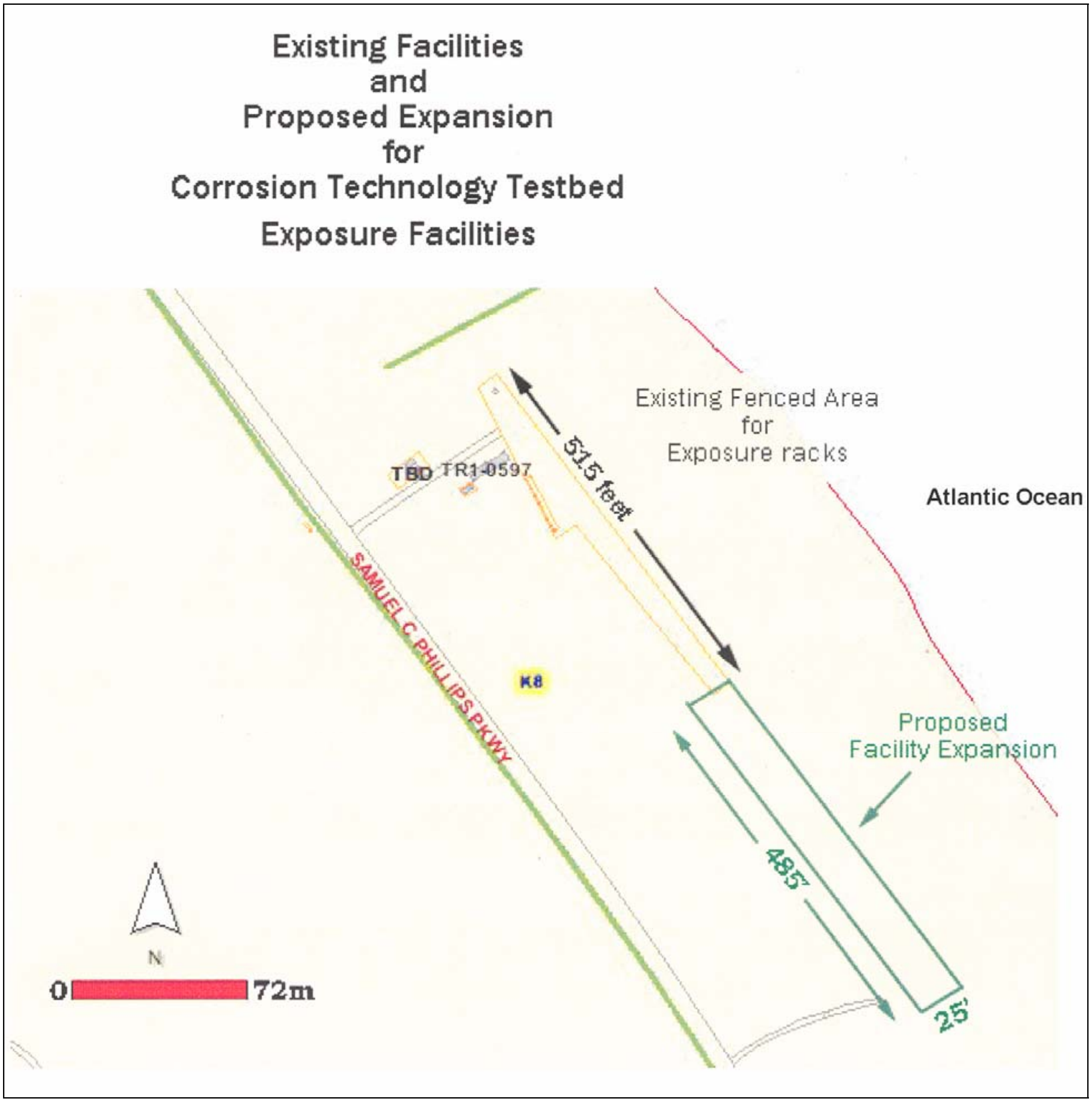


Figure 21. Expansion Plan of the KSC CTLS.

Experiments can be performed in either an exposed or sheltered configuration. Over the years, thousands of coated test panels, stress corrosion cracking specimens, non-metallic materials, and commercially produced products have been evaluated in the high salt, high humidity, and high ultraviolet (UV) Florida seacoast environment.

The site has close proximity to launch sites and the beach to provide ideal conditions for the testing of materials used at the launch site. Results from these tests have helped KSC find new materials and procedures that enhance the safety and reliability of spacecraft, structures, and ground support equipment at the launch site. The lab and outdoor site are located within 200 ft of a paved road that provides good accessibility to the site.

The distance of the test area from the water is considered to be directly related to the corrosion rate at the site. The site is approximately 100 ft from the high-tide line directly on the Atlantic Ocean. Test results from the site show three times the mass loss of uncoated steel panels at the 100-ft site compared to a site 1000 ft inland.

Tests performed at the site include atmospheric corrosion, UV degradation, limited rebar corrosion, seawater immersion and spray-down tests. There is no test using tide differentials as most corrosion at the site is for exposure to salt spray or salt fog. Tests last as long as seven years, and as short as one month. The length of tests depends on NASA's requirements. Coatings are subject to a 1.5 year atmospheric exposure for qualification, and five years to remain on the qualified products list. Frequency of data collection and test result recording depends on the type of tests. It varies from every two weeks to once a year. Weather data are recorded at 20-minute intervals. Generally, documentation, organization of data, and distribution are made per the customer's requirements. Reports and data are collected and stored in accord with International Standards Organization (ISO) 9001 documented procedures.

The site contains a weather station, an on-site laboratory, warehouse, and video/camera system. The weather station shown in Figure 22 is located near the center of the outdoor exposure test site. It is fully instrumented and provides continuous information on air temperature, humidity, wind direction and speed, rainfall, total incident solar radiation, and incident ultraviolet B radiation levels. The site is outfitted with network connectivity for data acquisition and live video of samples through the Internet. Other available utilities include telephones, electricity, and potable water.

Figure 22. Weather Station at the KSC CTLS.

The on-site laboratory in Figure 23 is located in the same vicinity of the exposure test site. Activities performed at the laboratory include electrochemistry testing, data acquisition, and photo-documentation. The laboratory has complete electrochemistry capabilities to conduct all of the standard corrosion-related electrochemistry tests including polarization resistance, Tafel extrapolation, Alternating Current (AC) Impedance and potentiodynamic scanning.

A warehouse is used for archiving past experiments and for hurricane evacuations. It is necessary to have a warehouse far enough inland to prevent damage to the stored items. The site has experienced hurricane and tropical storms and NASA has developed a hurricane evacuation plan. The plan calls for complete evacuation of all test articles inland to a secure location until the storm passes and the site is given an all clear. Customers have the ability to see how their products perform in "real time." The cameras are also useful to ensure the safety of personnel and operability of mechanical devices. There are six cameras: five outside and one in the laboratory.

Figure 23. On-Site Laboratory at the KSC CTLS.

The site is owned by NASA and operated by a combination of NASA and contractor personnel. NASA provides infrastructure support. Other funding is secured through contractual arrangements with federal agencies and industry partners. NASA partners with federal and state government agencies, with U.S. businesses, and with universities through agreements where each partner provides resources such as funding, facilities, or expertise, to achieve a common goal. The site is marketed through a website, conferences, and federally funded meetings. Information about the site is also available from the website (*21*).

A standardized fee structure is in place for repetitive operations. For instance, a per panel cost for exposure is standardized. Often, tests specific to the needs of the customer are required and the cost is based upon projected labor and other costs.

KSC personnel consider that overall efficiency would increase if all sites were closer to each other. The close proximity of the atmospheric test site to other facilities is important. Travel to the location is necessary to deliver and retrieve samples, take data, and maintain/repair equipment. Long travel times would increase labor costs. The collected data cannot be shared without prior consent of NASA or the customers. However, KSC personnel showed a willingness to perform tests for TxDOT if TxDOT pays for the tests.

U.S. Army Natural Weathering Exposure Station, Treat Island, Maine

The research team visited this site on May 23, 2007. The site is located on the Bay of Fundy near Eastport, Maine. The site was originally acquired for a potential power plant on the shoreline in the 1950s, the Passamaquoddy Power Project, but when this plant was subsequently cancelled, the U.S. Army Corps of Engineers decided to retain the site for long-term exposure testing. Figure 24 shows the rack and the pier at the Treat Island site.

Figure 24. The Army NWES, Maine.

Users of the site facilities come from government, universities, and industry. Users are charged minimal fees to cover maintenance costs only. Annual maintenance costs are approximately $10,000 and annual testing expenditures amount to about $25,000. Maintenance and testing functions are outsourced under contract to the University of New Brunswick, which in turn subcontracts maintenance to local firms. The major maintenance item is replacement of deteriorated wood dock elements.

Observations are made and data are recorded on an annual cycle. The results are disseminated by the researchers through written reports and a website *(22)*. Current problems and relevant data and pictures of test specimens are provided on the website. No attempts are made to market the services of the exposure test site, as the site has no revenues other than recovery of maintenance and testing costs. The types of activities performed at the site include:

- visual examination,
- pulse velocity,
- resonant frequency,
- corrosion measurement (linear polarization, LP),
- specimen retrieval, and
- lab evaluation.

Visual examinations are the most-performed test, with corrosion measurements the least, because most test specimens are unreinforced concrete. There are about 100 freeze-thaw cycles per year, and the tidal range is 20 to 26 feet. The site personnel reported a shore distance of 165 ft for a splash zone within the tidal fluctuation region for wet/dry cycles. Specimens on the shore are at an angle of 10 to 15 degrees to the horizontal, and the slope makes it difficult to maneuver the specimens and has an impact on final findings.

No personnel are permanently located on site. Technicians and graduate students from the University of New Brunswick visit the site once a year for annual inspections, which take about five days per year. Access to the site, for testing and occasional maintenance, is by boat and is provided by local fishermen. The distance from the boat dock to the site by water is 1.5 miles. The site wharf is made of timber, 50 ft long, located at the mid-tide level. Due to limited access by fishing boat, there are no vehicles on the site.

Specimens under testing are placed in a single rack, with two levels, on the shoreline at mid-tide level. Figures 25 and 26 show test specimens placed on the rack and on the beach, respectively. Specimens are exposed to differing conditions, either submerged, mid-tide, or high tide. Capacity of the rack is 200 specimens, of which 180 are at mid-tide level and the rest either submerged or at high tide. Consequently, specimens can be examined only at low tide. Because of buildup of marine growth, specimens are pressure washed once a year prior to testing; this cleaning likely damages the specimens.

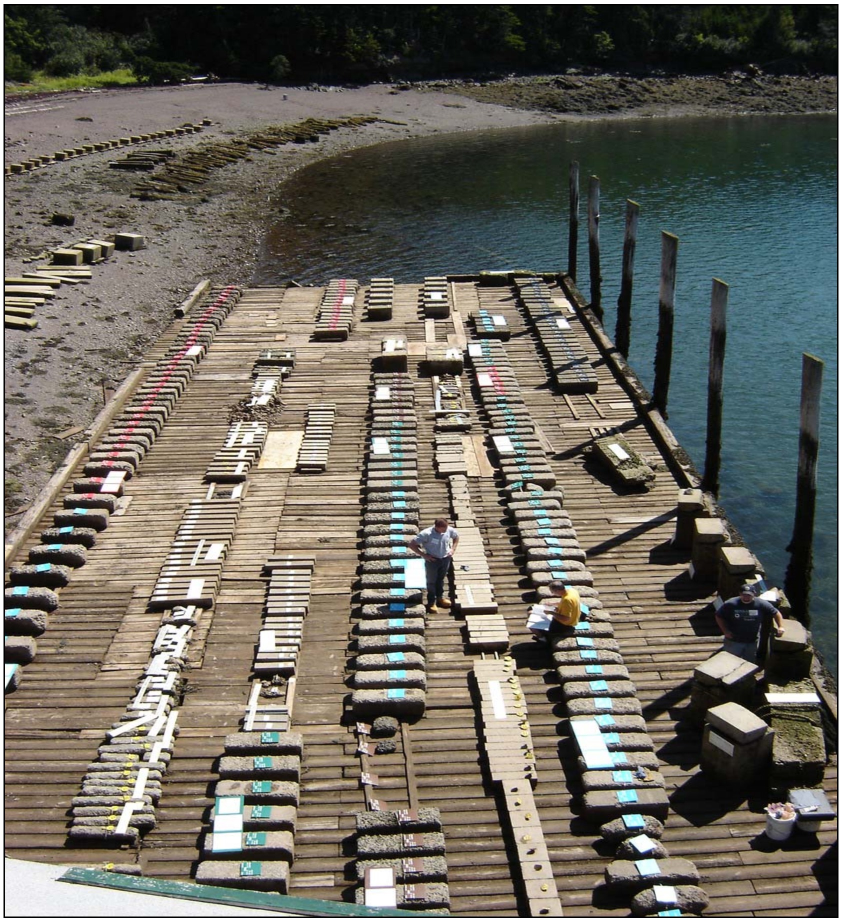


Figure 25. Test Specimens on the Rack.

Figure 26. Test Specimens on the Beach.

Specimens are of various sizes, the largest typically being about 3 cubic ft, although there are some non-standard sizes that are larger. Smaller specimens, 6- by 12-inch cylinders, have been evaluated and are considered too small to provide realistic data. Specimens are unloaded from boats on the dock or directly on the shore. Specimens of 3 cubic ft would weigh about 450 pounds, so the maximum specimen size is limited by manpower, considering the lack of transport vehicles on the site. The site has limited access. Figure 27 shows the difficulties in transporting specimens: cranes need to be used twice—for loading specimens on the boat and then on vehicles inland.

Figure 27. Loading/Unloading Specimens.

Currently there are various types of tests being performed at the site. Figure 28 shows a durability test of high-strength concrete. As indicated in the figure, these specimens were placed at the site in 1991. Figure 29 represents the severity of deterioration. These specimens have been undergoing exposure since 1975.

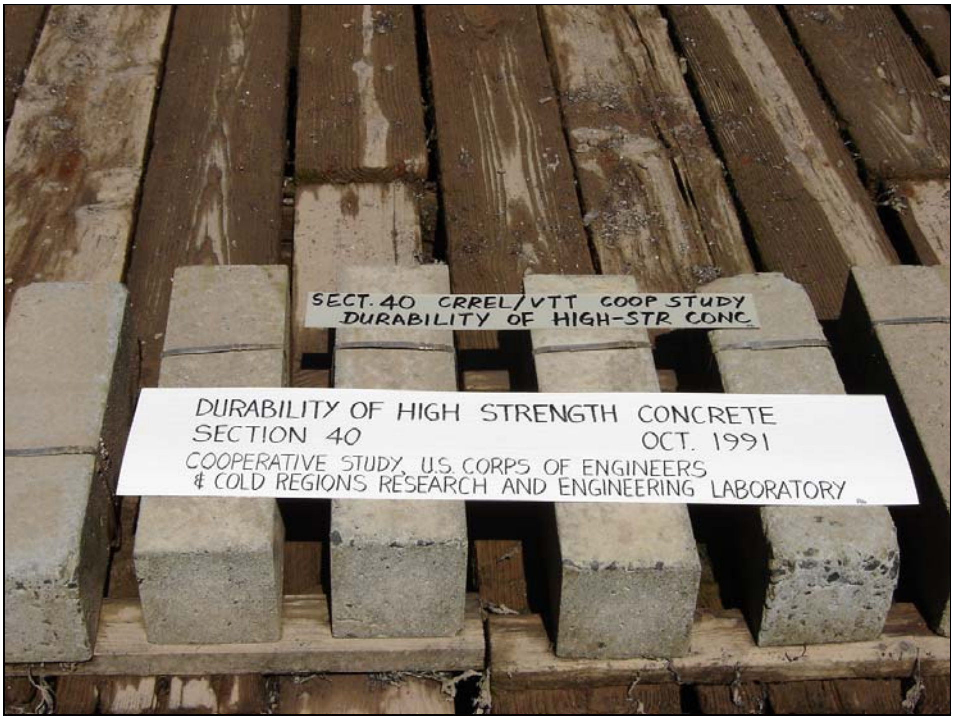


Figure 28. Durability Test of High-Strength Concrete.

Figure 29. Severity of Deterioration.

The site manager would prefer to have automated equipment to record temperature, relative humidity, wind speed, and precipitation, but the site at present only automatically records temperatures, and no other environmental conditions. Instruments are battery powered, as there is no electricity or water service on the island.

The site has a small storage shed but no warehouse or other buildings. The site is on an island, which is considered by Treat Island personnel to be highly undesirable with respect to access, although the isolation that limits access to researchers may also limit access by vandals. There is no surveillance camera on site.

Treat Island personnel expect that a marine exposure test site in Texas would generate much different results, due to the lack of freeze-thaw cycles present in Maine, and higher temperatures would accelerate chemical reactions (i.e., ASR and DEF) and would accelerate wetting/drying cycles and diffusion of chemical elements (such as chlorides) into the concrete. The Treat Island personnel interviewed indicated a willingness to collaborate with researchers on a marine exposure test site in Texas, which would complement the cold weather environmental conditions at Treat Island with hot weather conditions in Texas.

U.S. Navy Advanced Waterfront Technology Test Site, Port Hueneme, California

The research team visited this site on July 23, 2007. The Navy AWTTS was developed by the Navy in 1993. The site houses a 150-ft, all-composite demonstration pier, as shown in Figure 30. "This facility serves as a national center for evaluation and demonstration of new concepts for upgrading, repair, and life extension of waterfront structures, now with special emphasis on composite materials *(23)*." Unlike the KSC CTLS, this facility has limited field equipment and most studies are performed by placing scaled or full-scale infrastructure systems directly in the waters of the Pacific Ocean. Cranes and riggers are used at the site to lift large test sections into place.

The site is one of the facilities owned and managed by the Naval Facilities Engineering Service Center (NFESC). NFESC provides worldwide support to the Navy, Marine Corps, and other Department of Defense (DOD) agencies *(23)*. Currently the Navy is the exclusive user of this facility.

Figure 30. The Navy AWTTS, California.

This facility has a storage building and 1400 sq ft storage areas (permanent storage capacity is 1200 sq ft and temporary storage capacity is 200 sq ft) near the test facility (Figure 31).

Figure 31. Storage Building and Area near the Access to the Facility.

Tests and evaluations performed in the Navy AWTTS include pier upgrade techniques, corrosion mitigation, pier load safety testing, evaluation of modular hybrid pier and new construction systems (*24*). The most-performed tests are material degradation and structural capacity tests. The cycle time of tests varies from several years up to 12 years. The frequency of specimen observation and data recording varies depending on specific project needs. Also, documentation of test results is project-specific.

The substructure of the facility is monitored using the access structure, as shown in Figure 32. The site also has pier slabs exposed, as shown in Figure 33.

Figure 32. Pier Substructure with Access Structure.

Figure 33. Exposed Pier Slabs.

Instead of having its own weather station, the site uses weather records from the Oxnard airport that is five miles away from the site. Utilities available at the site include water and power.

The site does not have internal support from the agency. All funds are delivered through projects. The site development costs were $250,000 to $300,000 in 1993 dollars and annual expenditure is about $10,000/year. Maintenance work at the site is outsourced. The site has experienced mild earthquakes. However, it has not affected the site performance. The site was designed for earthquakes.

Port Hueneme personnel expect that a marine exposure test site in Texas would provide a better condition for the exposure tests because the environmental conditions are more severe in Texas than at Port Hueneme. Also, the personnel interviewed showed a willingness to share test results with TxDOT and to perform certain tests for TxDOT on an hourly rate or contract basis.

IDENTIFICATION OF SITE REQUIREMENTS AND SUCCESS FACTORS

Site Requirements

As emphasized in the proposal, a marine test site requires a long-term commitment. Researchers identified this as a key requirement from the questionnaire results. Deterioration tests need significant amounts of time to materialize. Also, test results need to be accumulated in the long-term to develop relevant time-related knowledge and to realize benefits from these tests. Therefore, the site should preferably be on TxDOT property to obtain the benefits of long-term commitment and stability of the site.

Success Factors and Site Evaluation Matrix

A list of potential success factors for a marine exposure test site was prepared as a part of the questionnaire. At each site visit, the interviewees were asked to score the potential success factors. They were also asked to provide any other factors they thought were critical to success. As a result, the research team obtained evaluation of the potential success factors through the interviews. Table 12 shows the relative importance values of the success factors.

Table 12. Scores of Success Factors.

No.	Success Factors	Relative Importance (0 to 10) 10 being of highest importance		
		KSC CTLS	Army NWES	Navy AWTTS
1	**Size of site**	10	9	9
2	**Site locations/conditions**	10	10	9
3	**Site proximity to civilization, etc.**	5	5	10
4	**All-weather road access**	10	9	10
5	**Shore conditions (water surface, beach, tide)**	No score	9	0
6	**Protection against hurricanes and flooding**	10	7	10
7	**Access to equipment (handling equipment, etc.)**	No score	9	10
8	**Utilities**	10	8	9
9	**Site security/absence of interfering activities**	9.5	10	10
10	**General test conditions (weather, etc.)**	10	8	8
11	**Specimen housing facilities**	10	8	7
12	**Site docking facility**	0	8	5
13	**On-site laboratory**	10	6	4*
14	**On-site weather station**	10	9	2 to 5**
15	**On-site web-based camera system**	10	5	No score
16	**Any other factors**	Long-term Commit-ment	No response	No response

* Not high because the Navy AWTTS does visual observations only.
** Low score is because the weather in California is very uniform.

Based on the relative importance values of the success factors in Table 12, the research team developed a site evaluation matrix (shown in Table 13). In this table, relative importance for each success factor is the average of the scores obtained from the interviews.

Table 13. Site Evaluation Matrix.

No.	Success factors	Average Relative Importance (0 to 10)
1	Size of site	9
2	Site locations/conditions	10
3	Site proximity to civilization, etc.	7
4	All-weather road access	10
5	Shore conditions (water surface, beach, tide)	5*
6	Protection against hurricanes and flooding	9
7	Access to equipment (handling equipment, etc.)	10
8	Utilities	9
9	Site security/absence of interfering activities	10
10	General test conditions (weather, etc.)	9
11	Specimen housing facilities	8
12	Site docking facility	4
13	On-site laboratory	7
14	On-site weather station	8
15	On-site web-based camera system	5**
16	Long-term commitment	10
Total Score		130

* Not considered important at the Navy AWTTS because their objective was to evaluate pier structures.
** Not important because the Navy AWTTS is very close to offices.

A description of these success factors is provided below:

- Overall size of site: The exposure test site should consist of specimen housing facilities, a weather station, docking facility, on-site laboratory, and a warehouse. A reasonable size is preferred considering capacity of the relevant facilities and some level of contingency.
- Site locations/conditions: Location characteristics that were considered for selection of the existing sites need to be accounted for in the site evaluations of the Texas site.
- Site proximity to civilization, etc.: Proximity to users can enhance business opportunities for the site.
- All-weather road access is necessary for efficient transportation of specimens, people, equipment, and materials into and out of the site.
- Shore conditions: Shore conditions such as distance of the test area to the shoreline, and slope and width of the shoreline will affect site operations. The Texas site should consider direct access to the shoreline.
- Protection against hurricanes and flooding: Protection from natural disasters is a critical requirement for long-term natural experiment sites. A warehouse, designed to resist damage during hurricanes, can be used to protect specimens.
- Access to equipment: Surface conditions and the slope of the overall site as well as the shore will affect efficiency in the use of specimen handling equipment and vehicles.
- Utilities: Utilities required basically include fresh water, electricity, high-speed Internet lines, and telephone service.
- Site security/absence of interfering activities: Interfering activities can impose constraints on activities and cause nonproductive efforts that lower the efficiency of site operations. In addition, vandals could damage specimens, resulting in loss of data. This criterion also concerns site security. Thus, the site should not be directly accessible by the public.
- General test conditions: The site is desired to provide general marine exposure conditions for different types of tests. If there is any unique condition for the site, its potential effects must be evaluated.

- Specimen housing facilities (rack/beach): Considerations here include the conditions of the shore including its width, shape, tide level, and the potential location of facilities.
- Site docking facility: The facility requires consideration of the shore conditions, as well as positive effects on convenience of site access.
- Potential for on-site laboratory: An on-site laboratory should be an initial requirement or an option for near future planning. Potential for the on-site laboratory facility should be considered during initial construction.
- On-site weather station: Technical requirements related to site conditions need to be considered for efficient operation of the facility and reliability of test results. A computerized record of temperature, humidity, and other environmental factors is essential.
- On-site camera with Web access: Technical requirements related to site conditions need to be considered for efficient operation of the facility. Location and number of cameras and technical needs can be determined once the site is selected.

SUMMARY AND LESSONS LEARNED

The research team visited three existing marine exposure test sites. It was found that these existing test sites are willing to perform tests for TxDOT for a fee and/or to collect data from other exposure test sites (e.g., the Texas marine exposure test site, if it is built) for the purpose of comparison. Interviewed personnel expect that a marine exposure test site in Texas could generate valuable test results in its environmental condition.

Valuable information obtained from the visits includes site characteristics, operations, management, equipment, and so on. Through interviews using the questionnaire, the success factors were derived with their relative importance. Based on the success factors and their relative importance, a site evaluation matrix was developed for the evaluation of potential sites on the Texas gulf coast (see section titled Identification of Site Requirements and Success Factors). The list and description of the factors were presented in the previous section. The following provides lessons learned from the site visits.

- Management: Except for the Navy AWTTS at Port Hueneme, the other sites have a separation between ownership and site operator. In general, infrastructure support is provided by the owner and maintenance is performed by contractor personnel. Existing sites in general do not generate positive profits and revenues (user fees) from site operations. Most fees are used to offset maintenance and operations costs. The KSC CTLS is the only site with an active advertising campaign. The KSC CTLS does generate revenues, but not for profit. None of the sites visited pays land costs to the parent agencies. Thus, a long-term commitment for agency support (i.e., land, infrastructure, and operation/maintenance expenditures) is critical to the success of a marine exposure test site in Texas.

- Operation: Cycles of inspection and data recording vary depending on project and test requirements. Efficiency of the site operation could be enhanced by locating relevant facilities in closer proximity of the site. The representative from the Army NWES on Treat Island reported the problems in handling and transporting specimens because of its site characteristic: an island. The initial site development plan should consider specimen handling and lifting equipment for large-scale samples that better mimic actual structures.

- Marketing and relationship with site users: Among the three existing sites, only the representative from the KSC CTLS reported their marketing efforts through a website, conferences, and federally funded meetings. Also, this site has a broader target market compared with the other sites. A more specific marketing study would be a valuable task for a marine exposure test site in Texas, considering that durability problems in infrastructure facilities are of interest to all state transportation agencies.

- Fee structure: All sites have variable user fees adjusted to cover the costs of the experiments, operations, and maintenance for each user. The KSC CTLS has a standardized fee structure such as a per panel cost for exposure. However, often tests specific to the customer needs are performed based on projected labor and other costs. The other two sites (the Navy AWTTS and the Army NWES) do not have a standardized fee structure.

CHAPTER 5. EVALUATION OF POTENTIAL SITES IN TEXAS

SITE ALTERNATIVES ON THE GULF COAST

The research team obtained information on the state-owned lands on the gulf shoreline from the Texas General Land Office (GLO). Ten sites were identified based on the following criteria:

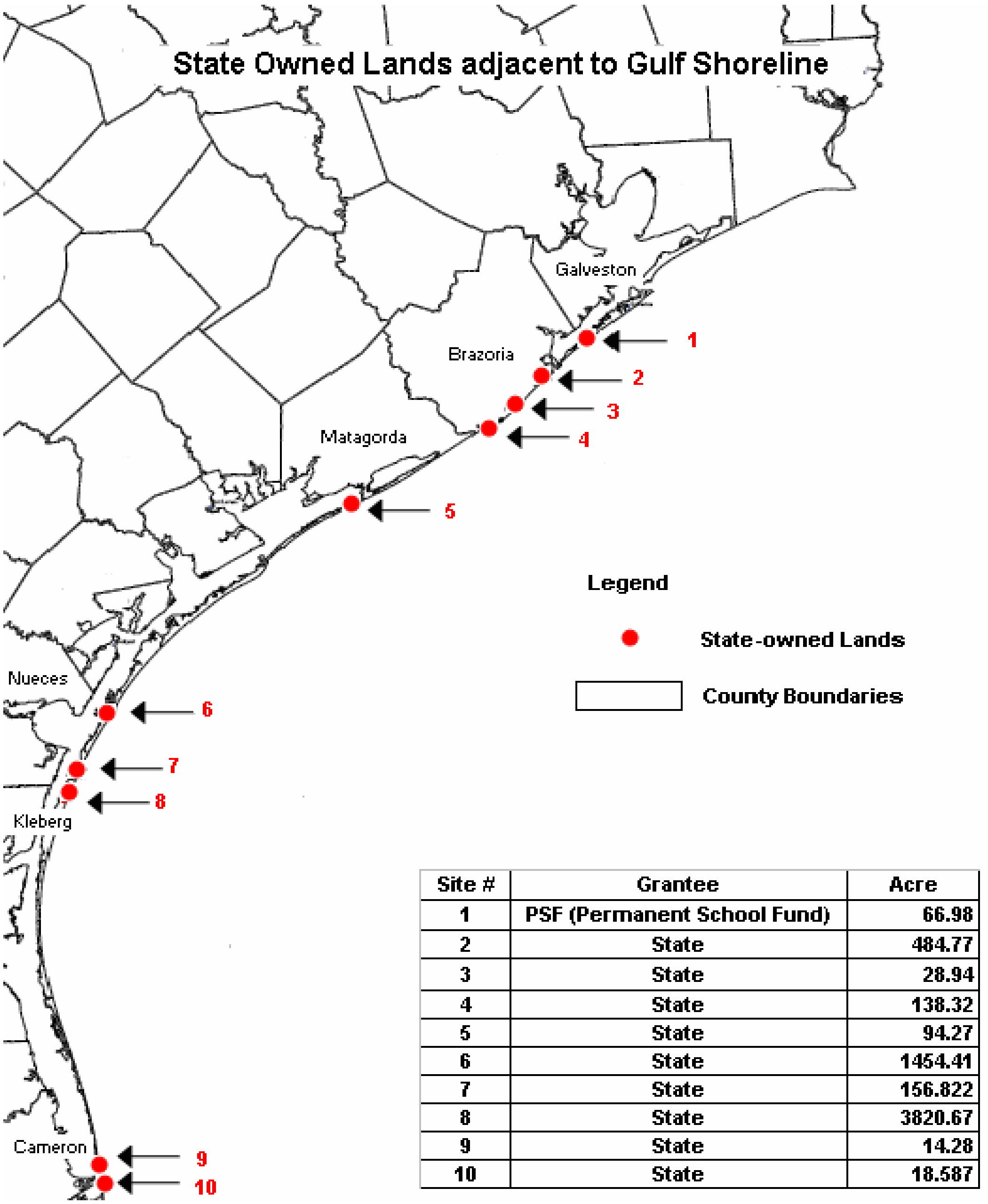
- owned by the state of Texas,
- direct access to seawater, and
- not currently in use by others.

These ten sites are shown in Figure 34 and, for simplicity, are labeled as sites 1 through 10, with site 1 being the most northern location and site 10 being the most southern location along the coastline. Table 14 provides a list of the 10 sites on the gulf shoreline with information about grantee, basefile number (by GLO), and size.

Table 14. State-Owned Lands on the Texas Gulf Shoreline.

Site #	Grantee	Basefile Number (by GLO)	Area, Acres	County
1	PSF*	155455	66.98	Galveston
2	State	154941	484.77	Brazoria
3	State	154922	28.94	Brazoria
4	State	SF-9714	138.32	Brazoria
5	State	150968	94.27	Matagorda
6	State	154945	1454.41	Nueces
7	State	153534	156.82	Nueces
8	State	154939	3820.67	Kleberg
9	State	154686	14.28	Cameron
10	State	154539	18.59	Cameron

*PSF: Permanent school fund.



Site #	Grantee	Acre
1	PSF (Permanent School Fund)	66.98
2	State	484.77
3	State	28.94
4	State	138.32
5	State	94.27
6	State	1454.41
7	State	156.822
8	State	3820.67
9	State	14.28
10	State	18.587

Figure 34. State-Owned Lands on the Texas Gulf Shoreline.

After initially selecting the ten potential sites shown in Figure 34, the research team evaluated these sites in more detail by obtaining detailed maps of the sites and surrounding areas. This evaluation allowed the team to better assess the suitability of the sites, with particular emphasis on exposure conditions and general access. Upon further evaluation, site 5 (in Matagorda County) was eliminated due to poor access, and site 9 was eliminated because it did not have direct gulf access. Sites 6 (in Nueces County), 7 (in Nueces County), and 8 (in Kleberg

County) were identified as sites that warranted visits by research team members to further assess their viability as locations for the proposed marine exposure test site. Magnified maps for these three selected sites are in Appendix V. The magnified maps were obtained from the Geographic Information System (GIS) website *(25)* and Google Earth *(26)*.

It would be advantageous to use or expand an existing marine facility if the facility satisfies the requirements identified in the current project. If that were the case, there could be significant savings in the costs (initial development, operation, and maintenance costs) and synergy through cooperation with the existing operations agency of the existing facility. To this point, the research team considered the following two existing test facilities on the Texas gulf coast as other alternatives, in addition to the above selected state-owned lands:

- University of Texas Marine Science Institute (UTMSI) in Port Aransas and
- Texas A&M University at Galveston (TAMUG) on Pelican Island.

VISITS ON THE STATE-OWNED LANDS

The research team visited the three state-owned lands selected. Site 8 was the first site to be visited, which was located in Kleberg County, just north of Padre Island National Seashore. There were several positive attributes for this site, including good access by paved roads and direct gulf access. Figure 35 shows the road access and Figure 36 shows the general conditions of the site, respectively. Despite these positive attributes, there is one major drawback to this site (and the other two sites visited) – the beach site is accessible by vehicular traffic (see Figure 37). It would be virtually impossible to construct a marine exposure test site here due to the free flow of vehicles across this site and most public beach sites along the Texas coastline. To construct and maintain a devoted marine exposure test site, it would be essential to protect the test specimens, weather station, and other associated equipment. Thus, the entire area would have to be fenced off and protected from vehicles, theft, vandalism, etc. In addition, for the specimens to be exposed to direct tidal action, one would have to have direct and protected access all the way to the seawater line, which again would be quite challenging given the open access and typical vehicular traffic of these and other sites evaluated.

Figure 35. Road Access from Texas 22 to Site 8.

Figure 36. General Conditions of Site 8, which Has Direct Gulf Access.

Figure 37. Photograph of Site 8, Showing Speed Limit Sign Posted for Vehicular Traffic.

Sites 7 and 6 were then visited, but the same vehicular traffic patterns were observed. In addition, these sites were in more developed areas, with nearby hotels, condos, houses, and businesses (see Figure 38 for photo of site 7). On top of this, the beach was extremely crowded with beachgoers, cars, kites, and even horses. The proximity of these sites to such developments and activities would make it even less practical for the development of a devoted and protected marine exposure test site.

Figure 38. Photograph of Site 7, Showing Proximity to Hotels and Other Developments.

After visiting sites 6, 7, and 8, it was quite apparent that the sites would likely not be viable exposure test site locations due to vehicular traffic, beach activities, and proximity to hotels, condos, and other developments. Although the other potential sites were not visited during the course of this feasibility study, if they are similar in terms of vehicular traffic (in particular), their viability as an exposure test site would also be quite limited.

OTHER SITE ALTERNATIVES

The research team visited the UTMSI site in Port Aransas. For the TAMUG site, relevant information about test facilities was obtained from faculty members at TAMUG.

University of Texas Marine Science Institute in Port Aransas

The one site that appears to show the most merit is the University of Texas Marine Science Institute in Port Aransas, which the project researchers also visited. This site, which has direct gulf access and has been in operation for over 60 years, appears to be a feasible site. It is a devoted research center, has significant gulf-front access, and discussions with institute personnel were quite encouraging. The site also has a sturdy and well-maintained two-level pier, complete with specimen handling equipment, weather stations, and other relevant instrumentation. Figure 39 shows the two-level pier that could potentially serve as an area for specimen storage (on either level or suspended below the water line) or as a staging area for transporting specimens and materials to other locations along the gulf coast.

Figure 39. Photograph of Two-Level Pier at UTMSI Site.

Texas A&M University at Galveston Marine Engineering and Research Center on Pelican Island

This site is that of Texas A&M University at Galveston (TAMUG), a branch campus of Texas A&M University in College Station. TAMUG is a special-purpose institution with a legislated mission calling for teaching, research, and public service pertaining to marine and maritime studies in science, engineering, and business.

Location

This potential site on the campus of TAMUG has excellent access. It is located on Pelican Island, Galveston, facing the Galveston Ship Channel, and connected to Galveston Island by the Pelican Island causeway, and is accessible from both landside and waterside. Figure 40 shows the physical layout of the area, including dock facilities and the 50,000 sq ft Marine Engineering and Research Center that opened in January 2005. Figure 41 shows a general location map and a detailed map showing the potential site on Pelican Island. Figure 42 shows the existing docking facilities, which can handle large vessels, and the causeway from Pelican Island to Galveston. Figure 43 shows the existing small boat basin at the potential site. As can be seen from the photographs, the area is already highly built up and industrialized. While open to the gulf, landside it is basically an extension of Galveston Island.

Figure 40. TAMUG Marine Engineering Research Center.

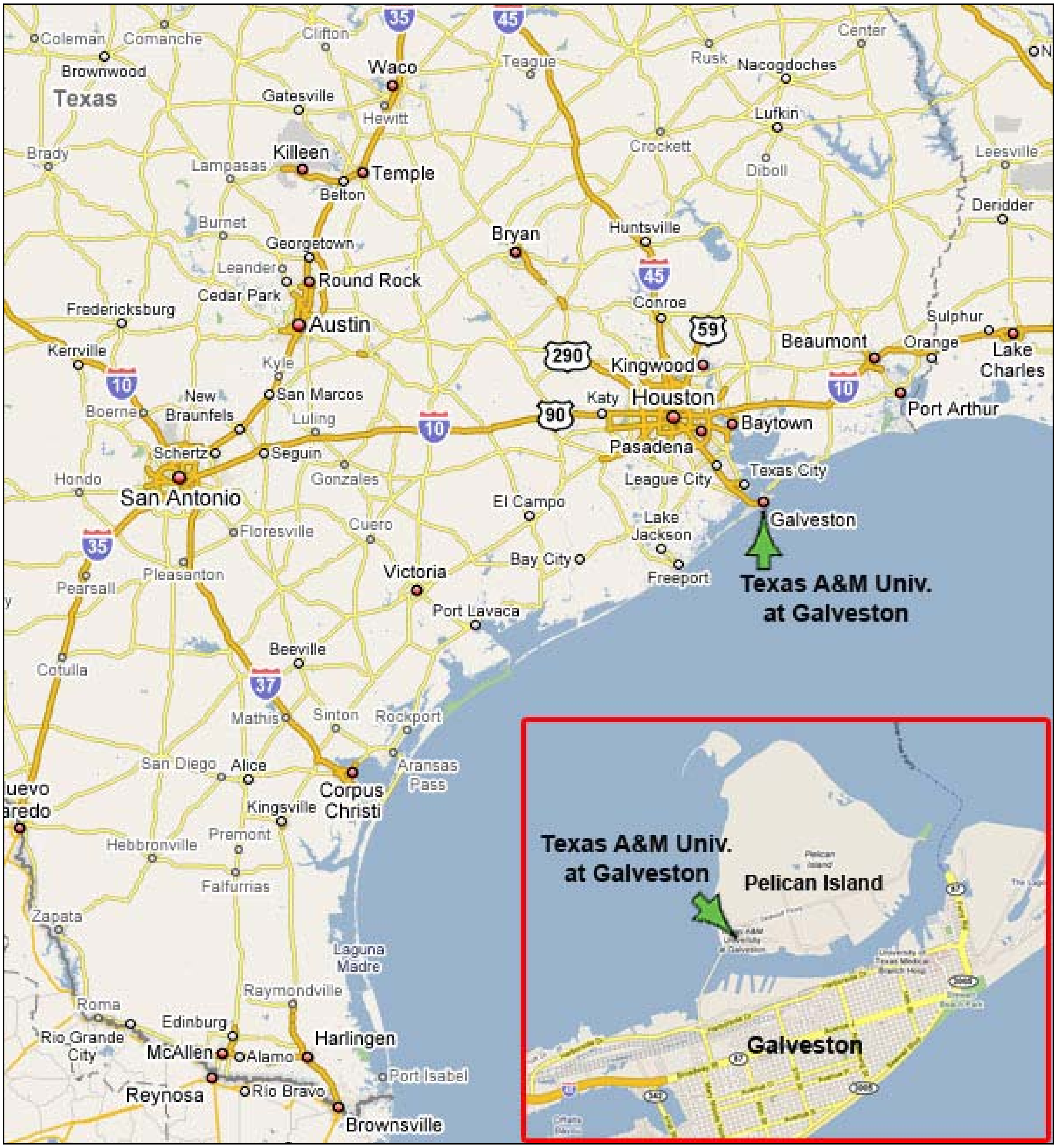


Figure 41. Location of TAMUG Campus and Potential Site.

Figure 42. Docking Facilities on Pelican Island and Causeway to Galveston.

Figure 43. Small Boat Basin on Pelican Island.

Marine Environment

The TAMUG campus site is on the waterfront. Seawater contains corrosive ions and numerous marine organisms harmful to construction materials. The marine environment is characterized by tidal action, storm waves, fog, spray etc., which are corrosive to construction materials such as concrete and steel. Figures 44 through 48 show the degradation and corrosion of some existing TAMUG facilities due to the marine exposure at the site.

- Figure 44 shows corrosion of an existing steel tie in a reinforced concrete column on site.
- Figure 45 shows corrosion of steel reinforcement on site.
- Figure 46 shows corrosion of steel sheet piles and reinforced concrete sewer pipe on site.
- Figure 47 shows corrosion of steel pipes on site.
- Figure 48 shows degradation of a reinforced concrete pile on site.

Figure 44. Corrosion of Steel Tie in a Reinforced Concrete Column on Site.

Figure 45. Corrosion of Steel Reinforcement on Site.

Figure 46. Corrosion of Steel Sheet Piles and Reinforced Concrete Sewer Pipe on Site.

Figure 47. Corrosion of Steel Pipes on Site.

Figure 48. Degradation of a Reinforced Concrete Pile on Site.

Engineering Research Programs

In addition to access to the shoreline and to Galveston, this potential site has access to the research and educational facilities on campus. TAMUG has two Bachelor of Science (B.S.) engineering programs - Maritime Systems Engineering (MASE) and Marine Engineering Technology (MARE). The Maritime Systems Engineering program has an emphasis on the design of offshore structures and coastal engineering works, and has a civil engineering basis.

Laboratories and Equipment

The following engineering laboratories already exist on site:

- Material Science Laboratory: Available equipment in the Material Science Laboratory includes a Universal Testing Machine (for tensile tests), Rockwell Hardness test machine, Officine Galileo Hardness test machine, impact test equipment, fatigue test equipment, a concrete strength-testing machine, a high-temperature oven, a micrographic viewer, a small torsion test machine, and a high-capacity torsion testing machine.
- Hydrodynamic and Thermodynamic Laboratory
- Electrical Engineering Laboratory
- Machine and Welding Shop
- Coastal Engineering Laboratory
- Flow and Acoustics Laboratory
- Geotechnical Engineering Laboratory
- University Training Ship (Texas Clipper III)

Existing Information Systems Facilities

TAMUG Computer Information Services (CIS) maintains the following computing resources:

- High-speed Internet connection for the campus which allows connections to the Internet II initiative for research with other universities with high-speed Internet II connections.
- Internal campus network connects all buildings on campus with fiber optic cable. In each building there are 100Mb/s switches using Virtual Local Area Network (VLAN) configurations to segment traffic and speed up access to servers.

- Access to the Trans-Texas Video Network (TTVN) for video conferencing, with five videoconference rooms, giving the ability to connect to any other videoconference system in the world that is on the Internet or with arrangements through TTVN in College Station, for Integrated Services Digital Network (ISDN) dial-up access or satellite connections.

Faculty and Research

At present, there are eleven full-time faculty members in the Department of Marine Engineering Technology. Three of the faculty members teach and perform research related to engineering materials.

EVALUATION OF SITE ALTERNATIVES

The current project developed a site evaluation matrix, shown in Table 14 in Chapter 4. Using the evaluation matrix, the five potential alternative sites were evaluated, as shown in Table 15. The importance factor was used as weight and multiplied by the score (0~10) given for each alternative site. The total sum of weights is 130, thus the maximum total score for an ideal site with full scores (10s) is 1300. On the bottom line of Table 15, total score and rank for each alternative site are presented. TAMUG obtained the highest rank due to its sound condition of existing facilities, which would provide significant advantages such as cost savings to TxDOT. UTMSI was a close second while the other three remaining potential sites obtained much lower scores.

Table 15. Evaluation of Alternative Sites.

	Alternative Sites		Site #6		Site #7		Site #8		UTMSI		TAMUG	
No	**Success Factors**	**Weight**	**Score (0~10)**	**Weighted Score**	**Score (0~10)**	**Weighted Score**	**Score (0~10)**	**Weighted Score**	**Score (0~10)**	**Weighted Score**	**Score (0~10)**	**Weighted Score**
1	**Size of site**	**9**	8	72	6	54	8	72	8	72	**9**	**81**
2	**Site location/ Site conditions**	**10**	6	60	6	60	6	60	8	80	**8**	**80**
3	**Site proximity to civilization**	**7**	8	56	5	35	9	63	7	49	**10**	**70**
4	**All-weather road access**	**10**	7	70	7	70	8	80	9	90	**10**	**100**
5	**Shore conditions**	**5**	8	40	8	40	7	35	9	45	**7**	**35**
6	**Protection against hurricanes and flooding**	**9**	5	45	5	45	5	45	8	72	**9**	**81**
7	**Access to equipment**	**10**	6	60	5	50	6	60	9	90	**10**	**100**
8	**Utilities**	**9**	4	36	8	72	2	18	8	72	**10**	**90**
9	**Site security/absence of interfering activities**	**10**	3	30	2	20	3	30	8	80	**10**	**100**
10	**General test conditions**	**9**	6	54	6	54	7	63	9	81	**8**	**72**
11	**Specimen housing facilities**	**8**	4	32	6	48	5	40	7	56	**10**	**80**
12	**Site docking facility**	**4**	3	12	4	16	2	8	6	24	**10**	**40**
13	**On-site laboratory**	**7**	5	35	3	21	5	35	8	56	**10**	**70**
14	**On-site weather station**	**8**	5	40	5	40	5	40	8	64	**10**	**80**
15	**On-site web-based camera system**	**5**	5	25	4	20	5	25	6	30	**10**	**50**
16	**Long-term commitment**	**10**	7	70	6	60	7	70	9	90	**10**	**100**
	SUM	**130**		**737**		**705**		**744**		**1051**		**1229**
	RANK			**4**		**5**		**3**		**2**		**1**

SUMMARY

Extensive research was performed for potential locations for a marine exposure test site along the Texas gulf coast. The research performed is summarized below.

The research team identified 10 state-owned lands on the Texas gulf coast from the GLO. In addition, two existing test facilities were considered as other alternatives, considering the potential advantages in using or expanding current facilities in accordance with the purpose of TxDOT. Therefore, a total of 12 potential sites were considered for evaluation.

Among the 10 state-owned sites, three possibly feasible sites (sites 6, 7, and 8) were selected and visited. After the site visits, it turned out these three locations are likely not feasible for a marine exposure test site, unless the area can be fully protected from vehicular traffic. As to the existing facilities, the UTMSI was visited by the research team while information on TAMUG facilities was obtained from TAMUG faculty members. The UTMSI and the TAMUG sites appear to be the most viable options for a marine exposure test site for TxDOT. Based on the evaluation using the site evaluation matrix with consideration of success factors (see Table 15), TAMUG turned out to be the best option and UTMSI to be the second best option.

Discussions with personnel from these two facilities were quite encouraging, and it is believed that developing a site at one of these locations would be quite viable and ideal from a scientific and practical perspective.

CHAPTER 6. FEASIBILITY OF THE MARINE EXPOSURE TEST SITE

MARINE EXPOSURE TEST SITE AS A RESEARCH FACILITY

The function of the proposed marine exposure test site is to conduct value-adding research and to support value-adding research conducted by others. The proposed marine exposure test site would occupy an intermediate position between laboratory tests and instrumentation of actual facilities in the field, such as pavements and bridges. Compared to laboratory tests, in which environmental factors and test conditions are very highly controlled, in the marine exposure test site the test conditions are highly controlled but the environmental conditions are uncontrolled. Laboratory tests confine themselves to a few test variables, whereas the marine exposure test site would have many variables, limited only by natural field conditions. Instrumented structures provide the realism associated with full-scale tests, but the test conditions and variables are highly limited; one cannot vary the design conditions outside the usual range because the structure must first and foremost provide the function it was intended to provide without risk to the public. A bridge exposed to saltwater cannot, for example, be designed to corrode in order to study corrosion; it must be designed not to corrode, and this fact limits the value of full-scale, operational facilities for experimentation.

It is important to observe that the materials research to be conducted at the proposed marine exposure test site is more than simply proof testing. If one has a bridge in Corpus Christi one must test the materials in Corpus Christi, but if one has a bridge in Lubbock one must test the materials in Lubbock. Therefore, a marine exposure test site on the Texas coast is only applicable to testing materials for bridges in the marine exposure coastal zone, not for bridges (or other facilities) outside the coastal zone, even though the materials used in the various locations are similar if not identical.

The viewpoint this report has taken is that the proposed facility is not simply for proof testing of materials to be used in marine environments but rather for establishing scientifically valid deterioration models derived from materials science and from the results of exposure testing. Therefore, its highest and best purpose of testing is to provide the data to validate such models, not merely to proof test samples. By proof testing, one makes samples using various materials combinations, exposes them to the destined environmental conditions, and chooses the best combination for use. There is no science involved, and no advancement of knowledge; for every subsequent facility design one has to repeat the process.

To put this point directly, if one is investigating the time to first corrosion, one would test samples with various values of parameters such as temperature, humidity, depth of cover, chloride concentration, corrosion critical threshold level, etc. From these tests, the experimenter builds models and the models are used to predict corrosion and to design materials systems. That is, if bridges are to be designed in Corpus Christi and in Lubbock, one would apply the same models, albeit with different values for the parameters in both locations, and would expect the corresponding results no matter where the behavioral models had been validated.

To put it another way, the proposed marine exposure test site is sited at the shore because that is a cost-effective way to obtain data, not because tests at the marine exposure test site are applicable only to structures in the marine environment.

Why not do the testing in laboratories? In fact, the testing could be done in laboratories under precisely controlled conditions of temperature, humidity, salinity, etc. There are however, two significant drawbacks:

- The environmental conditions in the laboratory, although precisely controlled, are not the environmental conditions in the field. Therefore, one needs to arrive at a correspondence between laboratory conditions and field conditions. Obtaining this correspondence will inevitably require instrumentation in the field to measure environmental variables. Therefore, laboratory tests alone, while valuable, are not sufficient.
- Laboratory space with controlled environmental conditions is limited and expensive. Rent is relatively high for laboratory space. These result in either reducing the size of the test specimens or limiting the number of test specimens.

However, nowhere in this report is it suggested that laboratory testing is not valuable, desirable, and necessary, even with the existence of the proposed marine exposure test site. In fact, the proposed Texas marine exposure test site is considered to be complementary to the other materials research facilities and laboratories supported by TxDOT.

One could avoid both the costs of laboratory testing and exposure at a marine test site by instrumenting existing structures in order to measure corrosion, temperature, humidity, salinity, etc. Then the environmental conditions would be known precisely. However, this method precludes varying the parameters; for example, concrete mix design, because the structure must be designed and built for safety and economy, not for scientific research. Therefore, only one structure can be built with only one set of parameter values, so that it is not possible to test parameters outside a narrow range. Statistical analysis, the foundation of scientific hypothesis testing, is impossible. However, nowhere in this report is it suggested that more instrumentation of existing structures would not be valuable, even with the existence of the marine exposure test site.

The presumed function of the marine environmental test site is to provide the facility to construct and validate material behavioral models in a cost effective way. It is needed not because the marine environment has high chloride loading; one can spray saltwater in a laboratory if one wishes. The point of the marine exposure test site is to be more cost effective in testing and model development because of the following:

- The actual environmental conditions (temperature, humidity, salinity, etc.) are those actually provided by nature and can be measured at the time of exposure.
- Land costs are relatively low compared to laboratory space, and so both the number of specimens and the sizes of specimens can be increased, leading to greater statistical validity.
- The proposed marine exposure test site would be an open-air laboratory, in which the behavior of material systems can be observed under measured (not controlled) environmental conditions. The results of such a facility, in testing and validating material behavior models, should be valuable for the cost-effective design of materials and facilities in Lubbock as well as in Corpus Christi, Dallas, and Houston.

The proposed marine exposure test site would complement the other research activities undertaken by TxDOT to achieve increased safety and service life and other goals with regard to deterioration and corrosion of the transportation infrastructure in Texas. In addition, the site could be used in combination with other exposure test sites in different environments, maximizing the findings from various climatic conditions. Figure 49 describes the anticipated contribution by the marine exposure test site. Operation of the site should improve the overall condition of the transportation infrastructure when this research is combined with other studies including laboratory experiments, in situ measurements, and materials science.

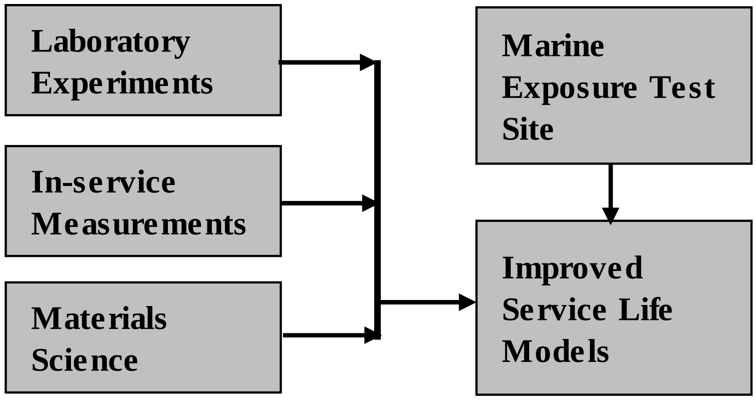


Figure 49. Contribution by the Marine Exposure Test Site.

ECONOMIC EVALUATION OF RESEARCH FACILITY

The economic evaluation of research facilities of any kind is a difficult proposition. There is no history to evaluate and to extrapolate into the future. Costs are difficult to estimate. There may be no direct revenues against which to offset costs. This investigation follows the principles for evaluating research costs and benefits promulgated by the Office of Applied Economics of the National Institute of Standards and Technology (NIST), as given by Chapman and Fuller *(27)*.

In general, research produces benefits, at some period in the future, determined by the diffusion rate (here diffusion rate is the rate at which the research results are implemented) and acceptance rate of the research findings, and costs to conduct the research and to generate those benefits. In time, the costs come far earlier than the benefits, so the economic analysis must be annualized or represented on a present worth basis.

Table 16, condensed from Table 2-1 in Chapman and Fuller *(27)*, provides a sample list of the benefits associated with research. The first column lists the general types of benefits or cost savings; the second column shows one to five Xs, depending on the judgment of the research team regarding the impacts of the proposed marine exposure test site. Five Xs indicate the maximum level of relevance. Empty cells indicate no relevance.

Table 16. Benefits Associated with Research.

Type of Benefits or Cost Savings	Relevance to the Marine Exposure Test Site
Adaptive Reuse	
Cycle Time Reduction	
Diffusion Process	X
Energy Conservation	
Improved Health and Safety	XXXXX
Improved Measurement Technology	
Improved Standards	XXX
Increased Durability	XXXXX
Increased Licensing Fees	XX
Increased Productivity	
Increased Reliability	XXXXX
Increased Royalties	XXX
Increased Sales	
Input Substitution	X
Reduced Property Losses	XXXXX
Reduced Rework	XXX
Reduced Scrap	
Reduced Variability	XXXX
Reductions in Acquisition Costs	
Reductions in Operations, Maintenance, and Repair Costs	XXXXX
Reductions in Waste and Pollution	XX

Innovations or discoveries made through research do not, however, generate benefits until the diffusion process operates to spread the information or technology to the practitioners and users. For an example of a diffusion process, see Appendix VI.

According to Chapman and Fuller *(27)*, "Basically, there are three ways in which the diffusion process affects the benefit stream. To better understand these three ways, consider the case of a product innovation. The first way concerns the time to "first use" of the innovation. Speeding up the time to first use means that the beneficiaries will begin to receive benefits or cost savings from the innovation earlier than would have been possible otherwise. The second way concerns the rate of adoption. If the contribution of the research organization is to increase the rate of innovation, then benefits and cost savings will accrue at a faster rate than otherwise in those years. The third way concerns the ultimate level of adoption (i.e., how completely the innovation penetrates the market). If the ultimate level of adoption is higher, then the overall potential magnitude for benefits and cost savings is increased. Because both the timing and the magnitude of the benefit stream is important in the calculation of the present value of benefits or the present value of savings, other things being equal, speeding up the time to first use, increasing the rate of diffusion, or increasing the ultimate level of adoption results in an increase in benefits."

The intention behind the management plan for the proposed marine exposure test site is to move aggressively not only in the performance of research but also in achieving a high rate of diffusion by reducing the time to first use, by increasing the rate of adoption, and by raising the level of adoption. TxDOT has control of this rate of adoption. These issues are addressed further in the section on the management plan.

Some of the specific types of benefits or cost reduction that would be addressed by the proposed marine exposure test site would include the following.

- Extension of the service life of infrastructure facilities by prevention of deterioration and corrosion through the use of advanced materials, processes, treatments, designs, and other factors. One objective would be to achieve the same service life from facilities in locations with aggressive environments, such as exposure to seawater, humidity, de-icing salts as from similar facilities located in benign environments.
- Reduction of the frequency, costs, and disruptions of maintenance, rehabilitation, replacement, and repair of facilities located in aggressive environments.
- Reduction of the initial costs of facilities that are expended to protect these facilities against deterioration and corrosion. That is, advanced technologies will be capable of extending service life while improving safety at lower cost.

Table 17 shows the classification of the costs associated with research given in Chapman and Fuller (*27*). The associated costs can be classified into two hierarchy levels: primary level and secondary level. Also, the costs are classified by organization depending on who bears the costs. As to the development of the marine exposure test site in the state of Texas, there could be multiple research organizations including TxDOT, other state agencies, universities, and companies that are willing to perform their own tests. Practitioners include TxDOT, construction contractors, material vendors, and so on. From the perspective of TxDOT, an important question is what part of costs should or need to be born by TxDOT for the success intended with the development of the site.

Table 17. Classification of Costs Associated with Research.

Type of Organization Bearing the Costs	Type of Cost	
	Primary Level	**Secondary Level**
Research Organization	Labor Salaries, Training, and Travel	Researchers Technicians Managers Contract Workers on Site Support, Administrative, and Secretarial Staff
	Capital Expenses	Site and Facilities Laboratory Equipment Computer Equipment Laboratory Materials
	Operation, Maintenance, and Repair of Facility and Equipment	
	Contract Costs for Technical Work Done by Others	
	Dissemination Costs	Printing/Publishing Research Results Distribution Professional Society Activities
		Other Meetings to Link to Industry
	Marketing Costs	World Wide Web
Practitioners	Training for Using the Innovation	
	Adapting the Innovation to Industry Use	
	Investments in New Equipment/Materials/Processes	
Others	Spillovers	

COST-BENEFIT ANALYSIS

To integrate the conclusions of the research, cost-benefit analyses for Texas highway bridges, especially on-system bridges, were performed. Off-system bridges were excluded in the model because other local agencies manage and maintain them. This assumption also makes the model conservative. Assuming the development of a marine exposure test site on the Texas gulf coast, the research team analyzed its potential effects in two different but interrelated dimensions:

1) the future condition of highway bridges (i.e., how much the condition of Texas bridges would be improved), and

2) economic feasibility (i.e., whether the benefits would be greater than the costs).

Thus, the dynamic model developed for the analysis tracks the condition of bridges over time periods to forecast future condition and incorporates cost and benefit elements together so that model results predict the future condition of Texas highway bridges, together with benefits and costs.

Systematic View on the Maintenance of Infrastructure Facilities

According to the *Report on Texas Bridges* (*5, 6, 7, and 8*), highway bridges are classified into two major groups by condition: 1) sufficient bridges and 2) deficient bridges. The deficient bridges are sub-classified into three groups:

- structurally deficient bridges,
- functionally obsolete bridges, and
- substandard-for-load-only bridges.

Basically, the developed flow model accepts this classification with some small adjustments. For the specified model with the adjustments, refer to Appendix VI.

The model developed takes a systematic view of the maintenance of infrastructure facilities (especially, Texas highway bridges). Figure 50 provides the basic concept of the model. Facilities are classified by their condition into two major groups: 1) sufficient facilities and 2) deficient facilities. There are three major flows in the system, as follows:

- the process of becoming deficient (e.g., by the effects of deterioration or corrosion);

- the process of becoming sufficient (e.g., through repair, replacement, and rehabilitation); and
- the construction of new facilities at new locations, which results in additions to the sufficient facility group.

Development of a marine exposure test site would influence this cyclic system by providing real test data and knowledge as the basis of future innovations such as effective deterioration prevention or repair technologies and advanced materials. The fields of these innovations include:

- specifications,
- construction methods,
- maintenance/repair methods,
- practices, and
- materials.

If future innovations are successful, the amount of the two flows (the process of becoming deficient and the process of becoming sufficient) could be reduced. More effective and efficient maintenance of infrastructure can be obtained when the amounts of these two flows are minimized.

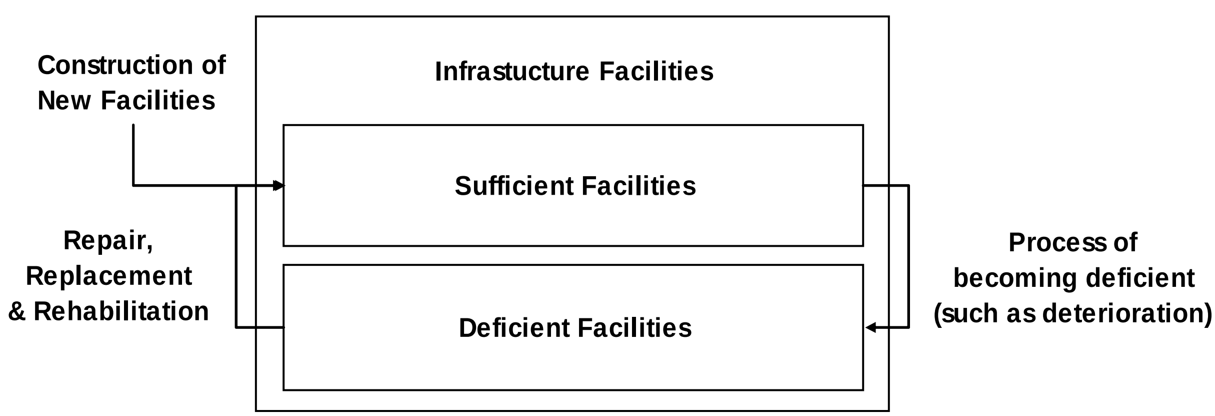


Figure 50. Maintenance of Infrastructure Facilities.

Life-Cycle of the Marine Exposure Test Site

Throughout the life-cycle of a marine exposure test site, different types of costs will occur starting with the initial site development costs and benefits would be realized after some delays. To represent these events over a long period of time, the current project takes a life-cycle perspective on the cost-benefit analysis. Figure 51 provides a generic time horizon for the cost-benefit analysis.

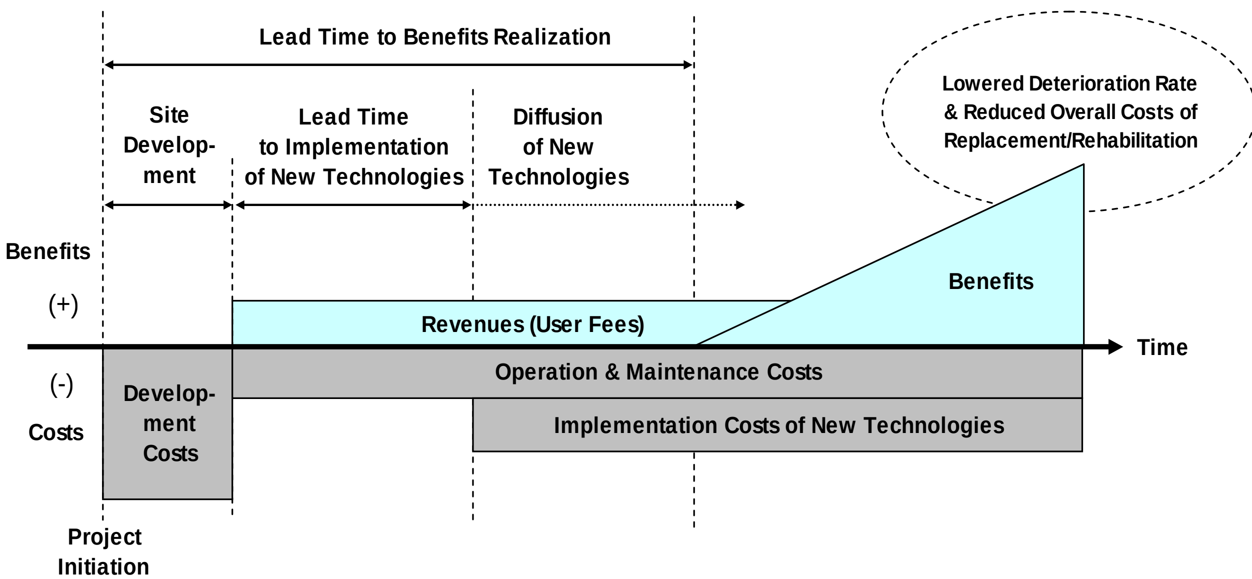


Figure 51. Time Horizon of the Cost-Benefit Analysis.

After the development of the site, various types of tests will be performed at the site. Relevant knowledge will be accumulated from the tests, while there will be recurring costs and revenues—site operation and maintenance costs and revenues from user fees.

It will take years to invent, evaluate, and implement new technologies/advanced materials for actual construction/repair projects. This lead time to the implementation will depend on test results from the site, financial support from TxDOT, decisions on implementation by TxDOT, and so on. In order to reduce lead time to the realization of benefits, TxDOT and researchers at the site should closely cooperate to develop an effective long-term plan that would include short-term plans in phases. The plans could be about prioritization of research needs, parallel accelerated tests, implementation plans, and so on.

After the first implementation of new technologies, the technologies will be deployed on future projects and will replace existing inefficient methods. The rate of deployment would depend on decisions by TxDOT concerning how fast all TxDOT districts adopt the new technologies.

Generally speaking, new products and technologies are usually more expensive than existing ones. However, new ones are adopted because they outperform existing ones and the higher costs are usually lowered over periods of time due to the increased level of deployment and the learning effects. New technologies invented from the site would likely follow a similar pattern.

If the implementation of new technologies is successful, the overall condition of bridges will be improved and the maintenance needs (repair/replacement/rehabilitation) will be reduced. The rate of the overall improvement will depend on the effectiveness of new technologies and the rate of diffusion of the new technologies. Reducing the number of structurally deficient bridges will result in savings in the rehabilitation costs and savings in traffic delay costs. However, these benefits will be realized after some delay. The length of the delay and the significance of the benefits will depend on the various factors discussed above.

The developed computer model considers all of these factors simultaneously, as well as tracking the maintenance needs. Thus, the model provides forecasts on the future condition of bridges and monetary flows taking into consideration all relevant costs and benefits. Economic feasibility is determined by calculating the net present value of cumulative cash flows, positive (income) and negative (payment). The forecast time period for this assessment was set at 50 years and a 4 percent discount rate was assumed.

Susceptibility of Bridges

In the current model, the susceptibility of bridges is defined as the relative weakness of bridges to durability problems including deterioration, corrosion, and so on—how easily bridges become structurally deficient because of durability problems. Higher susceptibility levels indicate more susceptible bridges. In Figure 50, the process of becoming deficient will be accelerated if the average susceptibility level of the sufficient bridges is high. In contrast, the process will be decelerated if the average susceptibility level is low. The most important benefit from the development of the site will be lowering this susceptibility level of bridges by inventing and implementing better technologies (deterioration prevention methods, advanced materials, practices, and so on), especially new technologies aimed at lowering the rate of bridges becoming structurally deficient.

The annual rates of the transition of bridges (in the processes of becoming deficient or sufficient) were estimated using historical data obtained from the *Bridge Facts* (*1*) and the *Report on Texas Bridges* (*5, 6, and 7*). Three assumptions were used for the estimation of the rates. The first assumption is that TxDOT will keep its present level of effort on the maintenance of highway bridges in the future (i.e., the percentage of deficient bridges that are rehabilitated will be held constant in the future). The second assumption is that the rates of becoming deficient would be relatively stable without the development of the marine exposure test site, but the rates, especially the rate of becoming structurally deficient, can be lowered by implementing new technologies. The last assumption is that the rate of new bridge construction would be stable in the future. For a detailed estimate of these rates, refer to Appendix VI. Appendix VII provides FHWA data that were used for the estimation.

As to lowering the susceptibility level, the following questions must be resolved:

- To what levels of susceptibility will new bridges and repaired bridges be lowered by implementing new technologies?
- How much will the overall condition of the bridges be improved through the use of these new construction/rehabilitation procedures?
- How much in the susceptibility level could be lowered using new technologies compared to using current practices?

New technologies are expected to reduce the number of sufficient bridges that become deficient by lowering their susceptibility level. Considering that the sufficient bridge population includes different types of bridges in terms of their susceptibility (in general, old bridges are more susceptible; new bridges and recently repaired bridges are less susceptible), it is necessary to differentiate these bridges by their susceptibility level in order to quantify the effect of new technologies. However, the effectiveness of new technologies to be invented is as yet unknown. Also, there are insufficient data to estimate different susceptibility levels for the bridges. (Developing such data might be one important function of the marine exposure test site.)

Relying on opinions from concrete durability experts, the relative susceptibility levels for the bridges (existing sufficient, new, and repaired bridges), as well as expected future improvements in the bridges by using new technologies, were estimated. The estimates are provided in the next section.

In the current model, improvements by new technologies are represented by lowered susceptibility levels of the bridges, which actually imply an increase in bridge service life. Appendix VIII provides an alternate and simple approach that represents reduced frequency of rehabilitation and repair as the improvements resulting from new technologies. The model in Appendix VIII is simple and limited in scope: the model focuses on repair of bridges located in the Texas coastal zone, thus it provides a lower bound on the total potential effects in Texas. However, the model forecasts the same generic pattern of costs and benefits over periods of time. Appendices IX and X provide basic concepts for measuring the economic values of extending service life and reducing of repair frequencies and costs.

Estimates of Model Parameters

The various model parameters were estimated by experts in materials science, corrosion, and deterioration working with this research project. The estimates of major parameters are provided below. For the detailed descriptions and estimates of all parameters, refer to Appendix VI.

Effectiveness of Current Technologies

- Assume that the possible susceptibility level of bridges ranges from 0.0 (least susceptible) to 2.0 (most susceptible) and the average susceptibility level of all existing sufficient bridges equals 1.0.
- The relative susceptibility level of new bridges using current practices equals 0.6.
- The relative susceptibility level of repaired bridges using current practices equals 0.85.

Effectiveness of New Technologies

- Assume 50 years of continuous implementation of new technologies.
- The expected susceptibility level of new bridges using new technologies equals 0.3 (after 50 years).

- The expected susceptibility level of repaired bridges using new technologies equals 0.45 (after 50 years).

Site Development

- Initial site development costs equal $2,750K.
- Duration of the development equal 1.5 years.

Recurring Costs and Revenues

- Annual site operation costs equal $175K.
- Annual maintenance costs equal $75K.
- Annual gross revenue equal $37.5K.

Implementation and Diffusion of New Technologies

- Lead time to implementation of new technologies is assumed to be 5.5 years.
- The shape of the diffusion pattern is an S-curve.
- The lead time to full diffusion is assumed to be10 years.

Annual Rates of Bridge Condition Changes

- Annual rate of becoming structurally deficient equals 0.11 percent of total on-system sufficient bridges.
- Annual rate of becoming functionally obsolete equals 0.89 percent of total on-system sufficient bridges.

Current Costs for Bridge Replacement/Rehabilitation and New Construction

- Average replacement/rehabilitation cost per bridge repair equals $1.38M.
- Average new construction cost per bridge equals $1.92M.

Changes in Construction/Repair Costs by New Technologies

- The changes in costs are assumed to follow an inverted S-curve from the maximum level to the minimum level.
- Maximum additional costs are assumed to be 6 percent of the current cost level.
- Maximum savings are assumed to be 15 percent of the current cost level.

- The lead time to reach maximum savings is assumed to be 15 years.

Average Traffic Delay Costs

- The estimated indirect corrosion costs for Texas highway bridges equal \$6.9B (see Table 10 in Chapter 3).
- The total indirect costs considering all durability problems equal \$11.4B = \$6.9B × 1.65 (the multiplier for all durability problems).
- The annual average number of bridge repairs (replacements and rehabilitations) equals 400 bridges per year.
- Average traffic delay costs equal \$28M per bridge repair (= \$11.4B / 400 bridge repairs).

Base Case versus Alternate Case

The model tested two cases. The base case is the null case assuming there will be no development of a marine exposure test site so that there would be no significant improvements in deterioration prevention technologies. The alternate case assumes the development of a marine exposure test site and this site will result in new technologies so that there would be apparent improvements in deterioration prevention technologies. The alternate case involves initial site development costs, annual recurring costs (site operation and maintenance costs), changes in bridge construction/repair costs, and future benefits. The benefits include tangible benefits (a better overall condition of Texas bridges, reduced number of rehabilitations/repairs with extended service life, savings in construction/repair costs) and intangible benefits (savings in traffic delay costs and enhanced safety).

The following results were obtained using the model and the estimated parameters. The results provide the comparison between the base case and the alternate case. Both cases have the same number of total bridges in the forecasts.

Structurally Deficient Bridges

Figures 52 and 53 provide forecasts on the percentage and the number of structurally deficient bridges, respectively, that directly relate to corrosion and deterioration processes and in which the actual improvements in bridge condition by new technologies are expected to be realized.

In the base case, the percentage of structurally deficient bridges becomes smaller over the time periods shown in Figure 52. However, this decrease is due to the increase in the total number of bridges (i.e., new bridges constructed). The actual number of structurally deficient bridges in Figure 53 decreases until year 22 but increases thereafter. Unfortunately, the number of structurally deficient bridges is expected to grow in the long-term even though the current level of effort by TxDOT in bridge rehabilitation (represented in the model by the annual percentage of structurally deficient bridges rehabilitated) continues in the future. Therefore, the current level of effort by TxDOT can be considered sufficient to reduce the number of structurally deficient bridges in the short-term. However, in the long-term, there will be more need for rehabilitation of structurally deficient bridges beyond the current effort.

For the alternate case, the following improvements are realized:

- the percentage of structurally deficient bridges becomes smaller than the base case (Figure 52) and
- the actual number of structurally deficient bridges continues to decrease, as shown in Figure 53.

In addition, the decreasing pattern seems to continue into the distant future. In Figure 53, the apparent differences between the base case and the alternate case, which can be considered as realized benefit from implementing new technologies, begin around year 16. This difference can be considered as the first realization of benefits, especially in the condition of bridges.

Figure 54 shows the cumulative difference in the number of structurally deficient bridges between the base case and the alternate case. The number of structurally deficient bridges will be reduced by approximately 800 bridges at year 50. This number is a significant reduction. This decrease in the number of structurally deficient bridges in the alternate case involves a significant savings in rehabilitation costs, as well as savings in traffic delay costs.

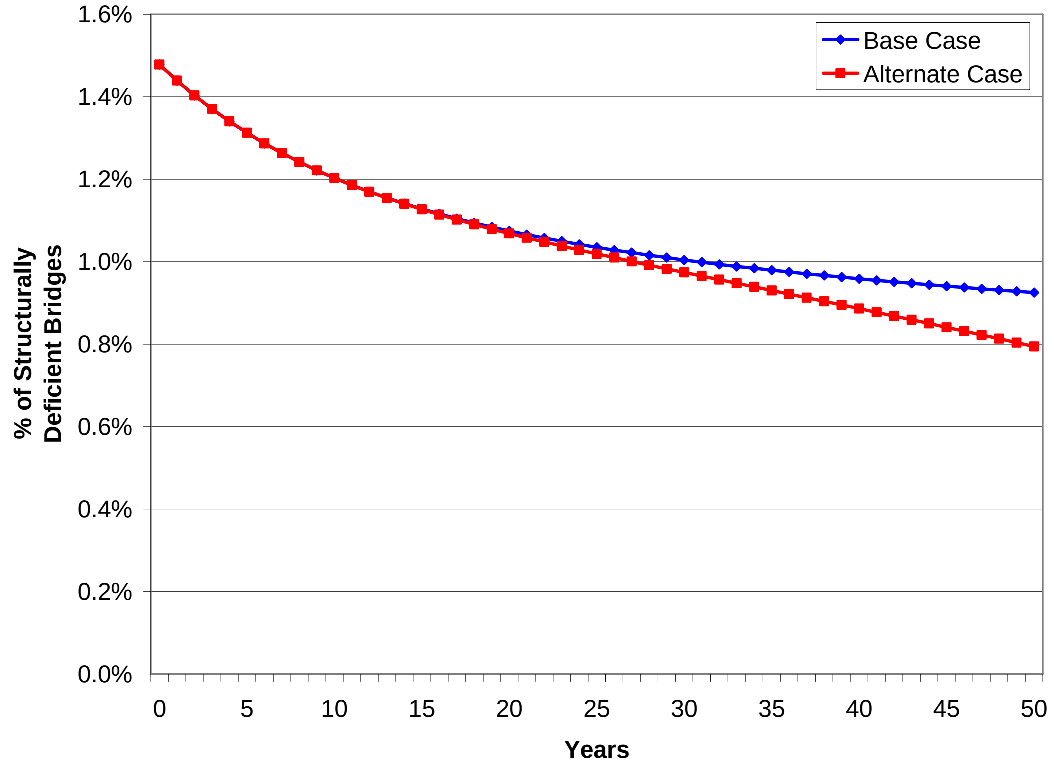


Figure 52. Forecast on the Percentage of Structurally Deficient Bridges.

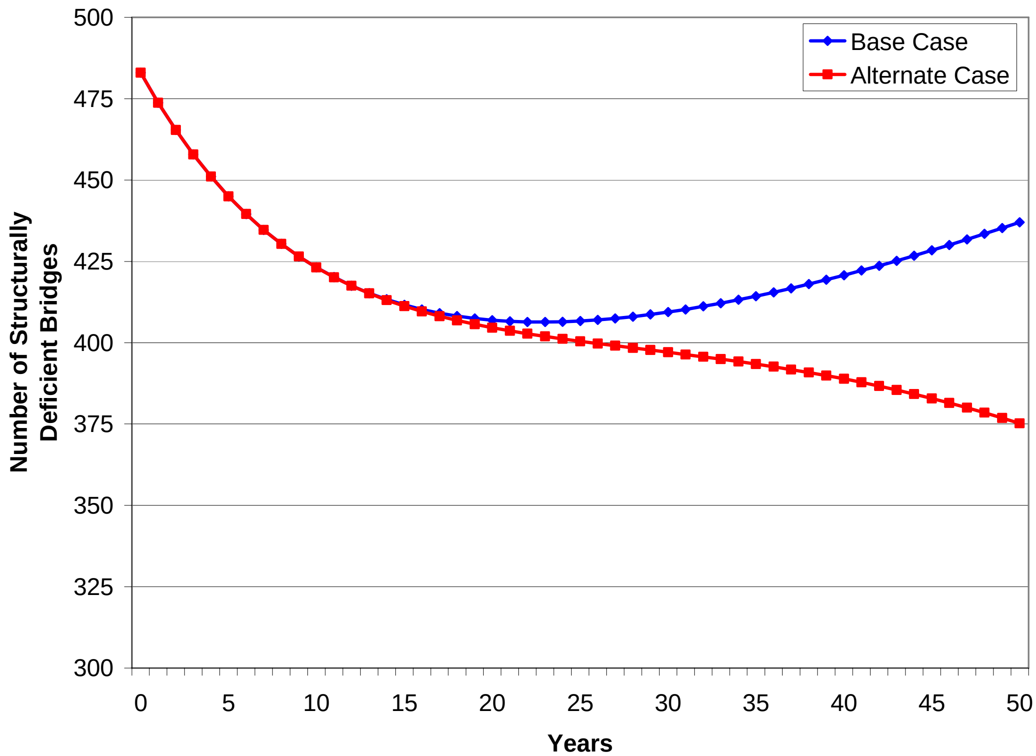


Figure 53. Forecast on the Number of Structurally Deficient Bridges.

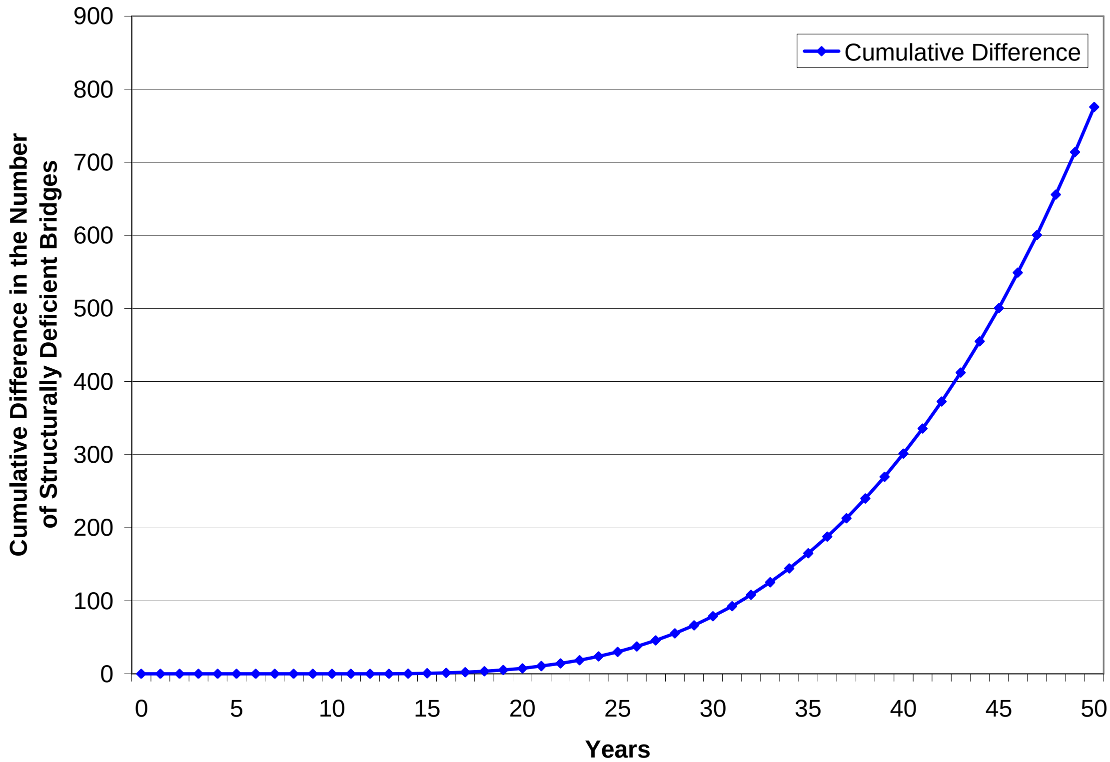


Figure 54. Cumulative Difference in the Number of Structurally Deficient Bridges.

Monetary Effects

Figure 55 provides forecasts on the bridge construction/rehabilitation costs. After the implementation of new technologies is initiated, the new technologies would be deployed to future TxDOT projects. Together with the implementation process, there likely will be changes in construction/repair costs. New technologies are expected to be more expensive than the current cost level at the beginning of the diffusion process but, when a high level of diffusion occurs (more bridge projects use the new technologies), the new cost level should be lowered as a result of the learning effects. The increases and decreases in the new construction and rehabilitation costs in Figure 55 represent these future effects (diffusion and changes in the costs).

Figure 56 shows resultant savings in the bridge construction/rehabilitation costs (the costs for the base case minus the costs for the alternate case). The negative values represent additional costs and the positive values represent savings in the comparison between the base case and the alternate case.

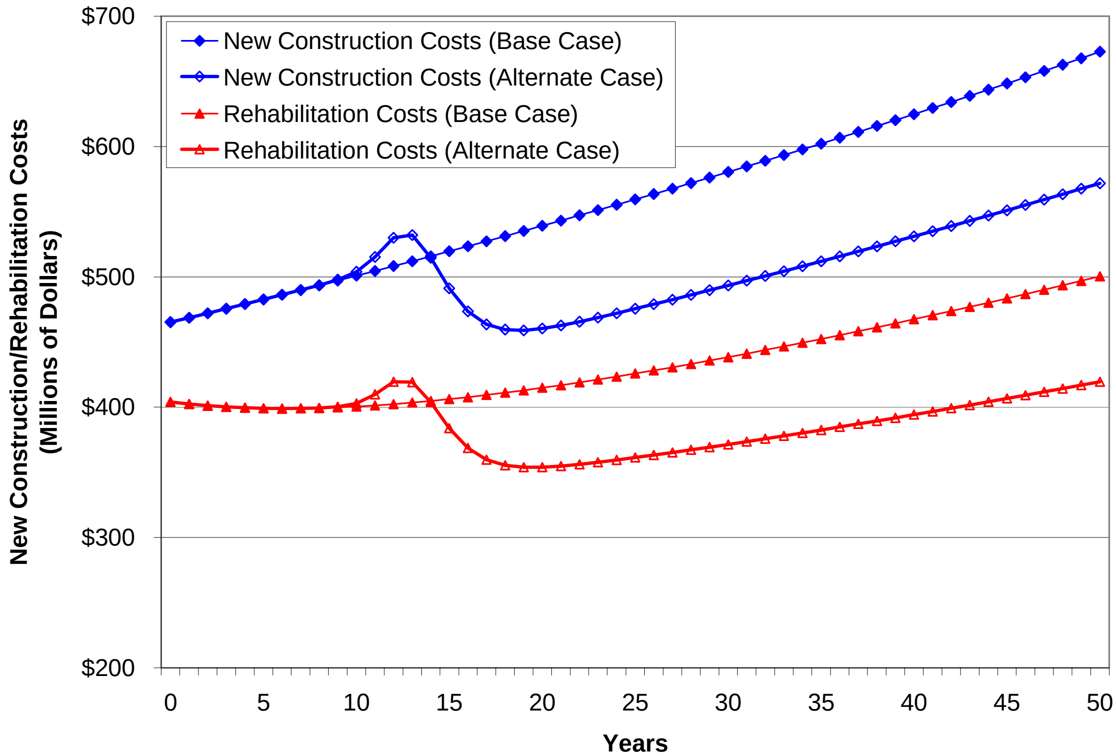


Figure 55. Changes in Bridge Construction/Rehabilitation Costs.

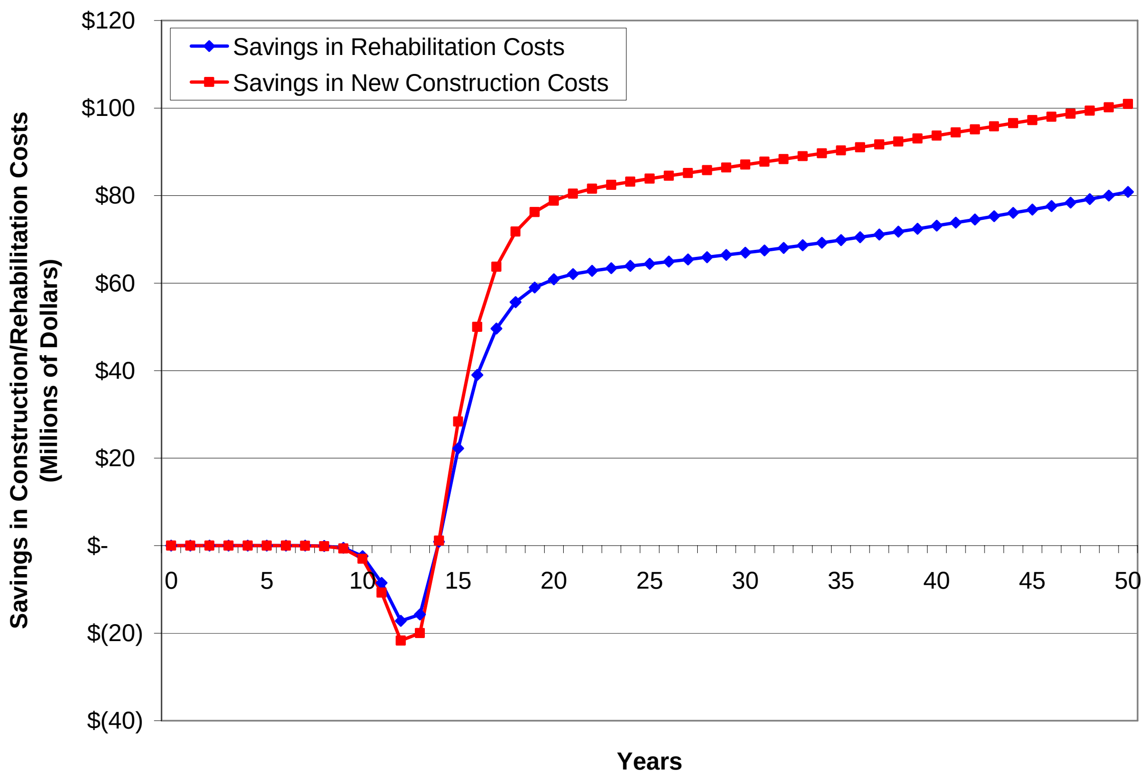


Figure 56. Savings in Bridge Construction/Rehabilitation Costs.

Traffic Delay Costs

Traffic delay costs due to bridge rehabilitations were estimated for both cases. The alternate case has smaller costs for rehabilitation than the base case because the total number of structurally deficient bridges is reduced (Figure 53). Figure 57 shows the difference in the traffic delay costs between the two cases (the costs for the base case minus the costs for the alternate case), which is considered as savings in the traffic delay costs.

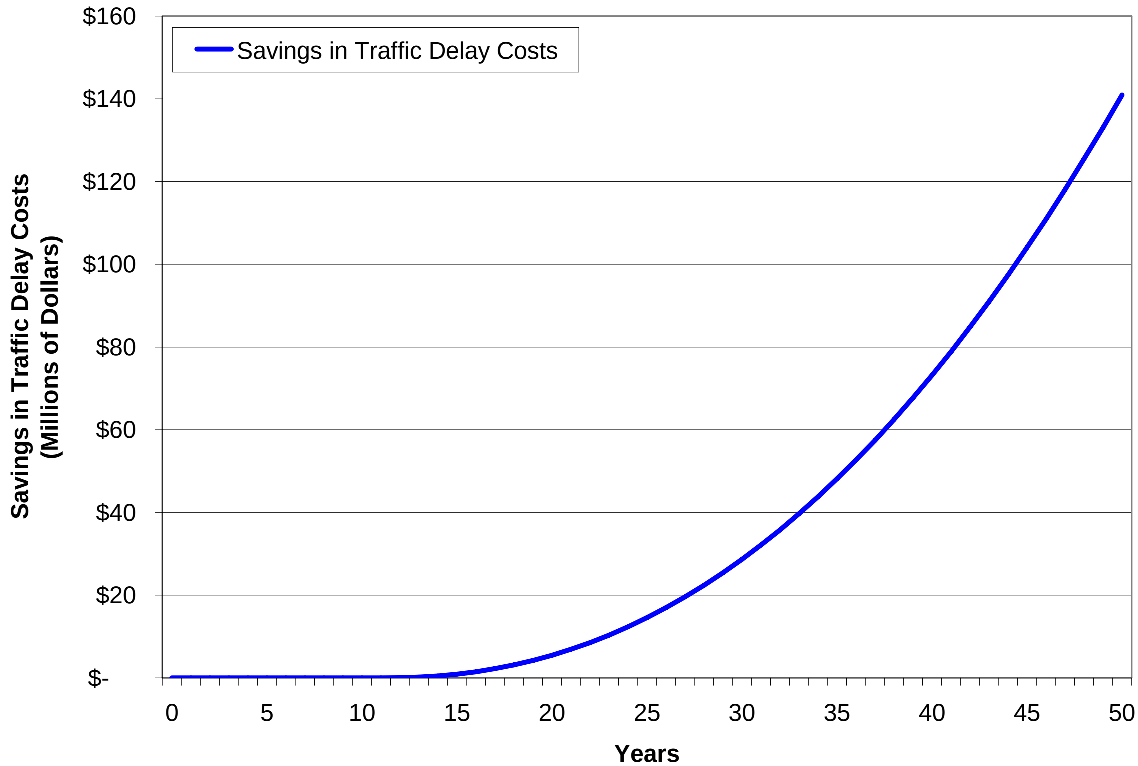


Figure 57. Savings in Traffic Delay Costs (Difference in Traffic Delay Costs between Two Cases).

Flows of Costs and Benefits

Taking into account all relevant costs and benefits, the net flow of costs and benefits was calculated. Figure 58 shows the net flow of costs and benefits in the alternate case. Before year 14 in the figure, the majority of the net flow consists of costs without significant benefits. During this time the benefits will be a small amount of the revenues (user fees), which are not sufficiently large to cover all the costs. Thus, negative net flows are present before year 14. These costs include initial site development costs, annual site operation and maintenance costs, and additional costs of implementation of new technologies. Starting from year 14, positive net flows occur due to:

- the decrease in the number of structurally deficient bridges (Figure 53, thus the decreases in the number of rehabilitations);
- the decreases in construction and rehabilitation costs below the cost level in the base case (Figure 55); and
- savings in the traffic costs (Figure 57).

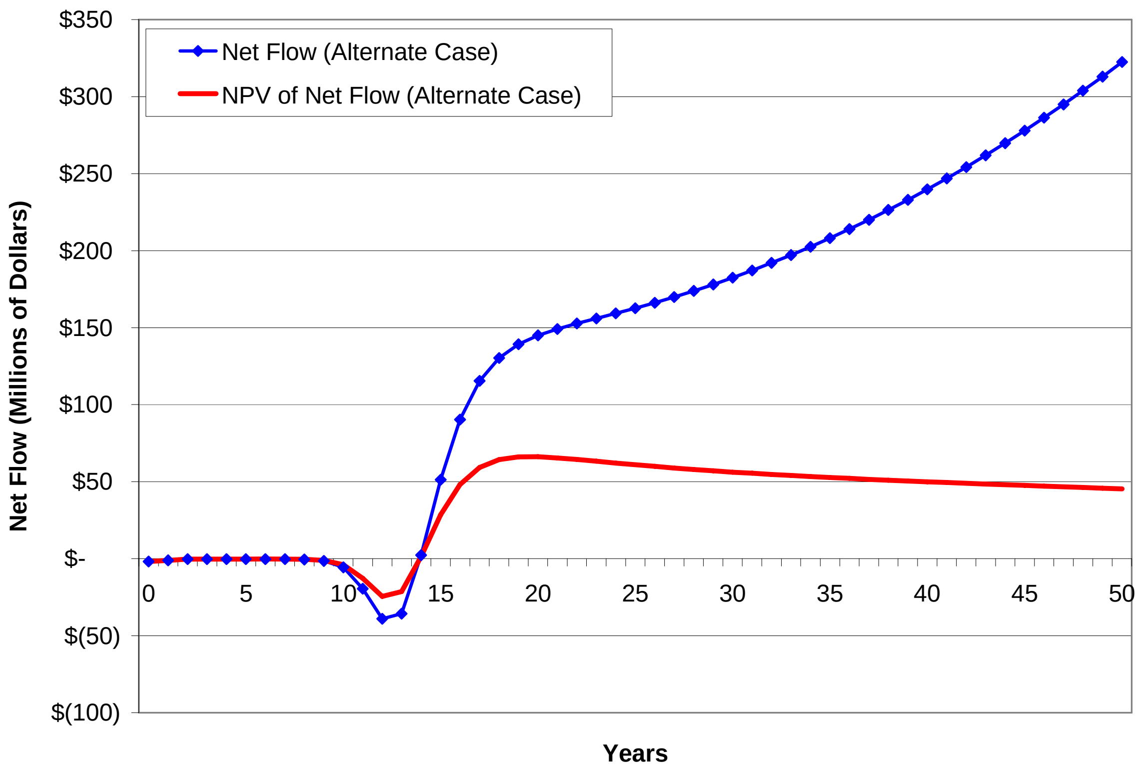


Figure 58. Net Flow of Costs and Benefits.

Figure 59 shows the cumulative flow of costs and benefits, which is the accumulation of new flows in Figure 58. Based on the Net Prevent Value (NPV) of the cumulative flow, the development of the site (including operation and maintenance) will be paid off after approximately 16 years. Therefore, the negative flows up to year 14 shown in Figure 58 can be recovered by the positive flows generated during the following two years. Even though the lead time to the break-even point is relatively long (about 16 years) the future benefits would be very substantial.

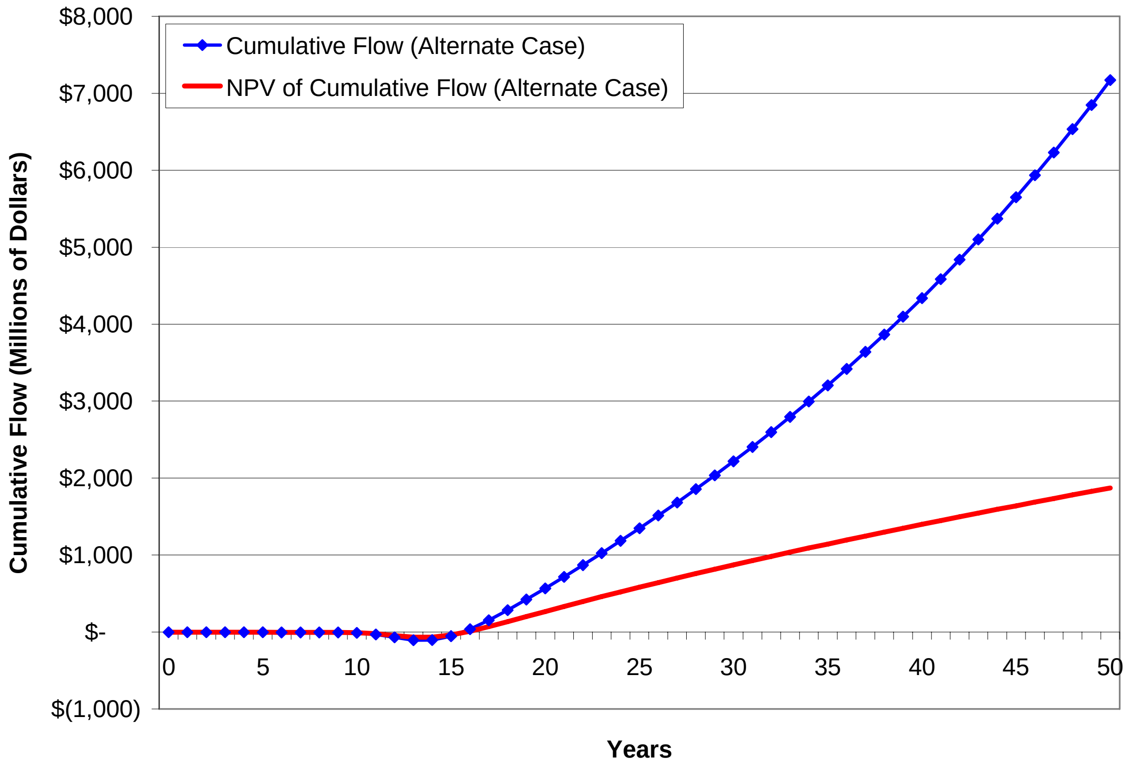


Figure 59. Cumulative Flow of Costs and Benefits.

Future Effects on Other Transportation Facilities

Of course, there are other types of facilities that can be improved by implementing new technologies developed at the marine site. Besides highway bridges, the most significant transportation facilities regarding the issues of deterioration and durability are highways. The relative size of future effects by the development of the site for highways was estimated to be about 0.5 assuming the size of future effects on highway bridges is 1.0. For all other remaining types of facilities, the relative size of future effects was estimated to be 0.4, also assuming 1.0 for the effects on highway bridges. Therefore, the overall future effects by implementing new technologies on all transportation facilities in Texas would have about two times the effects forecasted for highway bridges in the current analysis.

SUMMARY

The developed model forecasts future conditions of highway bridges with a financial projection assuming the development of the marine exposure test site and its potential future effects. The results indicate that there could be time delays before benefits are realized even though future benefits could be very significant. The length of delays (lead time to benefit realization) depends on several factors:

- The lead time to the implementation of new technologies: It could take several years to invent and implement new technologies. It also depends on the success of tests. To shorten the lead time, it will be necessary to develop a comprehensive test and implementation plan in phases.
- The diffusion of new technologies: The deployment rate will be under the control of TxDOT—how fast all districts adopt new technologies for their projects. If the technologies are successful, the faster rate of diffusion will lead to faster decreases in the number of structurally deficient bridges and in the number of rehabilitation needs.
- Decreases in the construction and rehabilitation costs by new technologies: There would be learning effects as the new technologies are diffused to future projects. Thus, the increased cost level is expected to be lowered after some delays. When the new cost level becomes lower than the current cost level, the decreases will be recognized as savings.

Before having positive net flows (especially tangible benefits such as savings in the construction/rehabilitation costs), most of the site-related costs would need to be supported by TxDOT. Chapter 7 discusses revenues from site operations.

Even though there are various uncertainties in the analysis, the results show that the development of a marine exposure test site in Texas could improve the overall condition of Texas bridges, as well as other infrastructure facilities, and result in significant tangible and intangible benefits for many years to come. However, the site development will require financial support and a long-term commitment in order to achieve these benefits.

CHAPTER 7. MANAGEMENT PLAN

INTRODUCTION

The Texas marine exposure test site will be aimed at increasing the service life, reducing the capital and maintenance costs, and improving the quality, performance, and safety of transportation infrastructure in Texas through real-exposure research, experimentation, and testing of construction materials and structural components leading to reduced degradation, deterioration, and corrosion. These goals would be difficult to obtain in an efficient way (minimizing overall financial burden and maximizing benefits) without a well-prepared management plan because there are various factors that can impede success.

The site would be wholly owned by TxDOT and managed and maintained by a contractor to be selected by TxDOT. The research team developed an organizational chart based on type of activities to be performed at the site.

As a state research facility, the Texas marine exposure test site would accommodate various users' research regarding infrastructure durability. The users could include research organizations, other state departments of transportation (DOTs), vendors, construction contractors, and so on. The types of users and their needs were identified, defining the target market. Also, types of services and required technologies were identified.

The Texas marine exposure test site will be a long-term operation. Measurable milestones were developed from a long-term perspective to achieve business goals.

Financial projections provide forecasts on the annual funds required and the expected lead time to the break-even point. The projection indicates there is a critical need for a long-term financial commitment and it identifies critical factors to make the site successful, especially by reducing the lead time to the realization of benefits.

ORGANIZATIONAL DESCRIPTION

Statement of Organizational Purpose and Objectives

The purpose of the Texas marine exposure test site is to increase the service life, reduce the capital and maintenance costs, and improve the quality, performance, and safety of transportation infrastructure in Texas through real-exposure research, experimentation, and testing of construction materials leading to reduced degradation, deterioration, and corrosion. These improvements would benefit the taxpayers and the traveling public in the state of Texas.

Organizational Chart

The Texas marine exposure test site would be wholly owned by the state of Texas (TxDOT) and managed and maintained by a contractor to be selected by TxDOT. Figure 60 shows a proposed organizational chart for the marine exposure test site based on types of activities performed by personnel. The organizational chart below describes each of the positions.

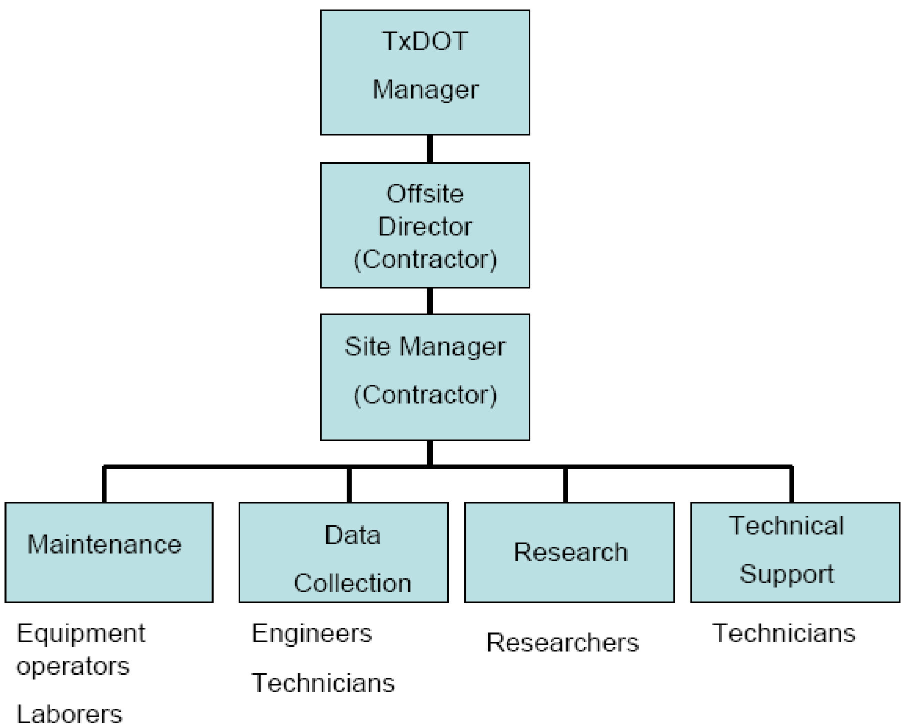


Figure 60. Organizational Chart.

The TxDOT Manager. The TxDOT manager represents TxDOT and monitors the contractor's management of the site. The TxDOT manager would request the contractor to submit management reports to TxDOT annually.

The off-Site Manager. The off-site manager, as the representative of the contractor, communicates directly with the TxDOT manager. The off-site manager provides the on-site manager with managerial support.

The on-Site Manager. The on-site manager takes overall responsibility for managing the exposure test site and reports relevant management and operation issues to the off-site manager. The contractor's on-site manager should be a recognized researcher in the area of construction materials, especially steel and concrete, deterioration, corrosion, and related subjects, in order to:

- give the Texas marine exposure test site credibility with researchers,
- prepare proposals for research work using the Texas marine exposure test site,
- conduct his/her own research, and
- make necessary timely decisions about research and testing issues when the actual researchers are not present on the site. The contractor should develop an annual management and marketing plan for submittal to TxDOT and obtain approval from TxDOT for reimbursement of marketing costs.

Maintenance: Maintenance work can be outsourced to a contractor who would perform routine maintenance on an annual contract basis.

Data Collection. Researchers and technicians will collect data. The frequency and significance of data collection will depend on types of data and specific test requirements (user needs). This division needs to have capabilities to collect, accumulate, and distribute the data collected.

Research. As a research facility, the site needs to have researchers who have significant experience on infrastructure facilities durability problems, especially transportation facilities. TxDOT needs to develop a master plan for TxDOT tests in cooperation with the site researchers.

Technical Support. The site should have an on-site laboratory that includes various types of testing equipment, a weather station, computer and network system, and so on. The technical support division can provide other divisions with technical support as needed.

All personnel at the site, whether permanent or temporary, employees of the contractor or employees of other organizations, would report to the contractor's on-site manager. The personnel positions shown would not necessarily be full-time positions, at least in the early phase of the proposed marine exposure test site. Growth in research could lead to some positions becoming full-time.

MANAGEMENT

Management Structure

The Texas marine exposure test site would be owned by the state of Texas (TxDOT) and managed and maintained by a contractor. It is anticipated that TxDOT would provide the following supports:

- the initial funding, including the site (selected from possible sites owned by the state);
- site improvements (roads, buildings, and other facilities); and
- equipment (vehicles, computers, laboratory equipment, surveillance cameras, etc.).

Users would be charged usage fees so that the marine exposure test site could recover the costs of operations, maintenance, and testing services, plus amortization of some portion of the capital costs. Users, in this context, are expected to include the following categories:

- universities performing research for TxDOT under contract to TxDOT;
- universities and other research organizations performing research under contract to others; for example, to departments of transportation in other states without comparable marine exposure test sites; and
- firms in industry performing research on their products for their own benefit or for the benefit of others.

In the initial phase of the marine exposure test site, it is anticipated that most if not all of the usage of the facility would be drawn from the first category, organizations performing research for TxDOT. Therefore, in the early phase, proposals to TxDOT would include annual funding for research support using the marine exposure test facility in order to assure that the user fees would cover all costs, or TxDOT would make up any cost deficits directly. As the usage of the marine exposure test site expands into the second and third categories, a three-tiered fee structure could be imposed, with the higher categories paying higher fees. A possible goal might be for the operational costs of the marine exposure test site to be borne entirely by research in the second and third categories, meaning that the use of the site would be at no cost to TxDOT-sponsored research projects. Therefore, the operational costs of the marine exposure test site would, from the beginning, include the costs of marketing the capabilities of the facility to organizations in the second and third categories.

SERVICES PROVIDED

Description of the Services

The marine exposure test site would provide space on the Texas gulf coast for locating test specimens at the designated proximity to the shoreline, or under other conditions as mutually agreed between the site operator (the contractor) and the user (the project manager or principal investigator for the experimental project). The site manager would also conduct maintenance, observations, measurements, and tests on the specimens as provided in the agreement between the site operator and the research project. The site operator might also have the ability to fabricate the sponsors' specimens to their specifications, on their request, thereby reducing transportation costs for experimental specimens.

The cost-recovery fee structure would consider the following criteria:

- size of the area required for specimen location, storage, and testing (based on location in the wetted zone, need for storage racks, number and weight of specimens);
- duration of testing;
- specialized equipment and instruments needed for testing;
- maintenance and cleaning of the specimens, as required;
- number and frequency of observations needed; and
- costs of making specimens (if applicable).

Other possible services include:

- access to or retrieval of data collected (measures and pictures) through a website,
- real time view of test specimens using remote control camera,
- consulting on test needs for customers, and
- providing weather information.

The Need the Facility Meets and Its Advantages

The Army NWES provides valuable information about deterioration under conditions in coastal Maine, including deterioration under freeze-thaw cycles (approximately 100 per year). This exposure certainly cannot be obtained in coastal Texas. However, the Army NWES personnel indicated an interest in comparing tests performed in Maine with those performed in Texas, because the higher temperatures and humidity in Texas greatly affect deterioration rates. In addition, the Navy AWTTS personnel expect that a Texas marine exposure test site would have accelerated chemical reactions, wetting/drying cycles, and diffusion of chemical elements into the concrete due to higher temperatures.

Therefore, the Army NWES, the Navy AWTTS, and the proposed Texas marine exposure test site are in many ways complementary rather than competitive, and there should be opportunities for research collaboration if the Texas site is built.

TARGET MARKET

Description of the Target Market

The target market for these experiments includes:

- Universities

  Universities with research contracts from TxDOT could use the Texas marine exposure test site to perform the tests required by research contracts.

- Other State DOTs (and Their Contractors)

  Other state DOTs and their contractors with needs for materials testing in marine environments identical or similar to the environment on the Texas gulf coast (either the gulf coast or the southern Atlantic coast). Other states having different weather and marine exposure conditions interested in testing their materials at the gulf coast site because the higher temperatures and humidity would accelerate deterioration, corrosion, coating failure, and other effects. An example would be the case of the Army NWES on Treat Island, Maine, which expressed an interest in testing under the accelerated conditions of the Texas gulf coast in order to obtain certain results sooner than would be possible in the Maine environment. Comparable tests performed in Maine and in Texas would provide valuable comparisons and calibration factors for the effects of temperature, humidity, and other environmental conditions.

- Vendors of Products

  Vendors having materials, systems, components or processes that are intended to increase service life and to reduce costs (degradation, deterioration, and corrosion) desiring to sell these products to TxDOT or other agencies and needing evidence of effectiveness. Some examples include: concrete admixtures (e.g., to reduce the rate of chloride diffusion, corrosion rate in concrete, or other deterioration mechanisms); non-corrosive steels (e.g., stainless steel coated reinforcement to raise the critical steel chloride corrosion threshold); and others such as coatings for metals and composite materials.

- Construction Contractors

  Contractors in the business of building state highways, bridges, and other transportation infrastructure or other facilities, particularly those projects located in the coastal zone. For TxDOT projects, TxDOT could establish its preference for building materials and construction processes tested and certified at the marine exposure test site. Contractors might expect some advantages in competition with other contractors by prior testing and qualification of their materials and processes at the marine exposure test site.

Identification of Trends that Influence Customer Needs

TxDOT, like many other state DOTs, is facing a fiscal squeeze in which demand for transportation facilities is increasing but funding is not (or may even be decreasing). Infrastructure is expected to cost less but to last longer, to reduce the life-cycle costs and to improve the users' satisfaction. Deterioration and corrosion of infrastructure materials destroy value and reduction of these parasitic losses is an obvious way to improve short- and long-term performance, as well as safety.

Identification of Characteristics of the Customer that Impact Purchasing Decisions

There are uncertainties about the customer needs even though many parties certainly have consensus about importance and necessity of making improvements in infrastructure facility durability problems. One of possible ways to promote customer needs is by developing cooperation with customers. When the type and specific purpose of customers' tests are compatible with or close to TxDOT test plans, the two parties could cooperate by paying expenditures and sharing test results together. All parties could be satisfied with reduced expenditures and efforts while attaining common goals. Thus, the critical task for this cooperation is to identify the test needs from customers that can be compatible with TxDOT objectives. The customers could be other state DOTs, research organizations, and vendors.

OPERATIONS AND CONTROL

Operating Characteristics of the Organization

The proposed test site will be owned by TxDOT and managed by a contractor to be selected by TxDOT. Researches and data collection will be performed by researchers and engineers. Meanwhile, routine maintenance and technical operation will be performed by a maintenance contractor and by technicians, respectively. Personnel positions would not necessarily be full-time positions, at least in the early phase of the proposed marine exposure test site. Growth in research could lead to some positions becoming full-time.

Facilities and Staff Needed

Facilities and staff would change based on site development and work contracted. The following personnel should be considered:

- site director or superintendent (on-site manager);
- materials engineers from universities;
- technicians (computers, electronic equipment, etc.);
- equipment operators;
- warehousemen; and
- laborers.

Capacity for Growth

Durability problems in infrastructure facilities are main interests by all state transportation agencies. When an improvement is realized as a result of research efforts at the proposed exposure test site, a significant consensus could be developed among other state agencies and in the construction market, especially building infrastructure facilities. If this is the case, there would be a need for expansion of the site. A reasonable size site would be preferred considering potential expansion in the future. Among the marine exposure test sites visited, the KSC CTLS has an expansion plan to have more beachfront exposure stands, which was shown in Figure 21 in Chapter 2.

TECHNOLOGY PLAN

Identification of Equipment and Technology Needs

As a new site, and particularly as an organization seeking additional work both inside and outside the state of Texas, the Texas marine exposure test site should make use of the best available technology. The model to follow is more along the lines of the NASA KSC CTLS in Cape Canaveral and the Navy AWTTS in Port Hueneme rather than the Army NWES on Treat Island, Maine. The proposed technology should include:

- advanced measurement instruments to, for example, evaluate reinforced concrete specimens to detect the amount of corrosion;
- automatic computer processing of measurements and environmental data;
- display of information on a website (when the client permits); and
- on-site laboratory.

Future Technology Improvements

By accumulating test data over a period of years, the Texas marine exposure test site could develop a database and provide it to the public on a website or for a fee. The Texas marine exposure test site could provide its users and sponsors with access to remote control cameras for visual inspection as well as access to databases.

MILESTONES

TxDOT needs to develop milestones based on long-term goals considering life-cycle of the Texas marine exposure test site.

Articulation of the Strategy to Achieve the Goals

A list of specified strategies includes:

- Development of a master plan for tests in accordance with TxDOT objectives with implementation plan for new technologies.
- Setting preference to materials and construction methods tested at Texas marine exposure test site. (Contractors and suppliers could be encouraged to test their materials and methods at the Texas marine exposure test site if they can obtain some advantages in competition for TxDOT projects.)
- Identifying common goals (especially type and purpose of potential tests) that can be shared between customers and TxDOT.
- Advertising and marketing to develop the publicity of the Texas marine exposure test site.
- Certificate on materials tested at Texas marine exposure test site: working with national institutes or organizations.
- Papers and presentations about the tests performed and any findings at Transportation Research Board (TRB), FHWA, and other conferences.

Establishment of Measurable Milestones

Milestones should be measurable in order to answer the question on whether the current situation and process is sufficient to reach the milestones established. Measurable milestones include:

- Development of a long-term master plan having multiple phases (multiple short-term plans) about tests to be performed (i.e., priority of tests) and implementation processes.
- Completion of obtaining the goals planned in each short-term plan.
- Establishment of a certificate program and setting preferences for TxDOT projects.
- Development of alliances with other exposure test sites.

FINANCIAL PROJECTIONS

The Texas marine exposure test site would have a long life-cycle, during which various tests are performed, relevant data and knowledge are accumulated, and new technologies are invented and implemented. Considering the life-cycle of the facility, long-term financial projections were made through cost-benefit analyses using the developed model. Chapter 6 provided detailed discussion about the analysis results. Also, an additional description on model parameter estimates is available in Appendix VI. This section provides a financial summary.

Projections of Establishment Costs

Assuming that a site will be selected among state-owned lands and there will be a long-term commitment by TxDOT for the basic support, no expenditures were projected as the land purchase costs and rent fee. The initial site development costs for equipment and construction of facilities were estimated to be about $2,750K and the duration of the development to be about one and a half years. Two-thirds of these costs would be spent during the first year of the development and the remaining amount in the next six months.

Projections of Operation and Maintenance Costs

The majority of site operation and maintenance costs would consist of labor costs assuming that TxDOT would support land and infrastructure for the site operation. Annual site operation costs and maintenance costs were estimated to be $175K and $75K, respectively. Thus, the average annual expenditure for site operation and maintenance sums to $250K.

Projections of Revenues

Relying on the results of the questionnaire from the existing exposure test sites and opinions from durability experts, average annual revenue was estimated to be about $37.5K. It was found that all existing sites do generate revenues but they are not large enough to make profits. Most revenues from user fees are spent for the site operation and maintenance costs. The questionnaire results about the operation/maintenance costs and annual revenues can be seen in Appendix VI.

Overall Profile of Costs at an Early Phase

A Texas marine exposure test site would have a generic profile of costs and benefits in its financial forecast as a research facility: first expenditures over time periods and then benefit realization later after some delay. The general types of costs and benefits associated with research facilities were discussed in Chapter 6. Figure 61 is a magnified part of Figure 58 in Chapter 6. It shows how much cost TxDOT would bear: net flow of costs and benefits before year 15.

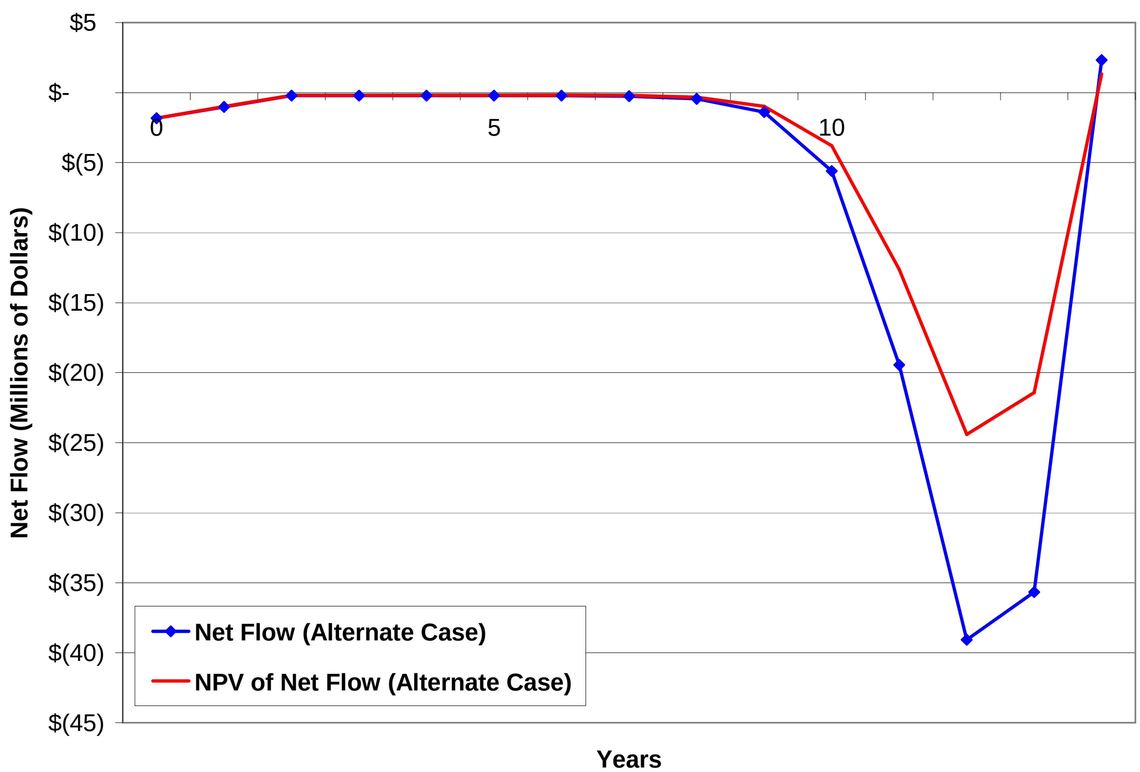


Figure 61. Net Flow of Costs before Year 15.

In Figure 61, there would be expenditures for the site development during the first one and a half years. Since then, TxDOT would have stable outflow (negative net flow) approximately $200K before new technologies are implemented. When the new technologies are invented and implemented (from around year 7) the outflow would start increasing because of the additional costs caused by implementing new technologies. Even though the increased cost level is anticipated to be lower after some delay as the new technologies are diffused more and it develops learning effects, the increasing outflow would be significant during five or six years before and after around year 12, as shown in the figure. TxDOT should be prepared for this significantly increasing outflow. As the benefits become greater than the costs, the net flow would become positive.

Annual Funding Required

Based on the results of the cost-benefit analyses, Table 18 summarizes financial projections. Contents (the expected time periods and expenditures) of the table can be identified in the Figure 61. These projections are subject to uncertainties that include the following (detailed descriptions about these uncertainties were provided in Chapter 6):

- lead time to the implementation of new technologies,
- diffusion rate of new technologies, and
- changes in the construction and rehabilitation costs by new technologies.

Table 18. Financial Projection in Various Phases.

Phase		Expected Time Period	Expected Funding Required
Site Development		Year 0 ~ Year 1.5	$2,750K
Initiation of Site Operation		Year 1.5 ~ Year 2	$100K / year
Normalization of Site Operation		Year 2 ~ Year 6	$200K / year
Implementation and Diffusion of New Technologies	**Early Phase**	Year 7 ~ Year 12	$200K / year → $40M / year
	Middle Phase	Year 12 ~ Year 14	$40M / year → $0 / year
Realization of Apparent Monetary Benefits		after Year 14	Net flow becomes positive

Projection of Break-Even Point

The break-even point can be estimated using the cumulative flow of costs and benefits, which is the accumulation of net flows of costs and benefits. The cumulative flow is shown in

Figure 62, which is actually a magnified part of Figure 59. The figure has a shorter period of time in order to show a detailed profile of cumulative flow and the break-even point.

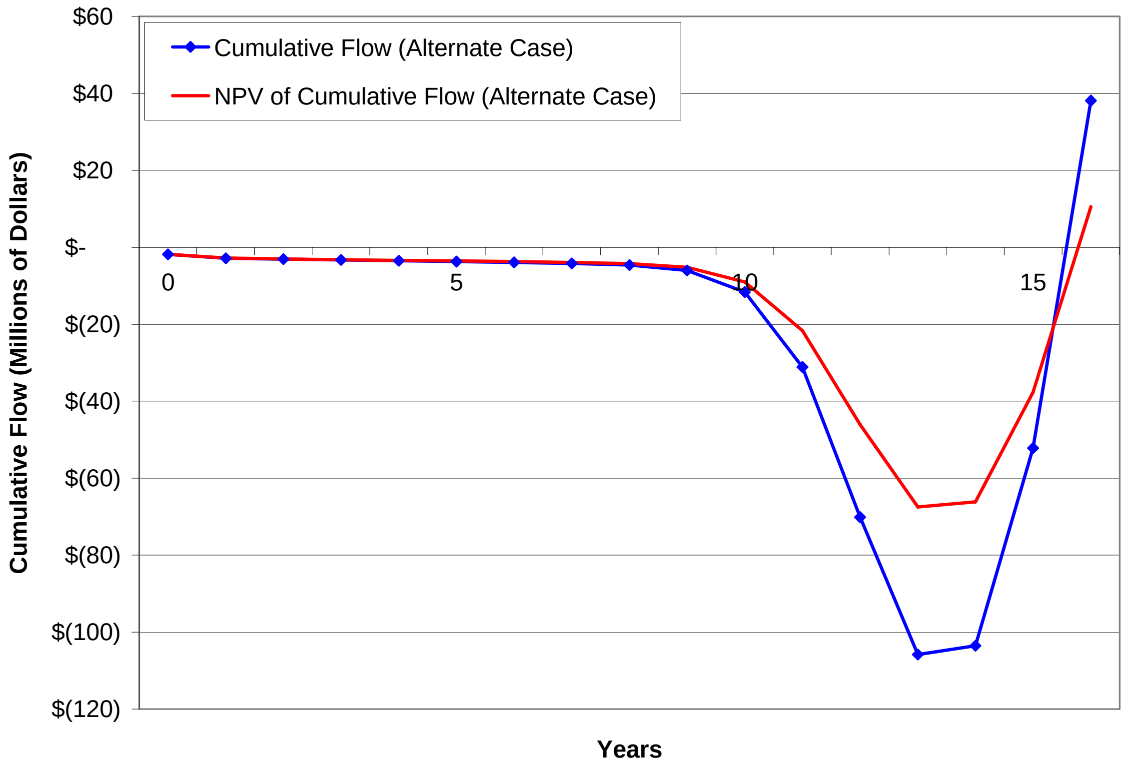


Figure 62. Cumulative Flow of Costs before Year 17.

In Figure 62, after the development of the Texas marine exposure test site, negative flows would be accumulated for more than 10 years before the apparent monetary benefits are realized. Due to the realized benefits accumulated since then, the cumulative flow that has been negative would become positive around year 16, which is the break-even point. The later benefits including intangible benefits could be more significant after the break-even point compared with the amount of cumulative expenditures TxDOT should bear until the break-even point. However, the duration until the break-even point and delays until the realization of more significant benefits are not negligible. Therefore, TxDOT should make a long-term commitment to realize significant benefits.

CHAPTER 8. CONCLUSIONS

IDENTIFICATION OF DURABILITY CHALLENGES AND THE CURRENT CONDITION OF TEXAS TRANSPORTATION FACILITIES

Materials commonly used in transportation infrastructure facilities are susceptible to a number of adverse environmental conditions, resulting in loss of performance due to alkali silica reaction, delayed ettringite formation, external sulfate attack, steel corrosion, and other natural deterioration mechanisms. Some of these mechanisms have been studied for some time, and some (e.g., ASR) have been discovered relatively recently. Therefore, there has been a trend in which the annual expenditures for replacement, rehabilitation, and repair of these deteriorated facilities can exceed the expenditures on new construction. Moreover, tighter budgets for transportation infrastructure put pressure on state transportation departments to choose between new construction and replacement or repair of existing deteriorated facilities.

ESTIMATE OF THE COSTS OF DETERIORATION AND CORROSION

This project shows that the best estimate for the annual direct costs of corrosion and deterioration for the state of Texas transportation infrastructure is $2 billion per year, a very substantial number. Indirect costs are estimated to be of the order of $12 billion per year in Texas, due to delays, increased fuel consumption, and inconveniencing the traveling public. These indirect costs, of course, translate into public dissatisfaction with the transportation system. Therefore, reductions in deterioration and corrosion of transportation materials through development of advanced materials and processes would be a highly cost-effective step toward reduction of this ongoing problem.

TxDOT manages the largest single state volume of transportation facilities in the United States, and among TxDOT's stated goals are the improvement of the condition metrics for Texas transportation infrastructure facilities and, in particular, the elimination of structurally deficient bridges. Therefore, alternative approaches, involving the development of materials and systems with longer service lives and lower life-cycle costs, are necessary in order to achieve TxDOT's ambitious goals.

INVESTIGATION OF THE EXISTING MARINE EXPOSURE TEST SITES IN THE UNITED STATES

The research team visited the three existing marine exposure test sites in the United States:

- NASA Kennedy Space Center Corrosion Technology Laboratory Site, Florida;
- U.S. Army Corps of Engineers Natural Weathering Exposure Station, Treat Island, Maine; and
- U.S. Navy Facilities Command Advanced Waterfront Technology Test Site.

These three sites have the following somewhat different missions.

- The Army NWES site has cold winter temperatures and frequent freeze-thaw cycles (about 100 per year).
- The KSC CTLS concentrates on tests of metallic corrosion on the beach near the Atlantic Ocean at Cape Canaveral.
- The Navy AWTTS performs reduced-scale or full-scale tests on infrastructure materials and components directly in the waters of the Pacific Ocean.

However, it was apparent from the discussions at the sites that none of the existing sites could duplicate the unique and severe hot, humid, and stormy environmental conditions on the Texas gulf coast. Therefore, it is felt that the proposed Texas site would be more complementary than competitive with the existing sites. In fact, the managers of all three sites offered to collaborate with TXDOT, if a Texas marine exposure test site is developed, to compare their results under their conditions with the more aggressive environmental conditions in Texas. The research team concludes that such collaboration would benefit the proposed Texas marine exposure test site.

It was determined from these visits that, although the Army NWES and Navy AWTTS sites perform services for others at a fee, no site has sufficient external revenues to do more than break even on operations and maintenance costs. None of these sites amortizes capital development costs, as various government agencies own the land and facilities. However, it was also noted that there is little publicity or promotion of these sites among possible research sponsors (e.g., state departments of transportation or commercial vendors), as the sites have little incentive to do so, and that a more aggressive approach by a Texas marine exposure test site might be more successful in building external revenues.

Based on the site visits, the research team identified the support facilities, equipment, and other factors that would be necessary or desirable for a Texas marine exposure test site.

The research team also developed a site evaluation matrix with sixteen success factors. The three marine exposure test sites were evaluated using this matrix, in most cases by the managers of these facilities themselves, to establish a baseline for comparison of proposed new sites with the existing marine exposure test sites. This comparison provides valuable information on how to establish, operate, and maintain such a marine exposure test site and the factors critical to its success.

EVALUATION OF POTENTIAL SITES

The research team identified a total of twelve sites on the Texas shore as potentially suitable for a Texas marine exposure test site as follows.

- ten sites owned by the state were identified through contacts with the Texas General Land Office,
- The University of Texas Marine Science Institute at Port Aransas, and
- the Marine Engineering Research Center (MERC) at Texas A&M University at Galveston on Pelican Island.

The project researchers visited three of the ten state-owned sites identified through the GLO and the UTMSI. Information on the MERC site was provided by faculty members at TAMUG.

The three sites visited from those identified by the GLO were not rated highly in the evaluation matrix, largely due to the lack of support facilities and lack of control over access to the shoreline. The sites at MERC and UTMSI were ranked higher due to the existing support infrastructure and control of access by the public.

COST-BENEFIT ANALYSIS

To estimate the value of the proposed Texas marine exposure test site, several cost-benefit analyses were run. The analyses evaluated the net present value for the proposed marine exposure test site under various benefit conditions, including increase in facility service life in the coastal zone, increase in time between repairs for facilities in the coastal zone, and reduction in structurally deficient bridges. In all cases the estimates are considered to be conservatively lower bounds on the savings or net present value. The results show that there are substantial returns on the investment in the Texas marine exposure test site, with break-even times ranging from four or five years upward, depending on the situation. (An increase in time between repairs due to improved repair materials and processes has a faster payback period than an increase in the service life of new facilities, for example.)

DEVELOPMENT OF MANAGEMENT PLAN

A draft management plan has been prepared by the project team. As the final site has not been selected, it is not possible to estimate accurately the costs of establishing the proposed Texas marine exposure test site. Selection of one of the greenfield sites identified by the GLO would require the capitalization of much more support infrastructure than the selection of MERC or UTMSI.

FINDINGS

The project team, based on the information obtained and studies performed, as described above, have several findings:

- TxDOT should identify a single best site for this facility.

- TxDOT should prepare a definitive cost estimate for the site and the support facilities, based on the site selected.
- TxDOT should prepare a research plan for the investigation, development, and deployment of improved materials and processes to reduce deterioration and corrosion in Texas transportation facilities.
- TxDOT should contract with some entity for the establishment, operation, and maintenance of the Texas marine exposure test site.
- The selected contractor should prepare and submit to TxDOT a:
  - research plan,
  - management plan,
  - marketing plan, and
  - technology deployment plan for the implementation of the materials and processes developed.

To reduce the future costs of deterioration and corrosion for the Texas transportation infrastructure, existing and proposed, TxDOT should establish the Texas marine exposure test site as soon as possible.

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APPENDICES

APPENDIX I. DATA ON TEXAS BRIDGES

Texas bridges are classified into two system bridges: 1) on-system bridges and 2) off-system bridges. This appendix provides historical data on both types of Texas bridges. There are three types of information presented in Table I.1 through Table I.7:

- number of bridges,
- replacement/rehabilitation projects let (the number of bridges and funds), and
- new-location bridge construction projects let (the number of bridges and funds).

The information in these tables came from the following two data sources: *Bridge Facts* (*1*) and *Report on Texas Bridges* (*5, 6, and 7*).

Number of Bridges

Table I.1. Number of on-System Bridges.

	2002		2003		2004		2006	
	No.	**Percent**	**No.**	**Percent**	**No.**	**Percent**	**No.**	**Percent**
Total	32,010	100.0	32,206	100.0	32,287	100.0	32,674	100.0
Sufficient	27,431	85.7	27,665	85.9	27,660	85.7	28,135	86.1
Structurally Deficient	688	2.1	645	2.0	565	1.7	483	1.5
Functionally Obsolete	3,661	11.4	3,701	11.5	3,888	12.0	3,951	12.1
Substandard-for-load-only	204	0.6	184	0.6	151	0.5	105	0.3
Not classified	No Info	No Info	11	0.0	23	0.1	No Info	No Info

Table I.2. Number of off-System Bridges.

	2002		2003		2004		2006	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Total	16,206	100.0	16,251	100.0	16,633	100.0	17,155	100.0
Sufficient	8,594	53.0	8,744	53.8	9,414	56.6	10,358	60.4
Structurally Deficient	2,117	13.1	2,033	12.5	1,851	11.1	1,642	9.6
Functionally Obsolete	3,746	23.1	3,776	23.2	3,808	22.9	3,851	22.4
Substandard-for-load-only	1,701	10.5	1,651	10.2	1,508	9.1	1,304	7.6
Not classified	No Info	No Info	47	0.3	52	0.3	No Info	No Info

Table I.3. Number of Total Bridges.

	2002		2003		2004		2006	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Total	48,216	100.0	48,457	100.0	48,920	100.0	49,829	100.0
Sufficient	36,025	74.7	36,409	75.1	37,074	75.8	38,493	77.3
Structurally Deficient	2,805	5.8	2,678	5.5	2,416	4.9	2,125	4.3
Functionally Obsolete	7,407	15.4	7,477	15.4	7,695	15.7	7,802	15.7
Substandard-for-load-only	1,905	4.0	1,835	3.8	1,659	3.4	1,409	2.8
Not classified	68	0.1	58	0.1	75	0.2	No Info	No Info

Replacement/Rehabilitation Projects Let: The Number of Bridges and Funds Allocated

Table I.4. Replacement/Rehabilitation Projects Let, on-System Bridges.

<table>
<tr><th></th><th>2002</th><th>2003</th><th>2004</th><th>2006</th></tr>
<tr><td>Replacement/Rehabilitation (HBRRP*-funded)</td><td>79</td><td>95</td><td>69</td><td>No Info</td></tr>
<tr><td>Replacement/Rehabilitation (Non-HBRRP-funded)</td><td>186</td><td>246</td><td>223</td><td>399</td></tr>
<tr><td>Total</td><td>265</td><td>341</td><td>292</td><td>399</td></tr>
<tr><td>Replacement/Rehabilitation (HBRRP-funded)</td><td>$84.3M</td><td>$220.5M</td><td>$87.1M</td><td rowspan="2">No Info</td></tr>
<tr><td>Replacement/Rehabilitation (Non-HBRRP-funded)</td><td>$153.7M</td><td>$406.0M</td><td>$362.5M</td></tr>
<tr><td>Total</td><td>$238.0M</td><td>$626.5M</td><td>$449.6M</td><td>$489.1M</td></tr>
</table>

*** HBRRP: Highway Bridge Replacement and Rehabilitation Program**

Table I.5. Replacement/Rehabilitation Projects Let, off-System Bridges.

<table>
<tr><th></th><th>2002</th><th>2003</th><th>2004</th><th>2006</th></tr>
<tr><td>Replacement/Rehabilitation (HBRRP-funded)</td><td>125</td><td>134</td><td>153</td><td rowspan="2">150</td></tr>
<tr><td>Replacement/Rehabilitation (Non-HBRRP-funded)</td><td>3</td><td>14</td><td>10</td></tr>
<tr><td>Total</td><td>128</td><td>148</td><td>163</td><td>150</td></tr>
<tr><td>Replacement/Rehabilitation (HBRRP-funded)</td><td>$28.6M</td><td>$32.4M</td><td>$45.6M</td><td rowspan="2">No Info</td></tr>
<tr><td>Replacement/Rehabilitation (Non-HBRRP-funded)</td><td>$0.6M</td><td>$11.2M</td><td>$9.7M</td></tr>
<tr><td>Total</td><td>$29.2M</td><td>$43.6M</td><td>$55.3M</td><td>$55.4M</td></tr>
</table>

Table I.6. Replacement/Rehabilitation Projects Let, Total Bridges.

	2002	2003	2004	2006
Replacement/Rehabilitation (HBRRP-funded)	204	229	222	No Info
Replacement/Rehabilitation (Non-HBRRP-funded)	189	260	233	
Total	393	489	455	549
Replacement/Rehabilitation (HBRRP-funded)	$112.9M	$252.9M	$132.7M	No Info
Replacement/Rehabilitation (Non-HBRRP-funded)	$154.3M	$417.2M	$372.2M	
Total	$267.2M	$670.1M	$504.9M	$544.5M

New-Location Bridge Construction Projects Let: The Number of Bridges and Funds Allocated

Table I.7. New-Location Bridge Construction.

	2002	2003	2004	2006
on-System Bridges	163	300	252	236
	$317.4M	$697.5M	$432.0M	$403.0M
off-System Bridges	14	5	8	13
	$11.0M	$2.3M	$7.3M	$26.9M
Total	177	305	260	249
	$328.4M	$699.8M	$439.3M	$429.9M

APPENDIX II. DATA ON TEXAS HIGHWAYS

Texas highways are classified by pavement type: 1) flexible or asphalt concrete pavement (ACP); 2) continuously reinforced concrete pavement (CRCP); and 3) joint concrete pavement (JCP). This appendix provides historical data on Texas highways. There are six types of information presented in Table II.1 through Table II.6:

- lane miles by pavement type,
- condition of highways by pavement type,
- comparison of different types of pavement,
- pavement needs for Texas highways,
- pavement needs by pavement type, and
- estimate and actual costs for maintenance.

Data were obtained from three sources: *Construction Division - Pocket Facts* (2), TxDOT *Annual Financial Report (11), and Condition of Texas Pavements* (12). The data from *Condition of Texas Pavements* cover 4 years from 2003 to 2006.

Table II.1. Lane Miles by Pavement Type.

	2003		2004		2005		2006	
Pavement Type	**Lane Miles**	**Percent**	**Lane Miles**	**Percent**	**Lane Miles**	**Percent**	**Lane Miles**	**Percent**
Flexible or Asphalt Concrete Pavement	176,774	93.0	175,807	92.7	177,072	92.5	177,399	92.3
Continuously Reinforced Concrete Pavement	9,119	4.8	9,426	5.0	9,940	5.2	10,270	5.3
Jointed Concrete Pavement	4,118	2.2	4,344	2.3	4,403	2.3	4,445	2.3
Statewide	190,011	100.0	189,578	100.0	191,415	100.0	192,113	100.0

Table II.2. Condition of Highways by Pavement Type.

		2005		2006	
Pavement Type	**Condition**	**Lane Miles**	**Percent**	**Lane Miles**	**Percent**
Flexible or Asphalt Concrete Pavement	Very Good	133,937.2	75.64	132,073.3	74.45
	Good	23,107.9	13.05	24,090.7	13.58
	Fair	13,510.6	7.63	14,440.3	8.14
	Poor	3,895.6	2.20	4,044.7	2.28
	Very Poor	2,585.2	1.46	2,749.7	1.55
	Sum	**177,036.5**	**100.0**	**177,398.7**	**100.0**
Continuously Reinforced Concrete Pavement	Very Good	7,084.5	71.27	7,183.7	69.95
	Good	1,271.4	12.79	1,352.5	13.17
	Fair	785.3	7.90	784.6	7.64
	Poor	374.7	3.77	424.1	4.13
	Very Poor	424.5	4.27	525.8	5.12
	Sum	**9,940.3**	**100.0**	**10,270.8**	**100.0**
Jointed Concrete Pavement	Very Good	1,880.1	42.70	1,777.4	39.99
	Good	687.8	15.62	736.0	16.56
	Fair	646.8	14.69	603.6	13.58
	Poor	383.1	8.70	416.0	9.36
	Very Poor	805.3	18.29	911.6	20.51
	Sum	**4,403.1**	**100.0**	**4,444.5**	**100.0**

Table II.3. Comparison of Different Types of Pavement.

	Percent of the TxDOT-Maintained Lane Mileage	**Percent Capacity of the Vehicle Miles Traveled**	**Percent of Total Pavement Needs (Funds)**
Flexible or Asphalt Concrete Pavement	92.34	72.62	60.50
Continuously Reinforced Concrete Pavement	5.35	21.99	25.22
Jointed Concrete Pavement	2.31	5.39	14.28

Table II.4. Pavement Needs for Texas Highways.

Pavement Type	Pavement Needs	2005 Million Dollars	2005 Percent	2005 Lane Miles	2005 Percent	2006 Million Dollars	2006 Percent	2006 Lane Miles	2006 Percent
Total Pavement	Preventive Maintenance	$329	20.7	51,682	27	$295	17.3	46,107	24
	Light Rehab	$256	16.1	11,485	6	$271	15.9	11,527	6
	Medium Rehab	$496	31.2	7,657	4	$555	32.5	9,606	5
	Heavy Rehab	$511	32.1	1,914	1	$585	34.3	1,921	1
	Total	**$1,592**	**100.0**	**72,738**	**38**	**$1,706**	**100.0**	**69,161**	**36**

Table II.5. Pavement Needs by Pavement Type.

		2005		2006	
Pavement Type	**Pavement Needs**	**Million Dollars**	**Percent**	**Million Dollars**	**Percent**
Flexible or Asphalt Concrete Pavement	Preventive Maintenance	$328	33.5	$294	28.5
	Light Rehab	$181	18.5	$198	19.2
	Medium Rehab	$293	29.9	$319	30.9
	Heavy Rehab	$178	18.2	$220	21.3
	Subtotal	**$980**	**100.0**	**$1,031**	**100.0**
Continuously Reinforced Concrete Pavement	Preventive Maintenance	$ 0	0.0	$ 0	0.0
	Light Rehab	$29	7.5	$32	7.4
	Medium Rehab	$100	25.9	$119	27.7
	Heavy Rehab	$257	66.6	$279	64.9
	Subtotal	**$386**	**100.0**	**$430**	**100.0**
Jointed Concrete Pavement	Preventive Maintenance	$1	0.4	$1	0.4
	Light Rehab	$46	20.4	$41	16.8
	Medium Rehab	$103	45.6	$116	47.5
	Heavy Rehab	$76	33.6	$86	35.2
	Subtotal	**$226**	**100.0**	**$244**	**100.0**

Table II.6. Estimate and Actual Costs for Maintenance.

Year	Interstate Highways		Other Highways		Highways Total	
	Estimate	Actual	Estimate	Actual	Estimate	Actual
2002	$210.0M	$386.0M	$1,444.0M	$1,489.7M	$1,654.0M	$1,875.8M
2003	$400.0M	$330.8M	$1,450.0M	$1,483.2M	$1,850.0M	$1,814.0M
2004	$400.0M	$383.9M	$1,450.0M	$1,378.9M	$1,850.0M	$1,762.8M
2005	$314.0M	$427.1M	$1,590.4M	$1,604.8M	$1,904.4M	$2,031.9M
2006	$469.8M	$434.1M	$1,608.0M	$1,750.4M	$2,077.8M	$2,184.5M

APPENDIX III. QUESTIONNAIRE RESPONSES

NASA KSC Corrosion Technology Laboratory Site in Cape Canaveral, Florida

Table III.1. Evaluation of Success Factors [NASA KSC].

No.	Success Factors	Relative Importance (0: least ~ 10: most)
1	Size of site	10
2	Site locations/conditions	10
3	Site proximity to civilization, etc.	5
4	All-weather road access	10
5	Shore conditions (water surface, beach, tide)	No score
6	Protection against hurricanes and flooding	10
7	Access to equipment (handling equipment, etc.)	10
8	Utilities	9-10
9	Site security/absence of interfering activities	10
10	General test conditions (weather, etc.)	10
11	Specimen housing facilities	10
12	Site docking facility	0
13	on-site laboratory	10
14	on-site weather station	10
15	on-site web-based camera system	10
16	Any other factors	Long-term commitment

Table III.2. Site Characteristics [NASA KSC].

Category	Questions and Answers
Site Characteristics	
Geographical Characteristics	
Size of site	What are the types of tests being performed at your site? Please provide a list of these tests. Atmospheric corrosion, UV degradation, rebar corrosion, seawater immersion and spray down. What are their approximate capacities (maximum number of specimens)? The site currently has 200+ stands with racks that hold 75- 4 inch × 6 inch test panels contained in a 20,000 sq ft fenced area and a 3000 sq ft fenced seawater immersion test site with two immersion tanks that have continuous once-through, filtered supply of seawater. What are the most performed tests and the least performed tests? Coating and material evaluations are most performed. Do you have a plan for future expansion? If so, what is the reason for the expansion? Yes, there is a need for more beachfront exposure stands.
Site locations/ conditions	What are site location characteristics that make your exposure test site successful? Close proximity to launch sites and beach. How was site chosen? What factors (salinity, temperature, etc.) went into the selection? Similar environment to launch complexes. What was the goal? Long-term exposure of protective coatings and corrosion resistant material testing for use at the Kennedy Space Center. What were the advantages/disadvantages of each location? N/A What would you have done differently? N/A
Distance to public roads	What is the distance to the highway and roadway? The lab and outdoor site is located within 200' of a paved road. Is it an influential factor for success? Yes
All-weather road access	Do you have all-weather road access to your site? Yes What is the load limit of the road? Unlimited
Distance to shoreline	What is the distance of the test area to the shoreline? 100 ft from mean high tide. Is this an influential factor for site operation? Distance from the water is directly related to corrosion rate of site. How far inland is practical for specimen testing? Tests show three times the mass loss of uncoated steel panels at the 100 ft site than at a site 1000 ft inland. How much shoreline and distance back from the shore is necessary? Dependant on how corrosive the site needs to be.

Table III.2. Site Characteristics [NASA KSC] (continued).

Category	Questions and Answers
Site Characteristics	
Geographical Characteristics	
Slope of shore	What is the approximate slope of the shore at your site? N/A How does the slope of the shore affect site operations? N/A
Tide differential	Is tide differential an important test condition? No What is the maximum tide differential? N/A
Protection against hurricanes/flooding	Has your group taken any special precautions to protect your site against natural disaster? Yes, we have a hurricane evacuation plan. Has your site ever experienced a natural disaster? Yes If so, what was it and what happened? Hurricanes and tropical storms. The plan calls for complete evacuation of all test articles inland to a secure location until the storm passes and the site is given an all clear. Do you have any lessons learned from it? Order and stock hurricane supplies (gloves, bubble wrap, tape, rope, mosquito spray, etc.) It is very helpful if the same personnel are available from previous evacuations.
Access to equipment	Does your site have any characteristics that impede use (efficiency) of equipment? No If so, what are they? N/A
Non-geographical Characteristics	
Utilities	Which kinds of utilities are used at your site? Computer networks, telephones, electricity, potable water. Please list available utilities. All listed above.
Site security	Do you have any problems with site security? No, the site is located in a secure area. If so, what are they? How are you resolving these? N/A Does your site have a surveillance camera? Yes
Interfering activities	Do you have any interfering activities (e.g., people from beach, etc.) at your site? Launches If so, how do you handle the interfering activities? From time to time the road to the site is closed due to scheduled launches, this is resolved by scheduling visits around the launch dates.
General condition	Have you ever identified specific site conditions that result in challenges during testing? Rain, heat, and mosquitoes. If so, please provide explanation.

Table III.3. Management [NASA KCS].

Category	Questions and Answers
Management	
Management plan	
Business goal	What was the original goal of the test site? How is this goal being met? Work on corrosion issues at KSC began in the 1960s with the evaluation of long-term protective coatings for the atmospheric protection of carbon steel. NASA established the KSC Beachside Atmospheric Exposure Test Site at that time. The site has provided over 40 years of information on the long-term performance of many materials. The Atmospheric Exposure Test Site is located at latitude 28.7° N, longitude 80.6° W, and is approximately 100 feet from the high tide line directly on the Atlantic Ocean. The site has approximately 600 feet of front row exposure for atmospheric corrosion specimens. Many types of test samples can be accommodated, including standard size test coupons (4 inch × 6 inch), stress corrosion cracking specimens and full-scale test articles. These experiments can be performed in either a boldly exposed or sheltered configuration. Both power and data connections are available within the site to power test articles and record onboard data instrumentation outputs. Over the years, thousands of coated test panels, stress corrosion cracking specimens, non-metallic materials, and commercially produced products have been evaluated in the high salt, high humidity, and high ultraviolet Florida seacoast environment. Results from these evaluations have helped KSC find new materials and processes that increase the safety and reliability of our launch structures and ground support equipment. A weather station that provides continuous information on air temperature, humidity, wind direction and speed, rainfall, total incident solar radiation, and incident Ultraviolet B radiation levels is located at the site. How does management assess the success and/or continued effectiveness of having the test site? N/A
Demand	What kinds of users (public/private users) perform tests at your site? NASA partners with Federal and state government agencies, with U.S. businesses, and with universities through agreements where each partner provides resources such as funding, facilities, or expertise, to achieve a common goal. Do you have a source of funds other than the primary funding from your agency? Infrastructure support is provided by NASA. Other funding is secured through contractual arrangements with federal agencies and industry partners.

Table III.3. Management [NASA KSC] (continued).

Category	Questions and Answers
Management	
Management plan	
Revenues	What is the annual revenue generated from site operations? Please provide the amount. <u>N/A</u> Do you have a standardized fee structure? If so, please provide a description. <u>Yes and no. A standardized fee structure is in place for repetitive operations. For instance, a per panel cost for exposure is easily standardized. Often, tests specific to the needs of the customer are required and the cost is based upon projected labor and other costs.</u> Do you think your fee structure is profitable enough? <u>N/A</u> Do you think your fee structure is affordable to your users? <u>Yes, it is comparable and competitive to other sites.</u> Do you think user demand is sensitive to the fees? <u>N/A</u> What is your typical contract method? <u>Contracts with individual companies, Department of Defense, and other NASA programs.</u>
Capital costs	How much did your agency spend in the development of your site? <u>N/A</u> How long did it take to develop your site? <u>Work on corrosion issues at KSC began in the 1960s with the evaluation of long-term protective coatings. Renovations, additions and capital improvements have occurred from 1960 – present.</u> Are there detailed data about the development costs of your site? If so, please provide a copy. <u>Detailed development costs would be difficult or impossible to obtain for capital expenditures.</u>
Expenditures	What is the annual expenditure? <u>N/A</u> What are the major elements of the annual expenditures? Please provide their amounts by element. <u>N/A</u>
Long-term commitment	When was your site developed? <u>From the 1960s to present.</u> Does your agency provide internal support? If so, what type of support are you provided? <u>Infrastructure support. Funding for personnel is provided through specific projects.</u> Provide detailed information about the support from your agency. Please specify the annual amount of financial support (the primary funding from your agency). <u>N/A</u> Are there other financial needs beyond the financial support from your agency? If so, please specify what they are and how they are resolved? <u>Infrastructure support is provided by KSC. Otherwise, salaries are funded through specific projects from NASA, outside federal agencies and industry partners.</u>
Annual report	Does your site produce annual reports? If so, please provide a copy. <u>No</u>

Table III.3. Management [NASA KSC] (continued).

Category	Questions and Answers
Management	
Operation & Maintenance	
Ownership	Are owner and operator separate organizations? If so, what is the reason for the separation? Owned by NASA. Operated by contracting personnel.
Operation	Does your site outsource work? Not usually. If so, what work is outsourced? If so, what is the general process of outsourcing? N/A
Maintenance	Does your site have a scheduled maintenance plan for facilities and equipment? Yes. Infrastructure maintenance is provided by NASA/KSC and performed by contracting personnel. What are the major maintenance activities for facilities and equipment? No answer given
Testing and data collection	What are the cycles of tests (the longest, the shortest, and the average test durations)? Typical tests are as long as seven years, and as short as one month. The NASA 5008 standard requires that coatings are subject to a 1.5 year atmospheric exposure for qualification, and 5 years to remain on the qualified products list. How often are specimens observed and data recorded? Some samples require data collection every two weeks. Other samples are exposed for longer durations (6 months to 1 year) before data are collected. Weather data are recorded in 20-minute intervals. How are results documented, organized, maintained, and distributed? Generally, documentation, organization of data, and distribution are made per the customer's requirements. One customer may be satisfied with a final report. Others may require updates throughout the life of the project. Reports and data are collected and stored in accord with ISO 9001 documented procedures.
Marketing plan	Is the exposure test site marketed? Yes If so, how? Through a website, conferences, and federally funded meetings. Is the marketing effective? N/A
Emergency plan	Does your site have an emergency response plan? Yes If so, which kinds of emergencies are under the plan? The site has a hurricane evacuation plan. Has your site ever experienced an emergency situation other than a natural disaster? No If so, what was it and what happened? N/A Do you have any lessons learned from it? N/A

Table III.3. Management [NASA KSC] (continued).

Category	Questions and Answers
Management	
Organization	
Organizational chart	Does your site have an organizational chart? No If so, please provide a copy. What are the type and the number of technicians? N/A Are there any other personnel? If so, please describe their general duties. Three contracting employees including two engineers and a Ph.D. Chemist. Three NASA civil servants. All three are Ph.D. chemists.

Table III.4. Facilities [NASA KSC].

Category	Questions and Answers
Facilities	
Site map	Do you have a map of your site? Yes If so, please provide a copy.
Specimen housing facilities	
Location	How many specimen housing facilities (exposure test places: rack/beach) does your site have? The site currently has 200+ stands with racks that hold 75- 4 inch × 6 inch test panels contained in a 20,000 sq ft fenced area. The seawater immersion test site backs up to the atmospheric test site and can accommodate four more test stands for seawater spray down capability. If your site has multiple specimen housing facilities, why are they separated? N/A Where are they located? All the atmospheric exposure and spray down capabilities are located in the same vicinity. Is there any preferred condition for a good location? If so, what is it? For corrosion high humidity, high salt, and UV radiation. For seawater immersion or spray close to seawater would be preferable.
Capacity	What is the capacity (maximum number of specimens) of (each of) the facilities? See above.
Maintenance of specimens	How are the specimens cleaned and how often? For corrosion rates and pitting characteristics the uncoated panels are cleaned and evaluated in accordance with ASTM (American Society for Testing and Material) G1. Typically panels are exposed for a one-year period.
Technical needs	Are there any specific technical needs for specimen housing facilities? N/A What kind of inspection/testing and data recording is done and how often? Visual inspections using ASTM standards such as D1654, D610, and D714, are used for coating evaluations. Inspections are performed according to each specific project.
Site docking facility	
Location	Does your site have a docking facility? No If so, what is the location of it with respect to other facilities? Is there any preferred condition for a good location? If so, what is it? N/A
Capacity	What is the size (sq ft) of your docking facility? N/A
Technical needs	Are there any specific technical requirements for a docking facility? No

Table III.4. Facilities [NASA KSC] (continued).

Category	Questions and Answers
Facilities	
on-site laboratory	
Location	Does your site have an on-site laboratory? Yes If so, what is the location of it with respect to other facilities? In the same vicinity of the exposure test sites. Is there any preferred condition for a good location? If so, what is it?
Type of tests and capacity	What kinds of tests are performed at your on-site laboratory? Electrochemistry, data acquisition, photo documentation. What is the capacity (number of samples or sq ft) of your on-site laboratory? 1,000 samples
Measuring equipment	What kinds of measuring equipment do you have, please list type. Data acquisition hardware, video camera network, weather station, etc. Is this generally sufficient? Yes
Technical needs	Are there any specific technical requirements for an on-site laboratory? N/A
On-site weather station	
Location	Does your site have an on-site weather station? Yes If so, what is the location of it on your site? It is located near the center of the outdoor exposure test site. Is there any preferred condition for a good location? Yes If so, what is it? Near the exposed test panels.
Technical needs	What kinds of parameters do the weather station measure? Continuous online monitoring of the following parameters is recorded and can be transmitted to any location: - Temperature - Humidity - Wind speed and direction - Rainfall - Total incident solar radiation UVB radiation. How are data recorded and how are they tied into test operations? The data are stored on a data logger and downloaded each night onto a server where they are stored and can be accessed for inclusion to other formats or experiments using commercial data analysis software. Are there any specific technical needs for an on-site weather station? No answer given

Table III.4. Facilities [NASA KSC] (continued).

Category	Questions and Answers
Facilities	
Web-based camera system	
Usages and benefits	Does your site have a web-based camera system? Yes If so, what are the benefits from it? Customers have the ability to see how their product performs in "real time." The cameras are also useful to ensure the safety of personnel and operability of mechanical devices. And, how many cameras are in operation? Five outside. One in the laboratory.
Technical needs	Are there any specific technical needs for a web-based camera system? High resolution and an indoor facility to house the video servers and computers.
Warehouse	
Usages	Does your site have a warehouse? Yes If so, is it regularly used? And, what is the usage of it? It is used for archiving past experiments and hurricane evacuations.
Location	Is there any preferred condition for a good location? Yes If so, what is it? Inland far enough to prevent damage to stored items.
Other facilities	Does your site have any other facility not in our list above? Yes If so, what is it? Please provide a description of the facility. The Corrosion Technology Laboratory at the NASA Kennedy Space Center is a network of capabilities – people, equipment, and facilities that provide technical innovations and engineering services in all areas of corrosion for NASA and external customers. It consists of a Corrosion Laboratory, Beach Corrosion Test Site, Coating Application Laboratory, Accelerated Corrosion Laboratory, and Photo documentation Facilities.
Locational relationship	How does locational relationship of those facilities affect the overall efficiency of operations? Overall efficiency would increase if all sites were closer to each other. The close proximity of the atmospheric test site to other facilities is important. Travel to the location is necessary to deliver and retrieve samples, take data, and maintain/repair equipment. Long travel times would increase labor costs.

Table III.5. Equipment [NASA KSC].

Category	Questions and Answers
Equipment	
Type of vehicles	What kinds of vehicles are used at your site? Please list type and number. Ford van (enclosed vehicle) – 1. Dodge ram pickup truck – 1. Dodge Ram flatbed – 1. Does your site have any special vehicles? If so, what are they and what are their uses? No
Type of equipment	What kinds of equipment are used at your site? Please list type and number. The on-site electrochemistry laboratory has complete electrochemistry capabilities to conduct all of the standard corrosion-related electrochemistry tests including Polarization resistance, Tafel extrapolation, AC Impedance and potentiodynamic scanning. The site has electronic connections and allows continuous monitoring of electronic data via dedicated data lines. Current data which are monitored continuously include air temperature, humidity, wind speed and direction, rainfall measured in 20 minute increments, total incident solar radiation and UVB radiation. Does your site have any special equipment? If so, what are they and what are their uses? A forklift and crane are available for heavy items.
Specimen size	Do specimens differ in size? If so, how do they differ? How are the differences handled? Items are "racked" based upon their size and weight.
Location of loading zone	Does your site have a designated loading zone? No If so, what is its location? N/A What is the location of it with respect to other facilities? N/A
Technical needs	Are there any specific technical needs for those vehicles and equipment? Protection from corrosion, or removal from the test site when not in use. Does your site have a separate warehouse to store vehicles and equipment? Yes

Table III.6. Alternatives [NASA KSC].

Category	Questions and Answers
Alternatives	
Significance of a site in Texas	Based on your experience, would you expect significantly different results if you had put your facility along the Texas coast? No answer given Do you feel there is a benefit to having another facility in Texas? Why/Why not? No answer given Do you feel they would be useful for the environment along the Texas coast? No answer given
Available options	Are you willing to share your results with TxDOT? Experimental results cannot be shared without prior consent of NASA or the customer. Otherwise, yes. Are you willing to perform certain tests for TxDOT if TxDOT pays for the tests? Yes

The United States Army Natural Weathering Exposure Station on Treat Island, Maine

Table III.7. Evaluation of Success Factors [Army NWES].

No.	Success Factors	Relative Importance (0: least ~ 10: most)
1	Size of site	9
2	Site locations/conditions	10
3	Site proximity to civilization, etc.	5
4	All-weather road access	9
5	Shore conditions (water surface, beach, tide)	9
6	Protection against hurricanes and flooding	7
7	Access to equipment (handling equipment, etc.)	9
8	Utilities	8
9	Site security/absence of interfering activities	10
10	General test conditions (weather, etc.)	8
11	Specimen housing facilities	8
12	Site docking facility	8
13	on-site laboratory	6
14	on-site weather station	9
15	on-site web-based camera system	5
16	Any other factors	No response

Table III.8. Site Characteristics [Army NWES].

Category	Questions and Answers
Site Characteristics	
Geographical Characteristics	
Size of site	What are the types of tests being performed at your site? Please provide a list of these. Visual examination, pulse velocity, resonant frequency, corrosion measurements (LP), specimen retrieval and lab evaluation. What are their approximate capacities (maximum number of specimens)? 200 What are the most performed tests and the least performed tests? Visual most, corrosion least (most are unreinforced). Do you have a plan for future expansion? If so, what is the reason for the expansion? No
Site locations/conditions	What are site location characteristics that make your exposure test site successful? Freeze-thaw (100 per year), tidal fluctuations (up to 26 feet). How was site chosen? What factors (salinity, temperature, etc.) went into the selection? What was the goal? What were the advantages/disadvantages of each location? What would you have done differently? Selected for potential development of Passamaquoddy Power Project (interested in performance of concrete structures in same environment).
Distance to public roads	What is the distance to the highway and roadway? Is it an influential factor for success? 1.5 miles (over water)
All-weather road access	Do you have all-weather road access to your site? What is the load limit of the road? No (boat access only)
Distance to shoreline	What is the distance of the test area to the shoreline? (1.5 miles to mainland, test site is in tidal zone). Is this an influential factor for site operation? Yes How far inland is practical for specimen testing? How much shoreline and distance back from the shore is necessary? Proximity is a key factor. 165 feet max for splash zone, within tidal fluctuation region for wet/dry cycles.
Slope of shore	What is the approximate slope of the shore at your site? Level timber deck for most specimens; specimens on shore are at approximately 10-15 degrees. How does the slope of the shore affect site operations? Makes it difficult to maneuver samples.
Tide differential	Is tide differential an important test condition? What is the maximum tide differential? Very important. 26 feet max

Table III.8. Site Characteristics [Army NWES] (continued).

Category	Questions and Answers
Site Characteristics	
Geographical Characteristics	
Protection against hurricanes/flooding	Has your group taken any special precautions to protect your site against natural disaster? No Has your site ever experienced a natural disaster? No If so, what was it and what happened? Do you have any lessons learned from it? N/A
Access to equipment	Does your site have any characteristics that impede use (efficiency) of equipment? Island site makes it quite difficult to transport equipment to site. Would not recommend island for Texas or any site! If so, what are they? See above.
Non-geographical Characteristics	
Utilities	Which kinds of utilities are used at your site? Please list available utilities. Data acquisition (by battery only). No power or water utilities available.
Site security	Do you have any problems with site security? If so, what are they? How are you resolving these? No (remote location). Does your site have a surveillance camera? No
Interfering activities	Do you have any interfering activities (e.g., people from beach, etc.) at your site? No (remote location). If so, how do you handle the interfering activities? N/A
General condition	Have you ever identified specific site conditions that result in challenges during testing? Can only evaluate during low tide. Build-up of marine growth requires specimen cleaning prior to testing, which could damage specimens (due to power washing). If so, please provide explanation. See above.

Table III.9. Management [Army NWES].

Category	Questions and Answers
Management	
Management plan	
Business goal	What was the original goal of the test site? How is this goal being met: How does management assess the success and/or continued effectiveness of having the test site? See Table III.7 (originally set up for potential power plant). Power plant project was rejected for environmental reasons in 1950s, but Army Corps decided to keep site for long-term exposure testing.
Demand	What kinds of users (public/private users) perform tests at your site? Government, University, and Industry. Do you have a source of funds other than the primary funding from your agency? Yes (CANMET).
Revenues	What is the annual revenue generated from site operations? Please provide the amount. None, just maintenance. We cover costs, but do not generate revenue. Do you have a standardized fee structure? If so, please provide a description. N/A Do you think your fee structure is profitable enough? N/A Do you think your fee structure is affordable to your users? N/A Do you think user demand is sensitive to the fees? N/A What is your typical contract method? N/A
Capital costs	How much did your agency spend in the development of your site? Not known. How long did it take to develop your site? Not known (developed 50 years ago). Are there detailed data about the development costs of your site? If so, please provide a copy. No
Expenditures	What is the annual expenditure? Please provide the total amount. About $35K for maintenance and testing. What are the major elements of the annual expenditures? Maintenance and testing. Please provide their amounts by element. ($10K for maintenance, $25K for testing).

Table III.9. Management [Army NWES] (continued).

Category	Questions and Answers
Management	
Management plan	
Long-term commitment	When was your site developed? About 1950 Does your agency provide internal support? If so, what type of support are you provided? None Provide detailed information about the support from your agency. Please specify the annual amount of financial support (the primary funding from your agency). N/A Are there other financial needs beyond the financial support from your agency? N/A If so, please specify what they are and how they are resolved? N/A
Annual report	Does your site produce annual reports? If so, please provide a copy. Yes. Will send.
Operation & Maintenance	
Ownership	Are owner and operator separate organizations? If so, what is the reason for the separation? Yes. Geographic convenience and local resources.
Operation	Does your site outsource work? If so, what work is outsourced? Maintenance and testing are outsourced to the University of New Brunswick (who then subcontracts maintenance to locals). If so, what is the general process of outsourcing? Contract
Maintenance	Does your site have a scheduled maintenance plan for facilities and equipment? Yes What are the major maintenance activities for facilities and equipment? Replacement of deteriorated deck elements.
Testing and data collection	What are the cycles of tests (the longest, the shortest, and the average test durations)? Annual tests. How often are specimens observed and data recorded? Annually How are results documented, organized, maintained, and distributed? Written reports and website.
Marketing plan	Is the exposure test site marketed? If so, how? Is the marketing effective? No
Emergency plan	Does your site have an emergency response plan? No If so, which kinds of emergencies are under the plan? N/A Has your site ever experienced an emergency situation other than a natural disaster? No If so, what was it and what happened? Do you have any lessons learned from it? N/A

Table III.9. Management [Army NWES] (continued).

Category	Questions and Answers
Management	
Organization	
Organizational chart	Does your site have an organizational chart? If so, please provide a copy. No What are the type and the number of technicians? Technicians and grad students from UNB present for annual inspections (about 5 days per year). Are there any other personnel? If so, please describe their general duties. Local fisherman provides access to site by boat and occasional maintenance.

Table III.10. Facilities [Army NWES].

Category	Questions and Answers
Facilities	
Site map	Do you have a map of your site? If so, please provide a copy. Yes. Contained in report that will be sent.
Specimen housing facilities	
Location	How many specimen housing facilities (exposure test places: rack/beach) does your site have? One rack (two levels), shoreline for specimen placement, (mid-tide level). If your site has multiple specimen housing facilities, why are they separated? To expose samples to different conditions. Where are they located? Is there any preferred condition for a good location? If so, what is it? Based on tidal location (submerged, mid tide, and high tide).
Capacity	What is the capacity (maximum number of specimens) of (each of) the facilities? 200 total (about 180 mid tide, and rest high tide or submerged).
Maintenance of specimens	How are the specimens cleaned and how often? Pressure washed once a year.
Technical needs	Are there any specific technical needs for specimen housing facilities? No What kind of inspection/testing and data recording is done and how often? Previously described.
Site docking facility	
Location	Does your site have a docking facility? If so, what is the location of it with respect to other facilities? Yes. At mid-tide wharf. Is there any preferred condition for a good location? If so, what is it? Easy and safe access.
Capacity	What is the size (sq ft) of your docking facility? 50 ft long.
Technical needs	Are there any specific technical requirements for a docking facility? Large enough (and deep enough) for a boat.

Table III.10. Facilities [Army NWES] (continued).

Category	Questions and Answers
Facilities	
On-site laboratory	
Location	Does your site have an on-site laboratory? If so, what is the location of it with respect to other facilities? No (rest of questions in this section N/A). Is there any preferred condition for a good location?
Type of tests and capacity	What kinds of tests are performed at your on-site laboratory? What is the capacity (number of samples or sq ft) of your on-site laboratory?
Measuring equipment	What kinds of measuring equipment do you have, please list type. Is this generally sufficient?
Technical needs	Are there any specific technical requirements for an on-site laboratory? No answer given
On-site weather station	
Location	Does your site have an on-site weather station? If so, what is the location of it on your site? Temperature only. Is there any preferred condition for a good location? If so, what is it?
Technical needs	What kinds of parameters do the weather station measure? How are data recorded and how are they tied into test operations? Are there any specific technical needs for an on-site weather station? Would be ideal to have one to measure T, RH, wind speed, and precipitation.
Web-based camera system	
Usages and benefits	Does your site have a web-based camera system? No If so, what are the benefits from it? And, how many cameras are in operation? N/A
Technical needs	Are there any specific technical needs for a web-based camera system? N/A
Warehouse	
Usages	Does your site have a warehouse? If so, is it regularly used? And, what is the usage of it? No (we do have a small storage shed).
Location	Is there any preferred condition for a good location? If so, what is it?
Other facilities	Does your site have any other facility not in our list above? No If so, what is it? Please provide a description of the facility.
Locational relationship	How does locational relationship of those facilities affect the overall efficiency of operations? Very important. Location on an island is not ideal for anything.

Table III.11. Equipment [Army NWES].

Category	Questions and Answers
Equipment	
Type of vehicles	What kinds of vehicles are used at your site? Please list type and number. Boat Does your site have any special vehicles? If so, what are they and what are their uses? No
Type of equipment	What kinds of equipment are used at your site? Please list type and number. See Table III.7 (pulse velocity, etc.) Does your site have any special equipment? If so, what are they and what are their uses? No
Specimen size	Do specimens differ in size? If so, how do they differ? How are the differences handled? Yes. Largest blocks are about 3 cubic feet. Some are larger but not standard. Smaller specimens (6 inch diameter cylinder, 12 inch length) have been evaluated but are too small to generate realistic data.
Location of loading zone	Does your site have a designated loading zone? If so, what is its location? Either unload directly to dock or beach boat on shore. What is the location of it with respect to other facilities? On site.
Technical needs	Are there any specific technical needs for those vehicles and equipment? No Does your site have a separate warehouse to store vehicles and equipment? No

Table III.12. Alternatives [Army NWES].

Category	Questions and Answers
Alternatives	
Significance of a site in Texas	Based on your experience, would you expect significantly different results if you had put your facility along the Texas coast? Yes, no freeze-thaw, hotter temperatures would accelerate wetting/drying, diffusion, etc. Do you feel there is a benefit to having another facility in Texas? Why/Why not? Absolutely! Hot weather marine site is essential. Do you feel they would be useful for the environment along the Texas coast? Yes
Available options	Are you willing to share your results with TxDOT? Yes Are you willing to perform certain tests for TxDOT if TxDOT pays for the tests? Yes

The United States Navy Advanced Waterfront Technology Test Site in Port Hueneme, California

Table III.13. Evaluation of Success Factors [Navy AWTTS].

No.	**Success Factors**	**Relative Importance (0: least ~ 10: most)**	
1	Size of site	Pier 15 ft x 150 ft	9
2	Site locations/conditions	Port Hueneme Harbor	9
3	Site proximity to civilization, etc.	On Navy Base – we are generally civilized	10
4	All-weather road access	Yes	10
5	Shore conditions (water surface, beach, tide)	Gravel lay down area 5,000 sq ft used for testing and staging	No score
6	Protection against hurricanes and flooding	Yes	10
7	Access to equipment (handling equipment, etc.)	Crane and riggers available to lift large test sections into place.	10
8	Utilities	Water and power	9
9	Site security/absence of interfering activities	Navy security on shore and Coast Guard in Harbor	10
10	General test conditions (weather, etc.)	Moderate Marine (a hotter area is better)	8
11	Specimen housing facilities	Yes (the more remote, the more important)	7
12	Site docking facility	Yes	No score
13	on-site laboratory	Yes (only because facilities are close; if facilities are far it is important (10))	5
14	on-site weather station	No Oxnard airport maintains records, 5 miles away (only because temperature is not extreme, the site uses local weather station)	4
15	on-site web-based camera system	No (not important because site is local but if it is remote it will be very important)	2 – 5
16	Any other factors	Site has been very good for full-scale testing. Also, site has full-scale test reaction frame > 150,000 pounds. The site has non-destructive facilities for assessing structures.	Hydraulic rams for structural loading and dead weights for creep testing

Table III.14. Site Characteristics [Navy AWTTS].

Category	Questions and Answers
Site Characteristics	
Geographical Characteristics	
Size of site	What are the types of tests being performed at your site? Please provide a list of these. None at the moment – Plans to install test 120 concrete panels (4 ft × 6 ft) in Sept – ask for test plan. Corrosion, repair, ASR, and long-term durability (all full-scale). What are their approximate capacities (maximum number of specimens)? Depends on the size of specimens. What are the most performed tests and the least performed tests? Materials degradation and structural capacity (least ASR). Do you have a plan for future expansion? If so, what is the reason for the expansion? No (or structural test site in San Diego).
Site locations/conditions	What are site location characteristics that make your exposure test site successful? Intertidal exposure. Access to top and bottom and base security. How was site chosen? What factors (salinity, temperature, etc.) went into the selection? What was the goal? What were the advantages/disadvantages of each location? What would you have done differently? Only Navy has close proximity.
Distance to public roads	What is the distance to the highway and roadway? Is it an influential factor for success? See photos; pavement to the site.
All-weather road access	Do you have all-weather road access to your site? What is the load limit of the road? Yes
Distance to shoreline	What is the distance of the test area to the shoreline? Over the water. Is this an influential factor for site operation? Yes How far inland is practical for specimen testing? How much shoreline and distance back from the shore is necessary?
Slope of shore	What is the approximate slope of the shore at your site? 1:1 How does the slope of the shore affect site operations? N/A (Not critical).
Tide differential	Is tide differential an important test condition? What is the maximum tide differential? 8 ft from tide chart.

Table III.14. Site Characteristics [Navy AWTTS] (continued).

Category	Questions and Answers
Site Characteristics	
Geographical Characteristics	
Protection against hurricanes/flooding	Has your group taken any special precautions to protect your site against natural disaster? No, but initial design was made considering earthquake. Has your site ever experienced a natural disaster? Mild earthquakes. If so, what was it and what happened? Do you have any lessons learned from it? No effect on site.
Access to equipment	Does your site have any characteristics that impede use (efficiency) of equipment? No If so, what are they? N/A
Non-geographical Characteristics	
Utilities	Which kinds of utilities are used at your site? Please list available utilities. Water and power available.
Site security	Do you have any problems with site security? If so, what are they? How are you resolving these? No (Navy Base). Does your site have a surveillance camera? No
Interfering activities	Do you have any interfering activities (e.g., people from beach, etc.) at your site? No If so, how do you handle the interfering activities?
General condition	Have you ever identified specific site conditions that result in challenges during testing? No If so, please provide explanation.

Table III.15. Management [Navy AWTTS].

Category	Questions and Answers
Management	
Management Plan	
Business goal	What was the original goal of the test site? To provide intermediate test stage between lab and construction in Navy environment – very successful. How is this being met: How does management assess the success and/or continued effectiveness of having the test site?
Demand	What kinds of users (public/private users) perform tests at your site? Exclusively Navy. Do you have a source of funds other than the primary funding from your agency? No
Revenues	What is the annual revenue generated from site operations? Please provide the amount. Zero Do you have a standardized fee structure? If so, please provide a description. No Do you think your fee structure is profitable enough? N/A Do you think your fee structure is affordable to your users? N/A Do you think user demand is sensitive to the fees? N/A What is your typical contract method? N/A
Capital costs	How much did your agency spend in the development of your site? $250,000 - $300,000 How long did it take to develop your site? Planning to construction: 2 years; for construction only: 1 year. Are there detailed data about the development costs of your site? If so, please provide a copy. No
Expenditures	What is the annual expenditure? Please provide the total amount. $10,000/year. What are the major elements of the annual expenditures? Specimen handling. Please provide their amounts by element.
Long-term commitment	When was your site developed? 1993 Does your agency provide internal support? If so, what type of support are you provided? Zero. All through projects. Provide detailed information about the support from your agency. Please specify the annual amount of financial support (the primary funding from your agency). Zero Are there other financial needs beyond the financial support from your agency? If so, please specify what they are and how they are resolved? Not yet.
Annual report	Does your site produce annual reports? If so, please provide a copy. No. All reports are project-related.

Table III.15. Management [Navy AWTTS] (continued).

Category	Questions and Answers
Management	
Operation & Maintenance	
Ownership	Are owner and operator separate organizations? No If so, what is the reason for the separation?
Operation	Does your site outsource work? Yes If so, what work is outsourced? Maintenance If so, what is the general process of outsourcing? Internal contract through naval base.
Maintenance	Does your site have a scheduled maintenance plan for facilities (No) and equipment (do not know)? Maintenance plan is developed by Navy. What are the major maintenance activities for facilities and equipment? Minimal
Testing and data collection	What are the cycles of tests (the longest, the shortest, and the average test durations)? Longest – 12 years, Shortest – several years. How often are specimens observed and data recorded? Varies depending on projects. How are results documented, organized, maintained, and distributed? Project reports.
Marketing plan	Is the exposure test site marketed? No If so, how? Is the marketing effective?
Emergency plan	Does your site have an emergency response plan? No specific plan. It is supposed to follow base standard procedure. If so, which kinds of emergencies are under the plan? Has your site ever experienced an emergency situation other than a natural disaster? No If so, what was it and what happened? Do you have any lessons learned from it? N/A
Organization	
Organizational chart	Does your site have an organizational chart? If so, please provide a copy. No What are the type and the number of technicians? None assigned to site but organization has 6 technicians and they are used for entire sites. Are there any other personnel? If so, please describe their general duties. None

Table III.16. Facilities [Navy AWTTS].

Category	Questions and Answers
Facilities	
Site map	Do you have a map of your site? If so, please provide a copy. Yes, Google Earth.
Specimen housing facilities	
Location	How many specimen housing facilities (exposure test places: rack/beach) does your site have? See pictures. If your site has multiple specimen housing facilities, why are they separated? Where are they located? Is there any preferred condition for a good location? If so, what is it? See pictures.
Capacity	What is the capacity (maximum number of specimens) of (each of) the facilities? Permanent storage capacity: 1,200 sq ft. Temporary storage capacity: 200 sq ft.
Maintenance of specimens	How are the specimens cleaned and how often? N/A
Technical needs	Are there any specific technical needs for specimen housing facilities? No What kind of inspection/testing and data recording is done and how often? Project specific.
Site docking facility	
Location	Does your site have a docking facility? If so, what is the location of it with respect to other facilities? N/A Is there any preferred condition for a good location? If so, what is it? N/A
Capacity	What is the size (sq ft) of your docking facility? N/A
Technical needs	Are there any specific technical requirements for a docking facility? N/A
on-site laboratory	
Location	Does your site have an on-site laboratory? If so, what is the location of it with respect to other facilities? Yes - It is 1 mile away from the base. Is there any preferred condition for a good location? If so, what is it?
Type of tests and capacity	What kinds of tests are performed at your on-site laboratory? What is the capacity (number of samples or sq ft) of your on-site laboratory? Storage capacity: 40,000 sq ft.
Measuring equipment	What kinds of measuring equipment do you have? Please list type. Is this generally sufficient? No answer given
Technical needs	Are there any specific technical requirements for an on-site laboratory? No answer given

Table III.16. Facilities [Navy AWTTS] (continued).

Category	Questions and Answers
Facilities	
on-site weather station	
Location	Does your site have an on-site weather station? If so, what is the location of it on your site? N/A Is there any preferred condition for a good location? If so, what is it? N/A
Technical needs	What kinds of parameters do the weather station measure? N/A How are data recorded and how are they tied into test operations? N/A Are there any specific technical needs for an on-site weather station? N/A
Web-based camera system	
Usages and benefits	Does your site have a web-based camera system? If so, what are the benefits from it? And, how many cameras are in operation?
Technical needs	Are there any specific technical needs for a web-based camera system?
Warehouse	
Usages	Does your site have a warehouse? If so, is it regularly used? And, what is the usage of it? Yes, warehouse and lay-down areas with concrete lab.
Location	Is there any preferred condition for a good location? If so, what is it? N/A
Other facilities	Does your site have any other facility not in our list above? Office and conference rooms. If so, what is it? Please provide a description of the facility.
Locational relationship	How does locational relationship of those facilities affect the overall efficiency of operations? Excellent, very effective.

Table III.17. Equipment [Navy AWTTS].

Category	Questions and Answers
Equipment	
Type of vehicles	What kinds of vehicles are used at your site? Please list type and number. Various equipment including cranes, trains, trucks, etc. are supplied by the Navy. Does your site have any special vehicles? If so, what are they and what are their uses? N/A
Type of equipment	What kinds of equipment are used at your site? Please list type and number. N/A Does your site have any special equipment? If so, what are they and what are their uses? N/A
Specimen size	Do specimens differ in size? If so, how do they differ? How are the differences handled? N/A
Location of loading zone	Does your site have a designated loading zone? If so, what is its location? N/A What is the location of it with respect to other facilities? N/A
Technical needs	Are there any specific technical needs for those vehicles and equipment? N/A Does your site have a separate warehouse to store vehicles and equipment? N/A

Table III.18. Alternatives [Navy AWTTS].

Category		Questions and Answers
Alternatives		
	Significance of a site in Texas	Based on your experience, would you expect significantly different results if you had put your facility along the Texas coast? Yes – better, more severe. Do you feel there is a benefit to having another facility in Texas? Why/Why not? Yes, for comparative purpose. Do you feel they would be useful for the environment along the Texas coast?
	Available options	Are you willing to share your results with TxDOT? Yes Are you willing to perform certain tests for TxDOT if TxDOT pays for the tests? Yes, at a rate $100/hr/person.

APPENDIX IV. ADDITIONAL PICTURES OF THE EXISTING SITES VISITED

NASA KSC Corrosion Technology Laboratory Site in Cape Canaveral, Florida

Figure IV.1. Corrosion Tests in a Fenced Area.

Figure IV.2. Piping under Exposure.

Figure IV.3. Seawater Immersion Test Site.

U.S. Army Natural Weathering Exposure Station on Treat Island, Maine

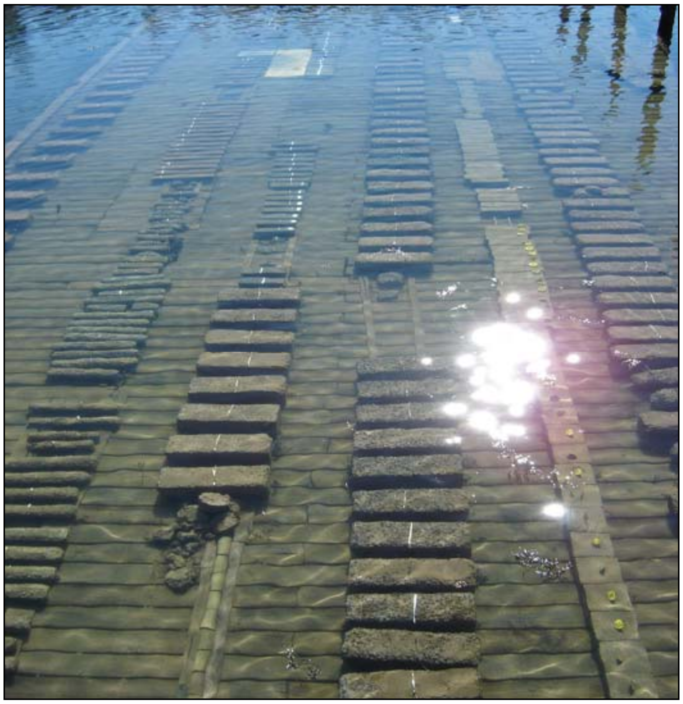

Figure IV.4. Test Specimens Submerged in High Tide (on the Rack).

Figure IV.5. Test Specimens Submerged in High Tide (on the Beach).

Figure IV.6. Large Size Specimens on the Beach.

Figure IV.7. Small Size Specimens on the Beach.

Figure IV.8. High-Pressure Washing with Water.

Figure IV.9. Visual Examination.

U.S. Navy Advanced Waterfront Technology Test Site in Port Hueneme, California

Figure IV.10. Storage Area near the Access to the Facility.

Figure IV.11. Pier Slab Exposed.

APPENDIX V. MAGNIFIED MAPS OF POTENTIAL SITES

Site No. 6 (File Number: 154945)

Figure V.1. Site No. 6.

Sites No. 7 (File Number: 153534) and No. 8 (File Number: 154939)

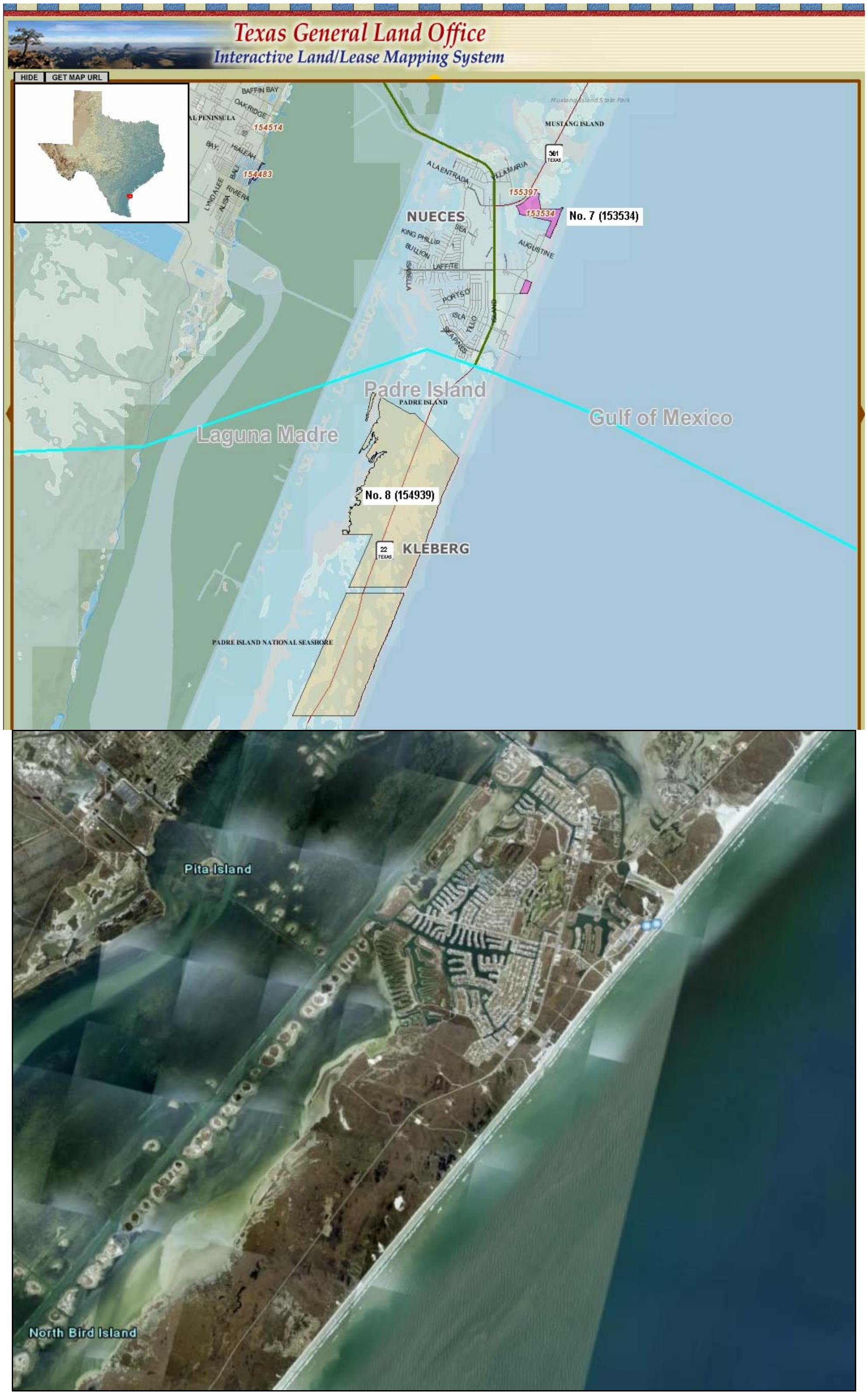

Figure V.2. Sites No. 7 and No. 8.

APPENDIX VI. FLOW MODEL

Description of the Model

The basic concept of the model has been simply described using Figure 51 in Chapter 6. In a systematic view, over the forecasting time periods, the model tracks the numbers of bridges in each of the stocks (the classified bridge groups) and the number of bridges in each flow between the stocks. Thus, the stocks and the flows are specified in the model.

Figure VI.1 describes the model that classifies the major stocks and flows in detail. The sufficient bridge group consists of existing sufficient bridges, new bridges, and repaired bridges that have transitioned from Deficient to Sufficient. The deficient bridge group consists of structurally deficient bridges and other types of deficient bridges. For simplicity, functionally obsolete bridges and substandard-for-load-only bridges are pooled into the *other deficient bridge* group since they do not have any direct relationship with deterioration. Terms in the figure are explained below in detail.

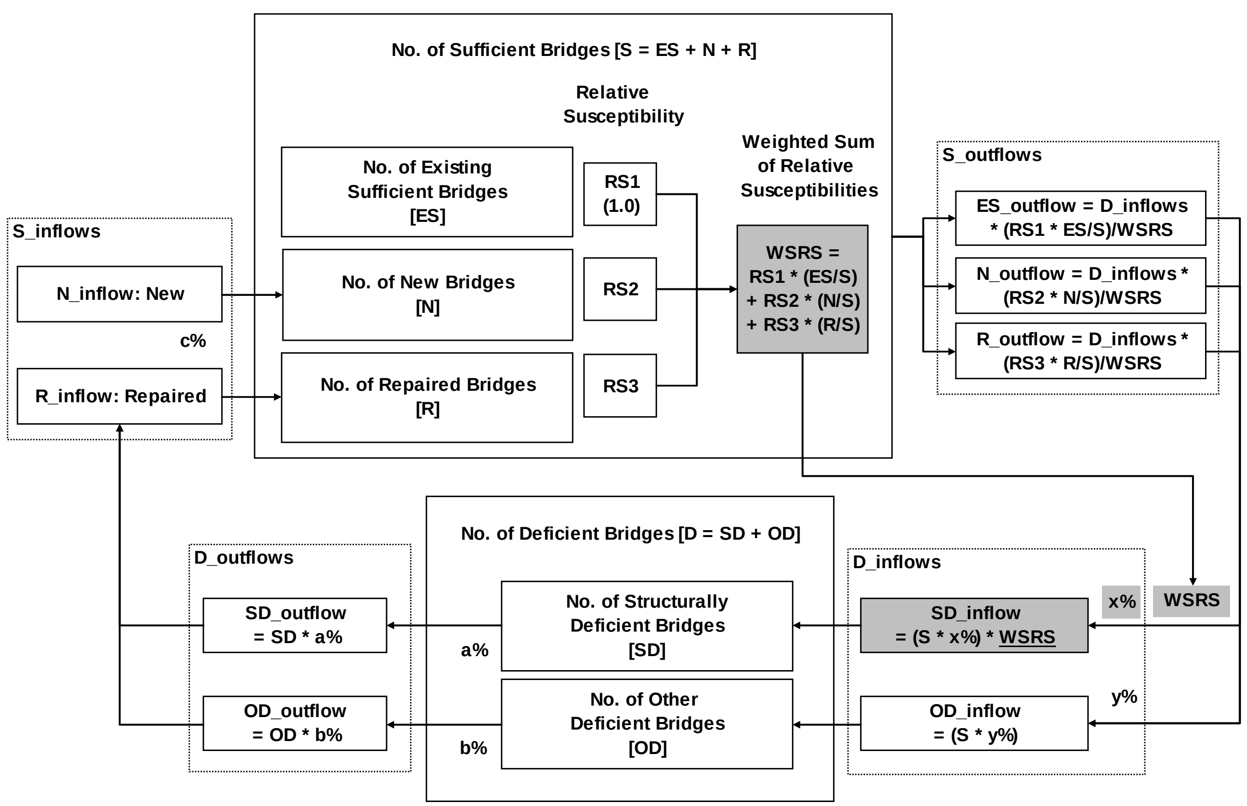

Figure VI.1. Model.

The flows between the classified bridge groups represent different types of transitions of bridges between the groups. The transitions of bridges are made through becoming deteriorated, being repaired, or being newly built. Major stocks and flows have their sub-stocks and sub-flows and they are all linked together. Note that construction of new bridges increases the size of the total bridge population and that an outflow from a stock is an inflow to another stock so that the outflows and the inflows are always balanced. Table VI.1 categorizes the stocks and flows in Figure VI.1.

Table VI.1. Stock and Flows in the Model.

Major Stocks / Flows	Sub-stocks / Sub-flows
S: No. of sufficient bridges (S = ES + R + N)	ES: No. of existing sufficient bridges R: No. of repaired bridges using new method N: No. of new bridges using new method
D: No. of deficient bridges (D = SD + OD)	SD = No. of structurally deficient bridges OD = No. of other types of deficient bridges
S_outflows: outflows from S (due to bridge deficiency)	ES_outflow = existing bridge group → deficient bridge group N_outflow = new bridge group → deficient bridge group R_outflow = repaired bridge group → deficient bridge group
D_inflows: inflows to D (D_inflows = S_outflows)	SD_inflow: sufficient bridge group → structurally deficient bridge group OD_inflow: sufficient bridge group → other deficient bridge group
D_outflows: outflows from D (through rehabilitation)	SD_outflow: structurally deficient bridge group → repaired bridge group OD_outflow: other deficient bridge group → repaired bridge group
S_inflows: inflows to S (S_inflows = D_outflows)	N_inflow: inflow of new bridges R_inflow: deficient bridge group → repaired bridge group

In Figure VI.1, there are five annual rates (a, b, c, x, and y) that represent how many bridges move (are rehabilitated, become deficient, or are bridges at new locations) within each flow. Table VI.2 provides definitions of these rates. The later parts of this appendix explain the estimation of these annual rates.

Table VI.2. Annual Rates in the Model.

Annual Rate		Definition
Rates of Replacement/Rehabilitation	*a*	Annual percentage of structurally deficient bridges that are rehabilitated
	b	Annual percentage of other types of deficient bridges that are rehabilitated
Rate of New Location Bridges	*c*	Annual percentage of new location bridges in the total number of bridges
Rates of Becoming Deficient	*x*	Annual percentage of sufficient bridges that become structurally deficient bridges
	y	Annual percentage of sufficient bridges that become other deficient bridges

Susceptibility of Bridges

The process of becoming deficient is a major interest in the model, especially for structural deficiency because it directly relates to deterioration and durability problems, and also safety issues.

Facilities would deteriorate more easily when they are in a high level of exposure such as a severe environmental condition and/or if they are not well protected by effective prevention methods, thus they are susceptible. In contrast, facilities would deteriorate less when they are in a low level of exposure to deterioration such as a mild environmental condition and/or they are built using effective prevention methods, thus they are less susceptible. In the current model, the susceptibility represents relative rate of deterioration for bridges. Unfortunately, there are insufficient data to estimate these different susceptibility levels. (Developing such data might be one important function of the marine exposure test site.) Therefore, the following assumptions are made to quantify levels of susceptibility to deterioration for the different bridge groups by their condition.

If the level of susceptibility to deterioration of current existing bridges is assumed to be 1.0 as the basis, recently repaired and newly built bridges would have lower levels of susceptibility to deterioration, such as 0.6 for new bridges and 0.85 for repaired/rehabilitated bridges. New bridges will have lower levels of susceptibility than repaired bridges. These relative levels can represent differences in the degree of their susceptibility to deterioration.

In the model in Figure VI.1, the sufficient bridge group consists of existing bridges, new bridges, and repaired bridges. To take into account different susceptibility levels of these bridge groups, a variable, *Weighted Sum of Relative Susceptibility* (WSRS), was designed to represent overall susceptibility level. As named, it is the weighted sum of each group's relative susceptibility level. The equation for the WSRS is:

$$WSRS = \left(RS1 \times \frac{ES}{S} \right) + \left(RS2 \times \frac{N}{S} \right) + \left(RS3 \times \frac{R}{S} \right)$$

Where,

RS1 = relative susceptibility of existing bridges.

RS2 = relative susceptibility of new bridges.

RS3 = relative susceptibility of repaired bridges.

Note that WSRS affects how many sufficient bridges become structurally deficient annually (annual increase in the number of structurally deficient bridges) as described in the Figure VI.2. The WSRS is multiplied to the current rate [*x*]: the smaller the overall susceptibility, the smaller the number of additional structurally deficient bridges.

These relative susceptibility levels could vary. Implementations of new technologies or advanced materials that are more effective in deterioration prevention can lower the susceptibility levels of bridges as they are repaired or newly built using new methods or materials.

Estimation of Parameters

Historical data were used to estimate the parameter values for the model. Unfortunately, the data available to the current project cover only several recent years: 2002, 2003, 2004, and 2006 (*Report on Texas Bridges* (*5, 6, and 7*) and *TxDOT's Bridge Facts* (*1*)). Thus, indirect estimates were made with some assumptions where there were not enough relevant data for a direct estimation.

Initial Values of Stocks

Table VI.3 shows the historical data on the number of on-system bridges classified by condition. The most recent year 2006 data (*1*) were used as the initial values of the stocks (the numbers of different types of bridges classified by condition) in the model. For the historical data on the numbers of off-system bridges and total bridges, refer to Appendix I.

Table VI.3. Condition of on-System Bridges in Texas—Same as Table 2 in Chapter 2.

on-system Bridges	2002		2003		2004		2006	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Total	32,010	100.0	32,206	100.0	32,287	100.0	32,674	100.0
Sufficient	27,431	85.7	27,665	85.9	27,660	85.7	28,135	86.1
Structurally Deficient	688	2.1	645	2.0	565	1.7	483	1.5
Functionally Obsolete	3,661	11.4	3,701	11.5	3,888	12.0	3,951	12.1
Substandard-for-load-only	204	0.6	184	0.6	151	0.5	105	0.3
Not Classified	No Info	No Info	11	0.0	23	0.1	No Info	No Info

Annual Rates of Flow

The following discusses how the annual rates of flow were estimated. There are five annual rates to be estimated:

- rate of replacement/rehabilitation for structurally deficient bridges (*Rate [a]*),
- rate of replacement/rehabilitation for other deficient bridges (*Rate [b]*),
- rate of new location bridges (*Rate [c]*),
- rate of becoming structurally deficient (*Rate [x]*), and
- rate of becoming functionally obsolete (*Rate [y]*).

For their definitions, refer to Table VI.2.

Rates of Replacement/Rehabilitation (Rate [a] and Rate [b])

There are two rates: 1) rate of replacement/rehabilitation for structurally deficient bridges and 2) rate of replacement/rehabilitation for other deficient bridges. One basic assumption made for the estimate is that TxDOT will perform replacement/rehabilitation activities as they have done in the past. The level of effort by TxDOT is represented as a percentage, not an absolute number. For instance, if 9 percent of deficient bridges were replaced or rehabilitated in the current year, TxDOT will maintain the same percentage for the future.

For the estimation, the following equations were used:

$$\text{Rate [a]} = \frac{\text{the annual number of structurally deficient bridges rehabilitated}}{\text{the total number of structurally deficient bridges}}$$

$$\text{Rate [b]} = \frac{\text{the annual number of other deficient bridges rehabilitated}}{\text{the total number of other deficient bridges}}$$

Table VI.4 shows the number of on-system bridges in replacement/rehabilitation projects let to contract, classified by bridge condition. Table VI.5 shows the estimated percentages for each year and their averages, using the data in Table VI.4. For historical data on the numbers of off-system bridges and total bridges, refer to Appendix I.

Table VI.4. Number of on-System Bridges in Replacement/Rehabilitation Projects Let to Contract.

Condition of Replaced or Rehabilitated Bridges	2002	2003	2004	2006
Structurally Deficient	66	47	47	No info
Functionally Obsolete	51	62	41	No info
Not Structurally Deficient or Functionally Obsolete	148	232	202	No info
Total Sum	265	341	290	399

Table VI.5. Rates of Bridge Replacement/Rehabilitation.

<table>
<tr><th colspan="2">Rates</th><th>2002</th><th>2003</th><th>2004</th><th>Average</th></tr>
<tr><td>Rate for Structurally Deficient Bridges</td><td>Rate [a]</td><td>9.59%</td><td>7.29%</td><td>8.32%</td><td>8.39% of total structurally deficient bridges</td></tr>
<tr><td rowspan="3">Rate for Other Deficient Bridges</td><td>Rate [b] = [b1] + [b2]</td><td>5.15%</td><td>7.57%</td><td>6.02%</td><td>6.24% of total other deficient bridges</td></tr>
<tr><td>[b1]: Functionally Obsolete</td><td>1.32%</td><td>1.60%</td><td>1.02%</td><td>1.31% of total other deficient bridges</td></tr>
<tr><td>[b2]: Not structurally deficient or functionally obsolete</td><td>3.83%</td><td>5.97%</td><td>5.00%</td><td>4.93% of total other deficient bridges</td></tr>
</table>

As a result, rate [a] = 8.39 percent of total structurally deficient bridges and rate [b] = 6.24 percent of total other deficient bridges.

Rate of New Location Bridges (Rate [c])

It is assumed that the percentage of new location bridges in the total number of bridges would not change significantly in the future. The equation used for the estimation is:

$$\text{Rate [c]} = \frac{\text{the annual number of new location bridges}}{\text{the total number of bridges}}$$

Table VI.6 shows the number of new on-system bridges in projects let to contract and the estimate of c. The average of the annual rates for the four years is 0.736 percent.

Table VI.6. Number of New on-System Bridges in Projects Let to Contract.

	2002	2003	2004	2006	Average
Number of new location bridges	163	300	252	236	237.7
Total number of bridges	32,010	32,206	32,287	32,674	32,294.3
Rate [c]	0.51%	0.93%	0.78%	0.72%	0.736%

As a result, rate [c] = 0.736 percent of total bridges.

Rates of Becoming Deficient (Rates [x] and [y])

Two rates discussed here are: 1) rate of becoming structurally deficient and 2) rate of becoming functionally obsolete. The rate of becoming structurally deficient directly relates to the deterioration while there is no direct relationship between the rate of becoming functionally obsolete and deterioration. Therefore, different approaches were used for the estimation of these two rates.

Unfortunately, there are no data available for direct estimation of the rate of becoming structurally deficient. In the model, this rate explains what percentage of the current existing sufficient bridges (not the total bridges) becomes structurally deficient annually. To see the direction of flow by this rate, refer to Figure VI.1.

Structural deficiency is related to deterioration. Also, deterioration is related to the age of structures, which represents how long structures have been exposed in an environmental condition. Therefore, there would be a significant relationship between the rate of structural deficiency and the age of structures. Since older bridges are usually more structurally deficient than newer bridges they have more deterioration prevention and rehabilitation needs. Therefore, the age of bridges can be used as a proxy for the level of structural deficiency.

As of year 2006, there were 32,674 on-system highway bridges in Texas and their average age was 41 years. The two oldest bridges in the state of Texas were built in 1911 based on the *Bridge Facts* (*1*). Their ages are a little less than one hundred years. It would be safe to presume that generally speaking, it is very uncommon that the maximum length of service life of highway bridges exceeds 100 years. They will be destroyed or fully replaced in the near future. As time passes, all bridges age simultaneously. Among them, older and more deficient bridges are replaced or rehabilitated first and so they become newer again. Meanwhile, new bridges are constructed at new locations. Considering that there are bridges whose ages are already close to 100 and the maximum service life of any highway bridges would not exceed 100 years, it can be assumed that the current bridge population counting 32,674 reached a stable state in terms of their average age and the average age of total bridge population would not vary significantly.

The FHWA National Bridge Inventory (NBI) (*28*) provides information about the age of highway bridges. The information shows the number of bridges by age, how many bridges are structurally deficient by age, and also how many bridges are functionally obsolete by age. The data cover all states in the U.S.; however, bridges are not classified as on-system versus off-system. To see the NBI data for the state of Texas, refer to Appendix VII.

Figure VI.2 shows the percentage of structurally deficient bridges compared to the number of sufficient bridges (not the number of total bridges) based on the NBI data. The obtained exponential trend line in the figure has a high R-squared (0.73). The function explains that older bridges are more structurally deficient, newer bridges are less structurally deficient, and their relationship is nonlinear. However, the function simply shows the static condition of bridges in terms of structural deficiency, not how many existing sufficient bridges *become* structurally deficient annually.

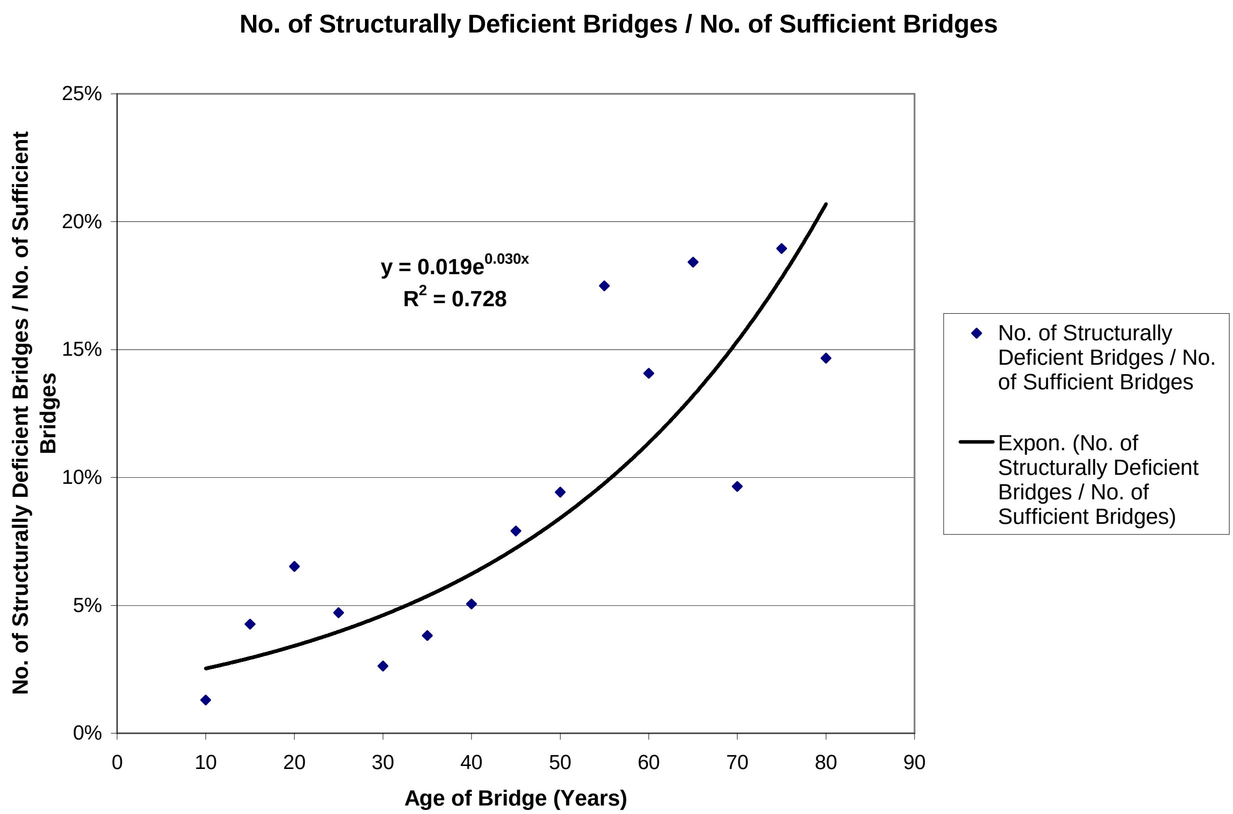

Figure VI.2. Number of Structurally Deficient Bridges / Number of Sufficient Bridges.

To estimate the annual rate, differentials (over ages) in the exponential function in Figure VI.2 were calculated. Figure VI.3 shows the differential increases by aging and the function in the new trend line provides information about the percentage of sufficient bridges that become structurally deficient annually as the bridges get older.

Differential Increases in the Trend Line [y = 0.019 * Exp(0.030x)]

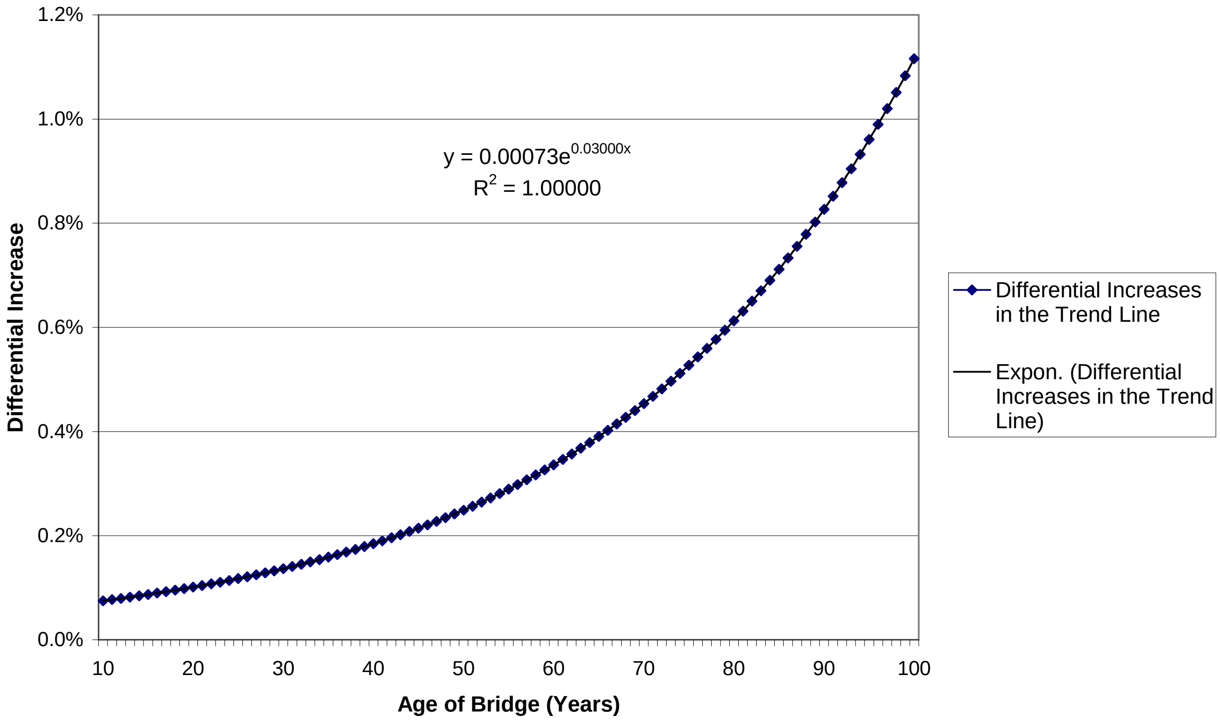

Figure VI.3. Differential Increases in the Trend Line.

As of 2006, the number of total sufficient bridges was 28,135. Also as of 2006 the average age of on-system bridges was 41 years and the average age of off-system bridges was 30 years (*1*). As mentioned above, the NBI data cover all bridges, but without classification by system. Based on the percentages of on-system and off-system bridges, the weighted average for the total bridges was calculated using the following equation:

$$41 \times \left(\frac{\text{the number of on-system bridges}}{\text{Total number of bridges}} \right) + 30 \times \left(\frac{\text{the number of off-system bridges}}{\text{Total number of bridges}} \right)$$

The calculated weighted average age is about 37 years for the total bridges in Texas. Applying this average age of the total bridges to the function of differentials in Figure VI.3 leads to an estimate of 47.4 bridges. It means that about 47.4 sufficient bridges become structurally deficient annually. It would not be an exact estimate for the annual rate [x]. However, it would be a reasonable estimate given that there are no relevant data for direct estimation.

Figure VI.4 shows the estimation of the annual number of sufficient bridges that become structurally deficient. Please note that the x axis is now the average age of total bridge population.

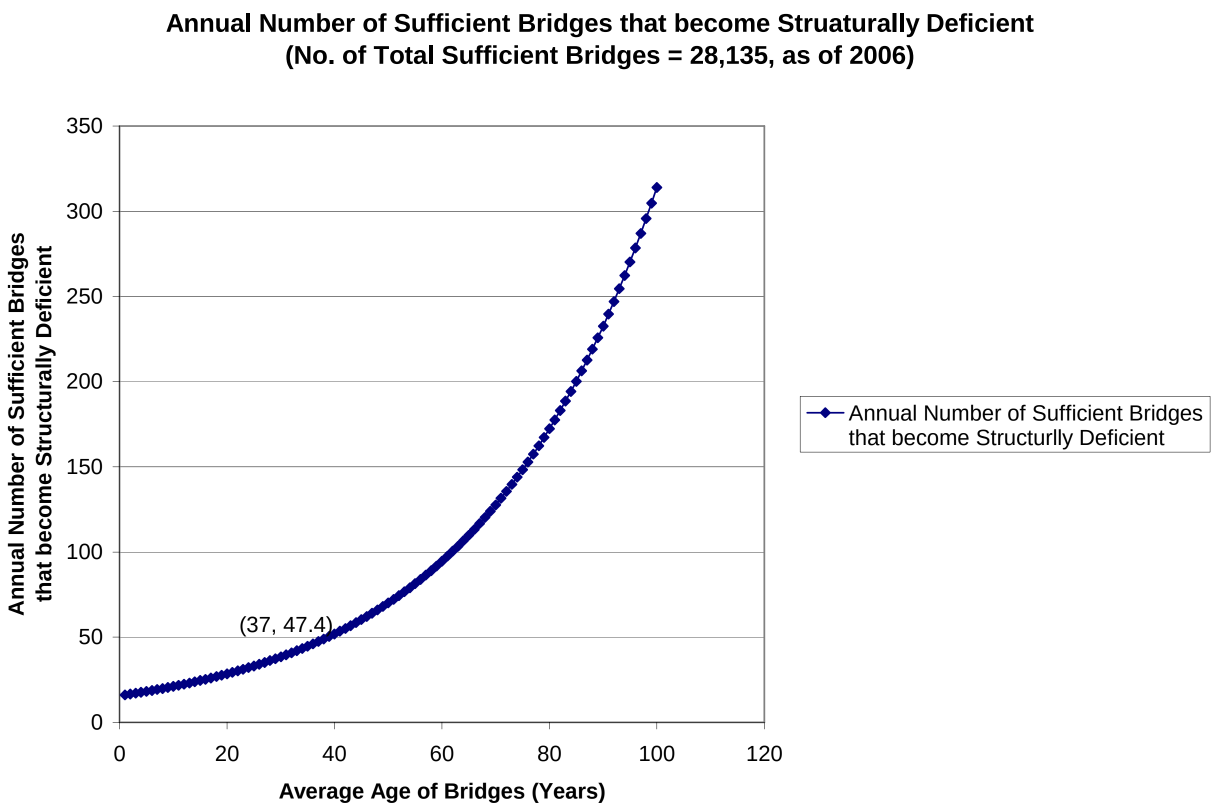

Figure VI.4. Annual Number of Sufficient Bridges that Become Structurally Deficient.

However, the estimates in Figure VI.4 are for the total system (on-system and off-system bridges). We are looking for the rate of structural deficiency for on-system bridges for the flow model. Because bridges are made of the same kinds of materials and similar types of construction methods regardless of whether bridges belong to on-system or off-system, the natural rate of being structurally deficient by deterioration should be equal for both systems. Using the percentages of on-system bridges (65.6 percent) and off-system bridges (34.4 percent) as of year 2006, the increases in the number of structurally deficient bridges are estimated to be 31.3 bridges for on-system bridges and 16.1 bridges for off-system bridges. These 31.3 structurally deficient bridges are equivalent to 0.11 percent of total on-system sufficient bridges (28,135). This most recent rate was selected as a parameter value for the flow model (note that the value for the average age of total bridges is as of the year 2006). As a result, rate [x] = 0.1105 percent of total sufficient bridges.

Similar to the rate of being structurally deficient, there are no data available to make a direct estimate of the functionally obsolete rate. In the model, this rate explains what percentage of the current existing sufficient bridges (not the total bridges) becomes functionally obsolete annually. Since functional obsolescence of bridges does not relate to deterioration, no relationship (no slope and no pattern) was found between age of bridges and functional obsolescence using the FHWA NBI data (*28*).

In Table VI.3, the proportional composition of bridge groups has been stable over recent years. There has been no significant sudden increase or decrease in the percentages of functionally obsolete bridges even though there has been a very small increased trend in the percentage of functionally obsolete bridges. This trend can be interpreted to mean that the annual number of sufficient bridges that become functionally obsolete would be close to the annual number of functionally obsolete bridges that are replaced or rehabilitated. Based on this assumption, the rate was estimated using the data on the number of replacements/rehabilitations of functionally obsolete bridges, which were shown in Table VI.4. Table VI.7 provides the annual rates calculated using these data.

Table VI.7. Rate of Being Functionally Obsolete.

Rate	2002	2003	2004	Average
[y]	0.73%	1.06%	0.88%	0.89% of total sufficient bridges

As a result, rate [y] = 0.89 percent of total sufficient bridges.

Relative Susceptibility

The model tests two cases. The base case is the null case assuming there will be no development of a marine exposure test site so that there would be no significant improvement in deterioration prevention technologies. The alternate case is the case with the development of a marine exposure test site that will result in new and advanced technologies and materials so that there would be apparent improvements in deterioration prevention technologies.

Depending on whether the bridges are newly built or repaired, and whether the new bridge construction and repair are performed using existing technologies or using new technologies, the relative susceptibility levels of bridges will vary. Table VI.8 shows the assumed susceptibility levels for different cases.

Relative susceptibility levels 0.6 and 0.85 for the base case in Table VI.8 represent that small but continuous improvements will be made in the future through new bridge constructions and repairs, respectively. These relative susceptibilities could be lowered thanks to new technologies from the development of a marine exposure test site. It is assumed that the lowered susceptibility levels, after 50 years (continuous implementation of new technologies), would be 0.3 and 0.45 for new bridges and for repaired bridges, respectively. During the 50 years, annual decreases in susceptibility levels are assumed to be uniform over time periods after full diffusion of new technologies. However, the annual decreases will be affected by how much the new technologies are implemented to real constructions and repairs. There will be lead time to the full diffusion of new technologies, which the next section discusses.

The model measures relative susceptibility levels for bridges to quantify the effects by new technologies versus by existing practices. The estimates were made by asking the following questions:

For the current condition:

Assuming a 1.0 average susceptibility level of all existing sufficient bridges (possible range of bridge susceptibilities: 0.0 ~ 2.0),

- What would be the relative susceptibility level of new bridges using current practices?
- What would be the relative susceptibility level of repaired bridges using current practices?

For the future condition:

Assuming 50 years of continuous implementation of new technologies,

- What would be the lowered level of susceptibility of new bridges using new technologies?
- What would be the lowered level of susceptibility of repaired bridges using new technologies?

Table VI.8. Estimates of Relative Susceptibility Levels.

	Existing Bridges	New Bridges	Repaired Bridges
Base Case (Current)	1.0	0.6	0.85
Alternate Case (New Technologies)	1.0	0.3 (after 50 years)	0.45 (after 50 years)

Diffusion of New Technologies

After the development of the marine exposure test site, tests will be performed at the site and relevant knowledge and data will be accumulated over time periods. As a result of these efforts, new technologies and advanced materials will be invented and implemented to real constructions and repairs. However, there will be lead time to this invention and implementation. The research team assumed that the lead time to implementation of new technologies after development of the site would be about 5.5 years.

When new technologies for deterioration protection/prevention are invented, the technologies will be deployed into the field of construction, especially bridge construction and repairs. The rate of diffusion would be low at the beginning of diffusion and increase at an increasing rate. As the overall diffusion level becomes close to the maximum level, the increasing rate will become smaller. This diffusion pattern is often described as an S-curve in the fields of management and sociology. Figure VI.5 below shows an S-curve to represent the diffusion of new technologies.

New and advanced technologies invented from the marine exposure test site are expected to follow similar patterns in their diffusions into the field of bridge construction/repairs. The function in Figure VI.5 was used in the current model to represent variable rates of diffusion of new technologies over time periods. The lead time to the maximum level of diffusion is assumed to be about 10 years after the first implementation of new technologies.

The annual decreases in the relative susceptibility levels are affected by this diffusion function. The full amount of annual decrease will be realized with the full diffusion. As the new technologies become more diffused, more effects will be realized. The maximum level of diffusion will be obtained when major existing methods (deterioration and corrosion prevention method) are replaced by new and more efficient methods.

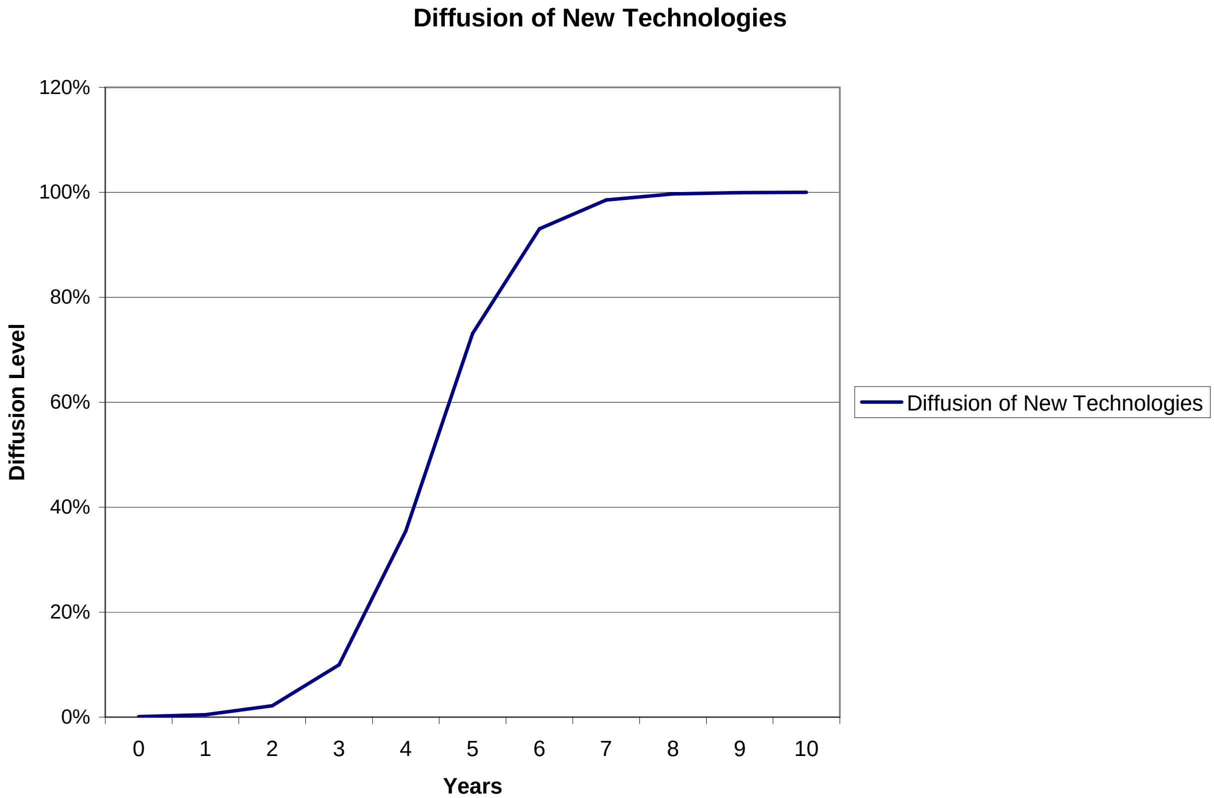

Figure VI.5. Diffusion of New Technologies.

Discount Rate

Using the model, the ultimate question concerning the economic benefits that the development of a marine exposure test site will bring to Texas is answered based on net present value of cumulative costs and benefits for the forecasting time periods. For the discounts of costs and benefits toward the current time, a 4 percent discount rate is assumed.

Monetary Values

Monetary values in the model are classified into three categories: 1) *costs*; 2) *benefits*; and 3) *additional costs/savings.*

- *Costs* include initial site development costs including the cost of purchasing land and the costs of annual operation and maintenance (O&M). However, the cost of purchasing land is assumed to be zero because a site will be selected among state-owned lands.

- *Benefits* include user fees (revenues) from site operations and savings in user costs (indirect costs).
- *Additional costs/savings* are monetary gains/losses resulting from the implementation of new technologies. The implementation of new technologies could result in additional costs or savings depending on the cost level of new technologies compared to the current cost level.

Costs

Table VI.9 shows the cost data obtained from the questionnaire. Site development cost information was obtained only from the Port Hueneme site. No cost information was obtained from the NASA site.

The current project assumed $2.75 million for the initial site development costs for the Texas marine exposure test site. As a new site, and particularly as an organization seeking additional work both inside and outside the state of Texas, the Texas marine exposure test site should make use of the best available technology. The Technology Plan section in Chapter 7 lists proposed technologies. The duration of the development is assumed to be one and a half years. No land purchasing cost is assumed since a site will be selected among state-owned lands.

For the operation and maintenance costs, the research team estimated annual:

- operation costs of $175,000,
- maintenance costs of $75,000, and
- gross revenue of $37,500.

These estimates are greater than the existing sites since the research team assume that the more extensive and intensive research activities will be performed at the marine exposure test site in Texas.

Table VI.9. Cost Data from the Questionnaire.

	KSC CTLS, Florida	Army NWES, Maine		Navy AWTTS, California
Site Development Cost	No information	No information		$250,000 ~ $300,000
Annual O&M Costs	No information	Maintenance	$10,000	$10,000
		Operation	$25,000	

Benefits

For all three sites, agencies provide infrastructure support while other funds are delivered through contractual arrangements. However, these sites do not generate enough revenue to do more than break even and most of the revenues are spent for site operations and maintenance, which means an optimistic O&M estimate would be close to $35,000 considering the annual operation and maintenance costs of the Army NWES. The research team expects the Texas site would have a similar level of revenue and assumes it would be close to $37,500.

Savings in user costs were estimated for bridge replacement/rehabilitation through interpolation from FHWA estimates *(17)* as shown below in Table VI.10. The FHWA report provides separate estimates, especially for highway bridges. Based on the fraction of ownership by the state of Texas in the total number of highway bridges, the direct and indirect costs were estimated using an interpolation method. In the FHWA report, the value of the multiplier to estimate indirect costs for highway bridges is ten. The current project uses the same value for the multiplier.

As a result, as shown in the Table VI.10, the total direct corrosion costs for Texas highway bridges are estimated to be approximately $689 million and total indirect corrosion costs $6,889 million. However, when all durability problems (including corrosion, deterioration, Alkali-Silica Reaction, Delayed Ettringite Formation, and so on) are considered the estimate should be much greater. The multiplier estimated by experts for the overall indirect costs is 1.65, which is applied to indirect corrosion costs. It results in $11,367 million for overall indirect costs. Assuming that the annual number of rehabilitated bridges in Texas is 400 (including off-system bridge rehabilitations because the FHWA report covers all bridges), average indirect costs per bridge rehabilitation are estimated at $28.4 million.

Table VI.10. Interpolation of Corrosion Costs for Texas Highway Bridges.

	Corrosion Costs in Highway Bridges	USA Total	State of Texas
FHWA Estimates (FHWA, 2001)	Direct corrosion costs	$8,300M	
	Indirect corrosion costs (multiplier applied to direct costs: 10 times)	$83,000M	
Current Project Estimate	Fraction of ownership in highway bridges	100.0%	8.3%
	Direct corrosion costs		$688.9M
	Estimate of indirect corrosion costs (multiplier applied to direct corrosion costs: 10 times)		$6,889M
	Estimate of overall indirect costs considering all durability problems, deterioration, corrosion, and so on. (multiplier applied to indirect corrosion costs: 1.65)		$11,367M
	Average number of rehabilitated bridges/year		400
	Overall indirect costs per bridge rehabilitation		$28.4M

Additional Costs/Savings

When new methods/materials are implemented for the first time, the implementation costs of new methods/materials would be higher than those of current methods, due to initial small volume of use. But the costs would decrease as time passes thanks to the learning curve and increased level of diffusion. When the costs of new technologies are more expensive than the current costs, they will be considered as additional costs even though the implementation of new technologies enhances performance of bridges in terms of deterioration prevention. In contrast, if the new technology costs become cheaper than the current level, they will be considered as savings. Figure VI.6 shows assumed changes in the bridge construction/repair costs caused by the implementation of new technologies in the model. The maximum increase is assumed to be about +6 percent and the maximum decrease to be about -15 percent from the current cost level (100 percent). It would take 15 years to reach the minimum cost level.

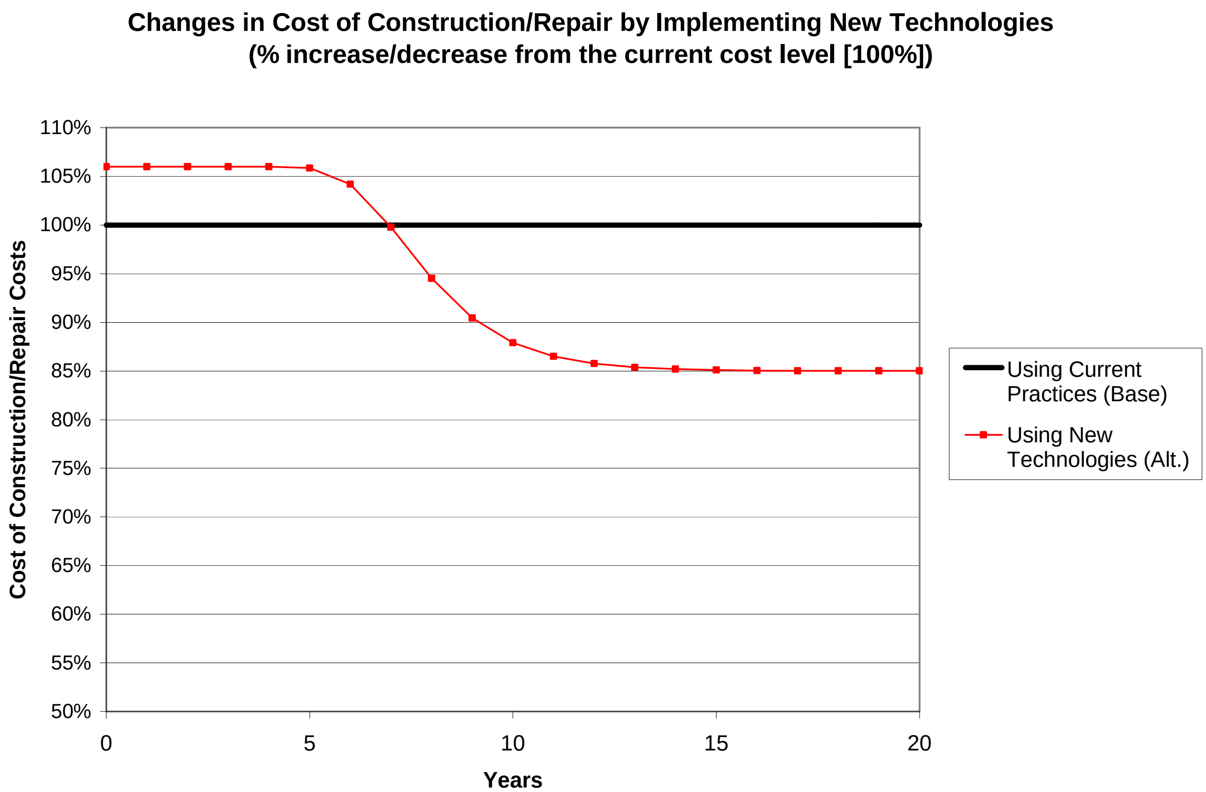

Figure VI.6. Changes in Cost of Construction/Repair.

As a summary, Table VI.11 shows the current project estimates of the monetary values.

Table VI.11. Estimates of Monetary Values.

Costs/Benefits		Current Estimates
Costs	Site Development Costs	$2.75M
	Annual Maintenance Costs	$75.0K
	Annual Operation Costs	$175.0K
Benefits	Annual Revenue	$37.5K
	Savings in User Costs (per one bridge replacement/rehabilitation)	$28.4M
Additional Costs/Savings	Additional Costs/Savings by Implementation of New Methods	Implementation costs/savings are assumed to follow an inversed S-curve.

For the costs of replacement/rehabilitation and new bridge construction, average costs were used in the model. Estimates were based on the data in Appendix I, which provides information about the annual numbers of bridges replaced/rehabilitated and new location bridges and the funds of the corresponding projects. Table VI.12 shows the estimated average costs per replacement/rehabilitation and per new location bridge. These estimates were made for on-system bridges.

Table VI.12. Estimates of Average Costs of Bridge Construction/Rehabilitation.

	2002	2003	2004	2006	Average Cost
Replacement/Rehabilitation	$0.90M	$1.84M	$1.54M	$1.23M	**$1.38M**
New Construction	$1.95M	$2.33M	$1.71M	$1.71M	**$1.92M**

APPENDIX VII. FHWA DATA ON BRIDGE AGE

The National Bridge Inventory in the Federal Highway Administration provides information about the age of highway bridges. The information shows the number of bridges by age, how many bridges are structurally deficient by age, and how many bridges are functionally obsolete, also by age. The data cover all states in the U.S. from year 2000 to year 2006. Tables VII.1 through VII.7 show the data for Texas. Unfortunately, these original data have some discrepancies such that some numbers for the same time period in tables are different. For the data about other states, refer to the FHWA National Bridge Inventory website *(28)*.

Table VII.1. Texas Bridges by Year Built (as of December 2000).

Yr Built	All Bridges	Structurally Deficient Bridges	Functionally Obsolete Bridges
1996-2000	1,662	0	0
1991-1995	2,872	0	0
1986-1990	4,518	152	875
1981-1985	2,799	146	541
1976-1980	2,721	113	400
1971-1975	3,545	87	459
1966-1970	4,613	154	627
1961-1965	5,062	239	823
1956-1960	5,005	336	959
1951-1955	3,037	259	621
1946-1650	2,786	397	520
1941-1945	947	115	140
1936-1940	3,066	497	435
1931-1935	2,193	186	236
1926-1930	1,701	276	232
1921-1925	729	101	110
1916-1920	214	96	41
1911-1915	65	37	15
1906-1910	61	42	5
1900-1905	90	69	10

Table VII.2. Texas Bridges by Year Built (as of December 2001).

Yr Built	All Bridges	Structurally Deficient Bridges	Functionally Obsolete Bridges
2001	7	0	0
1996-2000	2,065	0	0
1991-1995	2,887	13	171
1986-1990	4,510	145	894
1981-1985	2,788	137	552
1976-1980	2,704	106	401
1971-1975	3,606	82	502
1966-1970	4,596	152	635
1961-1965	5,025	227	839
1956-1960	4,968	313	957
1951-1955	3,014	245	629
1946-1950	2,764	374	537
1941-1945	937	111	144
1936-1940	3,036	474	444
1931-1935	2,184	184	231
1926-1930	1,691	274	234
1921-1925	724	105	104
1916-1920	211	92	40
1911-1915	62	34	16
1906-1910	57	39	5
1900-1905	86	64	10

Table VII.3. Texas Bridges by Year Built (as of December 2002).

Yr Built	All Bridges	Structurally Deficient Bridges	Functionally Obsolete Bridges
2001-2002	261	0	0
1996-2000	2,480	0	0
1991-1995	2,939	19	271
1986-1990	4,513	145	883
1981-1985	2,784	132	543
1976-1980	2,702	103	402
1971-1975	3,582	76	509
1966-1970	4,582	153	685
1961-1965	4,979	218	862
1956-1960	4,882	308	967
1951-1955	2,978	225	627
1946-1950	2,697	353	544
1941-1945	917	98	147
1936-1940	2,943	429	434
1931-1935	2,150	170	238
1926-1930	1,655	246	233
1921-1925	696	81	102
1916-1920	210	88	44
1911-1915	60	28	16
1906-1910	55	37	5
1900-1905	83	62	10

Table VII.4. Texas Bridges by Year Built (as of December 2003).

Yr Built	All Bridges	Structurally Deficient Bridges	Functionally Obsolete Bridges
2001-2003	785	0	0
1996-2000	2,762	0	0
1991-1995	3,029	38	394
1986-1990	4,511	153	895
1981-1985	2,772	127	550
1976-1980	2,693	103	404
1971-1975	3,572	78	509
1966-1970	4,542	151	678
1961-1965	4,940	197	845
1956-1960	4,785	295	929
1951-1955	2,914	191	619
1946-1950	2,616	322	515
1941-1945	924	93	139
1936-1940	2,847	375	423
1931-1935	2,128	156	237
1926-1930	1,626	231	233
1921-1925	675	69	101
1916-1920	203	88	43
1911-1915	57	30	15
1906-1910	45	28	8
1900-1905	65	51	6

Table VII.5. Texas Bridges by Year Built (as of December 2004).

Yr Built	All Bridges	Structurally Deficient Bridges	Functionally Obsolete Bridges
2001-2004	1,523	0	0
1996-2000	2,962	0	0
1991-1995	3,090	45	511
1986-1990	4,549	150	925
1981-1985	2,775	144	555
1976-1980	2,687	103	400
1971-1975	3,556	81	502
1966-1970	4,494	143	660
1961-1965	4,869	179	852
1956-1960	4,668	266	929
1951-1955	2,871	175	614
1946-1950	2,542	288	505
1941-1945	911	87	124
1936-1940	2,757	323	408
1931-1935	2,107	153	218
1926-1930	1,581	198	242
1921-1925	665	65	101
1916-1920	195	79	44
1911-1915	54	27	14
1906-1910	38	24	7
1900-1905	58	50	4

Table VII.6. Texas Bridges by Year Built (as of December 2005).

Yr Built	All Bridges	Structurally Deficient Bridges	Functionally Obsolete Bridges
2001-2005	2,211	0	0
1996-2000	3,062	0	0
1991-1995	3,101	58	637
1986-1990	4,544	154	927
1981-1985	2,750	132	557
1976-1980	2,675	99	407
1971-1975	3,534	72	547
1966-1970	4,458	122	731
1961-1965	4,820	171	895
1956-1960	4,600	243	927
1951-1955	2,840	161	620
1946-1950	2,458	252	490
1941-1945	894	86	118
1936-1940	2,686	304	401
1931-1935	2,072	149	217
1926-1930	1,546	176	239
1921-1925	663	56	100
1916-1920	178	64	41
1911-1915	51	24	14
1905-1910	39	22	9
1904 and earlier	44	40	2

Table VII.7. Texas Bridges by Year Built (as of December 2006).

Yr Built	All Bridges	Structurally Deficient Bridges	Functionally Obsolete Bridges
2002-2006	2,319	0	0
1997-2001	3,067	0	0
1992-1996	2,970	54	538
1987-1991	4,550	138	947
1982-1986	3,056	149	630
1977-1981	2,555	89	443
1972-1976	3,176	64	523
1967-1971	4,497	123	672
1962-1966	4,735	143	859
1957-1961	4,704	218	1,004
1952-1956	3,026	152	588
1947-1951	2,691	227	595
1942-1946	772	74	114
1937-1941	2,552	251	373
1932-1936	1,991	166	224
1927-1931	1,726	166	244
1922-1926	774	56	113
1917-1921	225	68	51
1912-1916	53	21	15
1906-1911	37	21	6
1905 and earlier	46	39	4

APPENDIX VIII. ALTERNATE APPROACH: TIME BETWEEN REPAIRS FOR BRIDGES IN THE COASTAL ZONE

This model is a simple cost-benefit model. As a computer model, it was developed to permit the calculation of costs and benefits under alternate assumptions. It assumes that bridges are located in the Texas coastal zone, where current conventional designs, materials, and processes have reduced the time between repairs to ten years. It assumes, for simplicity, that repairs on the bridges in the Texas coastal zone that use improved materials and processes developed and proven at the proposed marine exposure test site would last twice as long, i.e., twenty years. The model does not account for cost savings for bridges outside the coastal zone, although, as noted earlier in this report, there are substantial numbers of structurally deficient bridges in Texas far from the coastal zone, and these areas would also benefit from the developments of the proposed marine exposure test site. This model also does not consider pavements and other types of transportation facilities. Undoubtedly these other applications would exhibit benefits as well, but they are not captured in this model. Therefore, the results of the present model should be considered a lower bound on the total potential savings in Texas. The principle here is that, if the cost of the proposed marine exposure test site is justified based on only a fraction of the total statewide benefits, then the facility is cost-beneficial and further estimates of benefits are unnecessary to make a decision.

Figure VIII.1 was generated by this model for the parameters given below.

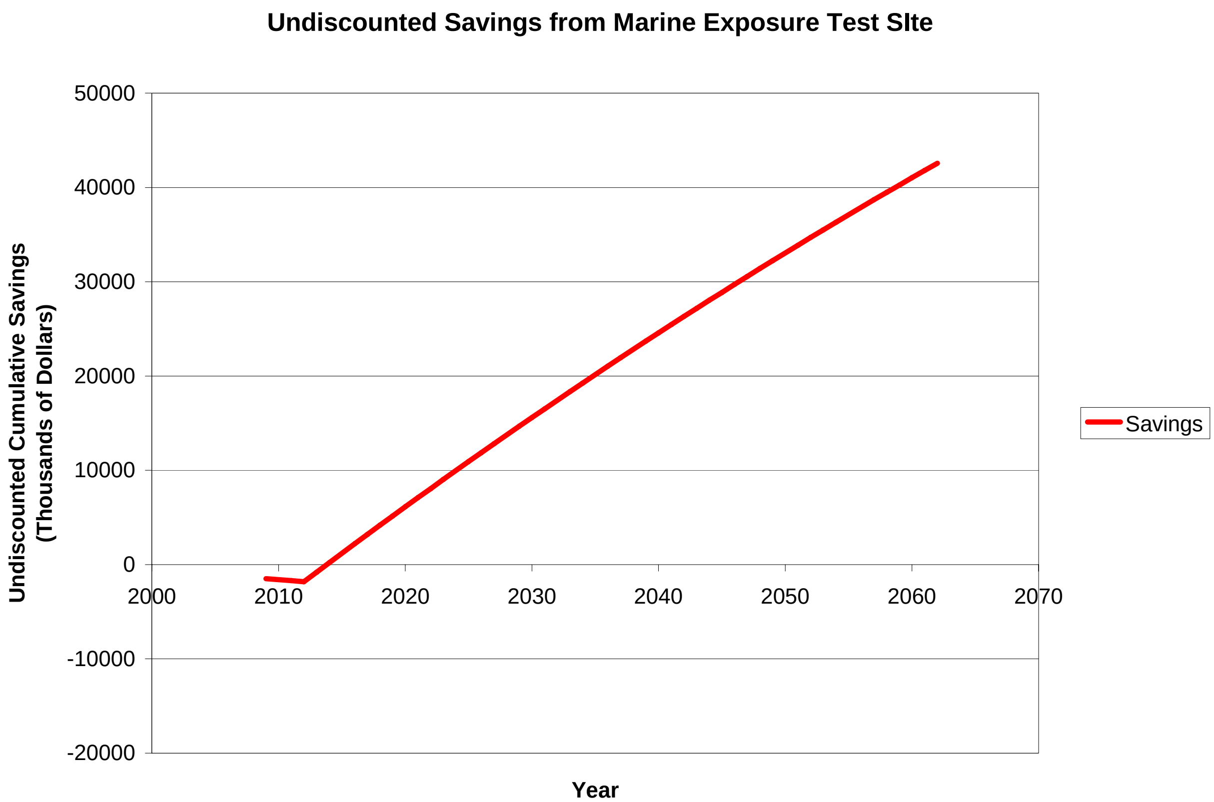

Figure VIII.1. Undiscounted Savings from Marine Exposure Test Site.

Figure VIII.I plots the net of costs and benefits, not discounted, comparing bridges with time between repairs = 20 years with bridges with time between repairs = 10 years, for 50 years forward (i.e., 25 bridge repairs per year using conventional methods and materials and 12.5 bridge repairs per year using improved method and materials).

Figure VIII.2 below shows the same model with the benefits discounted to the present.

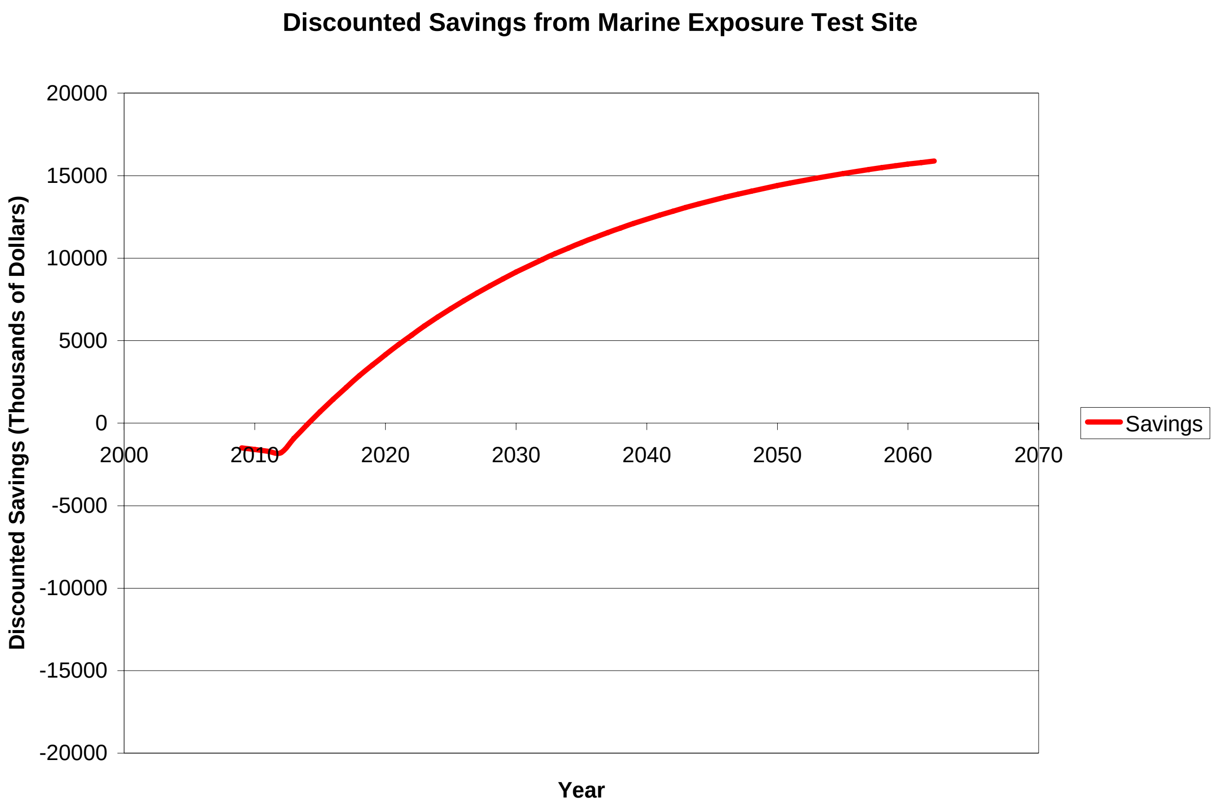

Figure VIII.2. Discounted Savings from Marine Exposure Test Site.

The following assumptions are used to generate these plots:

- The Texas marine exposure test site is established in 2009.
- The capital cost of the marine exposure test site is (not including land) $1,500K.
- Annual site operating costs start at $100K per year and increase by $5K per year thereafter.
- Twenty-five bridges are assumed to be repaired per year in the coastal zone by conventional methods. The time between conventional repairs is ten years.
- The cost of a conventional bridge repair is $100K.
- A half of the twenty-five bridges (12.5 bridges) are assumed to be repaired per year in the coastal zone by the improved methods and materials. The time between repairs using improved methods and materials is twenty years.
- TxDOT requires repairs using the new materials, methods, etc., in 2013.

- The cost premium for the research and for the use of the advanced materials and methods developed by the research at the marine exposure test site is 10 percent of the conventional repair cost.
- Annual discount rate is 4 percent.

APPENDIX IX. THE ECONOMIC VALUE OF RESEARCH I: REDUCTION OF REPAIR FREQUENCIES AND COSTS

The development of advanced materials and systems that can reduce maintenance and repair frequencies and costs would be a major activity of the proposed Texas marine exposure test site. This research and development would include improvements in material science, advances in the understanding of deterioration and corrosion mechanisms, and testing and verification of potential commercial products. The initial cost of research can reduce the direct costs associated with the repair or rehabilitation of deteriorated facilities, can reduce the costs to the facility users due to the reduction in user benefits during the time in which the performance of the facility is deteriorating, and can reduce the user costs resulting from the loss of service of the facility while the repairs are being made.

One of the major concerns of the proposed Texas marine exposure test site would be research on materials and processes to increase the time to the first repair and the time between additional repairs. Many high-performance materials and systems are available, but they increase, or are perceived to increase, initial costs, and are therefore seldom used. Consequently, a function of the proposed Texas marine exposure test site would be to conduct research to find ways to reduce the costs of these materials and systems, or to find less expensive replacements, such that they would be used more often. This section develops a simple, generic solution to the question, "How much research on advanced materials and systems to increase time to repair is justified by the subsequent savings in repair costs?"

It is useful to address this question from the bottom up, by addressing the costs of a generic facility. The model compares two alternatives: the economics of a facility to be constructed with advanced materials and processes based on research findings and a functionally identical facility constructed conventionally. As the economic value of the advanced alternatives is obtained over the lifetime of the structure, it is necessary to discount future costs and benefits to the present value. To be specific, suppose that the construction time is identical for both the conventional and the advanced alternatives, say T_0, measured from the present date. The total cost of the initial construction using the conventional approach is estimated to be $\$C_C$ and the total cost of the initial construction using the advanced approach, whatever it is, is estimated to be $\$C_D$. The subscript $_C$ represents conventional materials (as in $\$C_C$) and the subscript $_D$ represents durable materials and advanced methods (as in $\$C_D$).

If it is assumed that both the conventional and advanced alternatives result in a facility with exactly the same flow of benefits then the difference between the two alternate materials options is that, after some time, say z, the conventional construction must be rehabilitated or repaired, at a cost of $\$C_R$. The facility with the advanced approach, however, would need to be rehabilitated or repaired only after a period of n years, where $n > z$.

If $\tilde{k} = \lfloor n/z \rfloor$ where $\lfloor n/z \rfloor$ represents the largest integer $\leq n/z$, then there are $\tilde{k}$ cycles of repair for the conventional construction in about the same time as one cycle of repair for the advanced construction. Define $k = \tilde{k}\text{-}1$. Then in the time period from T_0 to $T_0 + k\,z$, the facility built conventionally would require repair k times, and the facility built with the results of the research would not yet require repair.

The cost for each repair, $\$C_R$, of the conventional alternative is assumed to include the direct costs of repair plus the imputed costs to the users of the facility due to the reduction in benefits during the time in which the performance of the facility is degenerating (for example, damage or loss of service due to potholes, detours, lane restrictions, weight restrictions, and other effects associated with degraded performance), plus the loss of user value resulting from the loss of service of the facility while the repairs are being made.

The flow of benefits to the users is assumed to be the same in both the conventional and the advanced scenarios, except for the value of the loss of service due to deterioration and repair of the facility built with conventional materials, which is assumed, as already discussed, to be captured in the estimated repair cost $\$C_R$. Therefore, the actual benefits stream does not affect the analysis, because it is taken to be identical for both alternatives. Further, it is assumed that the conventional project has been cost-justified on its own merits; that is, the net present worth (PW) of all the costs (including both the initial costs and the future repair costs) equals the net present value of the flow of future benefits at some discount rate r, which is at least as large as the minimum acceptable discount rate for this type of project.

Because the conventional project is economically justified at the discount rate r, the question is how the project using more durable technology compares with the conventional project. On the basis of initial cost only, the conventional alternate would have the advantage, as typically more durable materials and processes are more expensive than conventional (that is,

$\$C_D > \$C_C$), if only because of the effects of scale (by definition, conventional materials and methods are much more often used than durable materials and advanced methods), unless there are some offsetting savings in construction time or cost using the advanced approach. If $\$C_D \leq \$C_C$, then the more durable methodology would be less expensive on an initial cost basis and no further analysis would be needed. However, in the more typical case, the initial costs of the advanced systems are higher than those of the conventional project, although the subsequent repair costs are lower, so the comparison between advanced materials and processes must consider the combined life-cycle costs on a discounted present value basis.

Instead of attempting to estimate the additional costs directly, the present analysis examines the complementary question: How much more could the advanced material cost, including the distributed costs of research and development, relative to the conventional approach, and still be more economical than the conventional approach on a life-cycle cost basis? Here, a critical value of $\$C_D / \$C_C$ is defined such that, if the ratio of cost using advanced systems to the conventional cost is less than this critical value, then the advanced approach would be more economical and should be used. That is, the method used here estimates the approximate ratio of these costs without estimating their actual dollar amounts.

Assume for simplicity, as shown in Figure IX.1, that the cost of construction in either scenario can be approximated by a discrete cash flow at the endpoint of the construction period; that is, at time T_0, when the facility is put into service. This assumption is the same for both alternatives, and avoids the need to make estimates of the construction cash flows over time, which are approximately the same for both alternatives. Also, as will be seen later, this assumption allows the construction time T_0 to be eliminated from the resulting equations, resulting in some simplification to the model. With this assumption, the present worth discounted to the present (that is, to time 0) of each initial construction alternative, using the discount rate r and standard engineering economics notation, is:

$$PW_{CC} = \frac{\$C_C}{(1+r)^{T_0}} \quad (1)$$

for the initial cost using the conventional approach and

$$PW_{DC} = \frac{\$C_D}{(1+r)^{T_0}} \tag{2}$$

for initial cost using the advanced methodology.

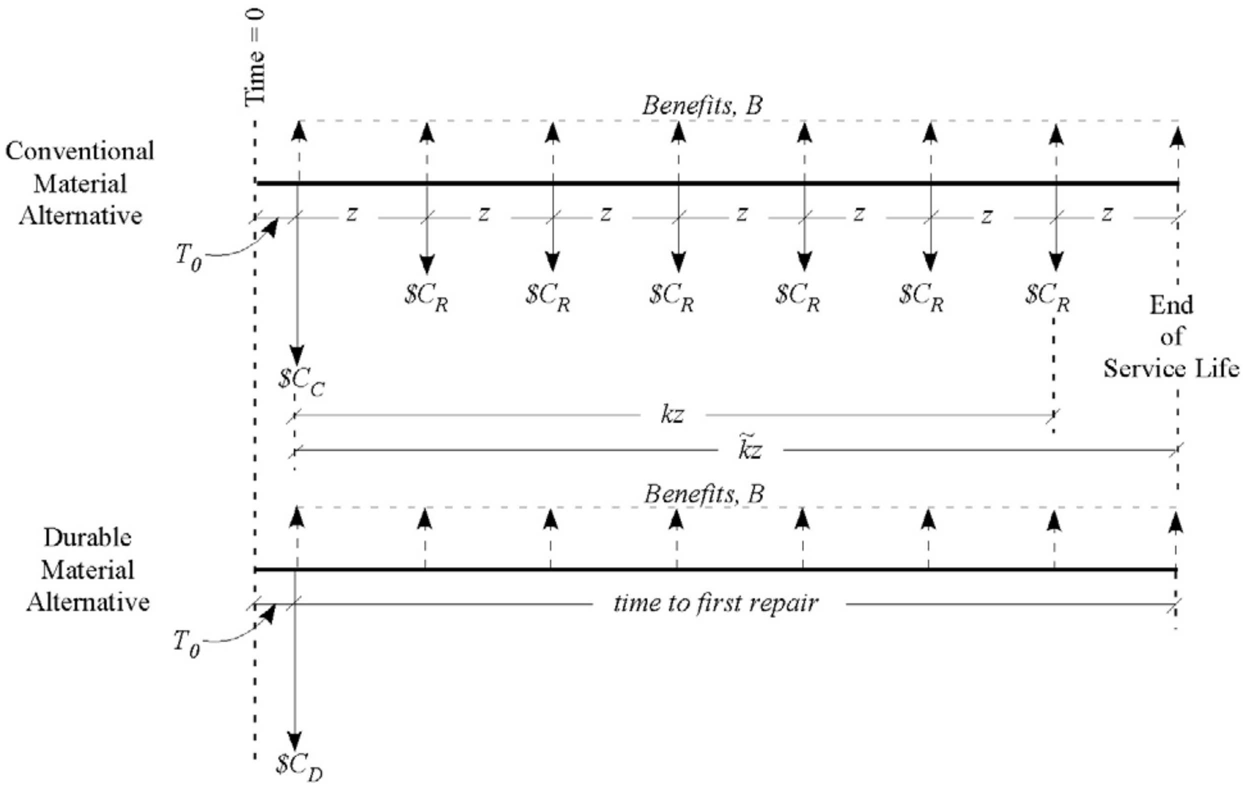

Figure IX.1. Flows of Benefits and Repair Costs for Projects Built with Conventional and Unconventional Materials and Processes.

In the conventional facility the present worth of all future repairs is the present worth of a series of k repairs starting at time $T_0 + z$ and spaced at time-to-repair z (see Figure IX.1):

$$PW_{CR} = \frac{\left(\sum_{j=1}^{k} \frac{\$C_R}{(1+r)^{jz}} \right)}{(1+r)^{T_0}} \tag{3}$$

It is assumed for simplicity that the real repair cost $\$C_R$ is the same for all future repairs; hence inflation, if any, is subsumed in the overall discount rate r. The present worth of the costs of repairs for the facility constructed with advanced processes is zero, as the advanced system eliminates the need for periodic repairs:

$$PW_{DR} = 0 \tag{4}$$

The total present value of the costs, including initial construction and future repair costs, for the conventional facility is $PW_{CC} + PW_{CR}$, and the corresponding present worth for the advanced system is PW_{DC}. Then the advanced alternative should be preferred if its present value of all future costs is less than or equal to that for the conventional alternative; that is, if:

$$PW_{DC} \leq PW_{CC} + PW_{CR} \tag{5}$$

Using Equations 1, 2, 3, and 4 in Equation 5 gives the following condition for the advanced, durable alternative having the lower cost:

$$\frac{\$C_D}{(1+r)^{T_0}} \leq \frac{\$C_C}{(1+r)^{T_0}} + \left(\sum_{j=1}^{k} \frac{\$C_R}{(1+r)^{jz}} \right) \frac{1}{(1+r)^{T_0}} \tag{6}$$

Multiplying all the terms in Equation 6 by $(1+r)^{T_0}$, dividing by $\$C_C$, and collecting the terms' results in the following expression for the condition in which the advanced approach is less expensive (on a discounted basis):

$$\frac{\$C_D}{\$C_C} \leq 1 + \frac{\$C_R}{\$C_C} \left(\sum_{j=1}^{k} \frac{1}{(1+r)^{jz}} \right) \tag{7}$$

This equation may be stated succinctly as:

$$\frac{\$C_D}{\$C_C} \leq 1 + \frac{\$C_R}{\$C_C} F(r,z,k) \tag{8}$$

Where $F(r,z,k)$ is a factor independent of all costs:

$$F(r,z,k) = \sum_{j=1}^{k} \frac{1}{(1+r)^{jz}} . \tag{9}$$

This result indicates that the construction alternative using the advanced system would be more cost effective over the facility life-cycle than the conventional alternative as long as the initial cost ratio is less than the critical value given by Equation 8. In this expression, $\$C_D / \$C_C$ is the ratio of the initial cost using the advanced methodology compared to the initial cost conventionally; $\$C_R / \$C_C$ is the ratio of the cost of repair (including the value of lost user benefits due to deterioration and during repair) to the initial cost for the conventional materials; z is the expected time-to-repair for the facility built conventionally; $k \cong n/z-1$; and r is the discount rate.

The series expression in Equation 9 can be conveniently simplified to avoid the use of summations by first noting the following identity, which may be derived from the expansion of the binomial series, for any arbitrary positive integer k:

$$\sum_{j=1}^{k} x^{j} = \frac{\left(x-x^{k+1}\right)}{\left(1-x\right)}, \text{ for } |x|<1 \tag{10}$$

Setting $x=\dfrac{1}{\left(1+r\right)^{z}}$ in Equation 10 gives:

$$\sum_{j=1}^{k}\left(\frac{1}{1+r}\right)^{jz} = \frac{\left(\frac{1}{1+r}\right)^{z}-\left(\frac{1}{1+r}\right)^{z(k+1)}}{\left[1-\left(\frac{1}{1+r}\right)^{z}\right]} \tag{11}$$

or,

$$\sum_{j=1}^{k}\left(\frac{1}{1+r}\right)^{jz} = \frac{\frac{1}{\left(1+r\right)^{z}}-\frac{1}{\left(1+r\right)^{(k+1)z}}}{1-\frac{1}{\left(1+r\right)^{z}}} \tag{12}$$

But, by Equation 9,

$$F\left(r,z,k\right)=\sum_{j=1}^{k}\frac{1}{\left(1+r\right)^{jz}} \tag{13}$$

After further algebraic manipulation, this expression reduces to:

$$F(r,z,k)=\frac{1-(1+r)^{-kz}}{(1+r)^{z}-1} \tag{14}$$

Equation 14 can be used in Equation 8 for determining the critical ratio of $\$C_D / \$C_C$ as follows:

$$\frac{\$C_D}{\$C_C} \le 1+\frac{\$C_R}{\$C_C}F(r,z,k)=1+\left(\frac{\$C_R}{\$C_C}\right)\left[\frac{1-(1+r)^{-kz}}{(1+r)^{z}-1}\right] \tag{15}$$

We can rewrite this as a percentage:

$$100\left(\frac{\$C_D}{\$C_C}-1\right)\leq 100\left(\frac{\$C_R}{\$C_C}\right)F(r,z,k)=100\left(\frac{\$C_R}{\$C_C}\right)\left[\frac{1-(1+r)^{-kz}}{(1+r)^{z}-1}\right] \tag{16}$$

As an illustration, assume that:

- the discount rate is 4 percent ($r = 0.04$),
- the average periodic repair cost is about 10 percent of the initial cost of the facility ($\$C_R / \$C_C = 0.1$),
- repairs are done about once every 10 years ($z = 10$), and
- the service life of the facility is more than 50 and less than 60 years ($k = 5$).

Inserting these values into Equation 16, the advanced methods are more economical based on life-cycle costs if:

$$100\left(\frac{\$C_D}{\$C_C}-1\right)\leq 100\left(0.1\right)\left[\frac{1-(1.04)^{-50}}{(1.04)^{10}-1}\right]$$

or, (17)

$$100\left(\frac{\$C_D}{\$C_C}-1\right)\leq 10\left[1.789\right]=18\%$$

That is, when considering total life-cycle costs, as long as the initial cost of the advanced technology (with no repairs required in the facility's service life) is no more than 18 percent higher than the conventional initial cost, the advanced material solution is the most economical solution. In other words, an advanced technology that would allow a facility to last over 50 years without repair could initially cost up to 18 percent more than a conventional facility (that requires repair every 10 years) and still be competitive with the conventional facility on a life-cycle basis. This differential is, of course, to be apportioned among distributed research and development costs, additional material and process costs, if any, for the advanced technology, and life-cycle cost savings to TxDOT. Then the answer to the question posed above, "How much research and advanced materials and systems development can be paid for out of life-cycle cost savings?" is: up to 18 percent of the conventional project initial cost, given that the advanced method achieves the goal of eliminating the need for repairs for 50 years. Of course it is the business of the research program to demonstrate by testing that the advanced methodology can achieve this goal.

Conclusions

A significant number of materials are currently on the market to enhance the durability and performance of facilities. This section has derived equations and methodologies that can be used to determine if research into advanced materials, processes, and technology is cost-effective.

APPENDIX X. THE ECONOMIC VALUE OF RESEARCH II: THE ECONOMIC VALUE OF EXTENDING SERVICE LIFE OF INFRASTRUCTURE

Introduction

All project owners are interested in reducing project costs. However, in many cases, extending service life is economically justified even if initial cost is increased, especially when the service life of the facility is reduced due to environmental conditions, deterioration, and corrosion, such at the Texas gulf coast zone. One research objective of the proposed Texas marine exposure test site would be to assist in developing new technology, methodologies, or processes to reduce project capital costs, reduce maintenance and repair costs, and increase service life. However, research costs money.

Extended Service Life

Note that the derivation given here generally follows the presentations in Reinschmidt and Trejo [2006] (*29*), Trejo and Reinschmidt [2006] (*30*), Trejo and Reinschmidt [2005] (*31*), and Trejo and Reinschmidt [2003] (*32*).

The issue addressed here is, first, to determine how much the present value of an infrastructure project increases if the service life is increased through the development of new materials, processes, and technologies that reduce deterioration and corrosion, which is the function of the Texas marine exposure test site. That is, the present value of the benefits of increased service life is reduced by the costs of research at the Texas marine exposure test site and the increased initial cost, if any, of the materials and methods required to achieve this increased service life. The question addressed here is, "How much could be expended on research by the proposed Texas marine exposure test site and still have positive benefits due to increased service life?"

It is assumed here that it is possible to increase the project service life at some commensurate increase in research and development cost. Then simple models are developed to determine how much TxDOT could afford to pay to enhance the service life of facilities, as justified by the increase in economic benefits, to show that the economic surplus generated by increased project service life can pay for the research, development, and implementation of new materials, methods, and technologies.

Present Worth Analysis of Projects

A precise evaluation of the economic value of increasing project service life can be obtained in specific instances by analysis of the projected future time history of the project expenditures and the benefits of extended service life. Comparison of alternatives for service life can readily be performed by computer. Such calculations are typically project specific, however. Moreover, high precision in calculations may not be justified, considering that all the figures are forecasts, and hence uncertain. This discussion derives approximate formulas suitable for drawing some general conclusions by making some simplifying assumptions.

Figure X.1 represents a simplified cost-benefits situation for a generic infrastructure project, consisting of an investment phase followed by an operational phase. Project development completes at time 0, and the net benefits from the project, R_o per year, start at time 0 when the project is placed in service and starts to produce economic benefits, and extend to time n, where n is the service lifetime of the project. Note that this discussion applies to any project, no matter what its type, in which service life may be limited by deterioration and/or corrosion, and which may be improved by research performed at or by the Texas marine exposure test site.

Net benefits are the total discounted benefits to the users that are attributed to the project, less all variable costs of facility operations, maintenance, and repair, such as labor, consumables, energy, and materials. It may seem that R_o would be very difficult to estimate without detailed knowledge of the project's economic justification, but in fact, as will be seen later, the R_o term disappears from many of the results. It is assumed here that all TxDOT projects are justified on a cost-benefit basis, and that proposed projects that are not justified on a cost-benefit basis are not executed.

It is also assumed here that the benefit stream is uniform over time. This assumption is considered conservative, because in general the users of infrastructure are constantly increasing, and therefore the total benefits of the facility should also be increasing in time.

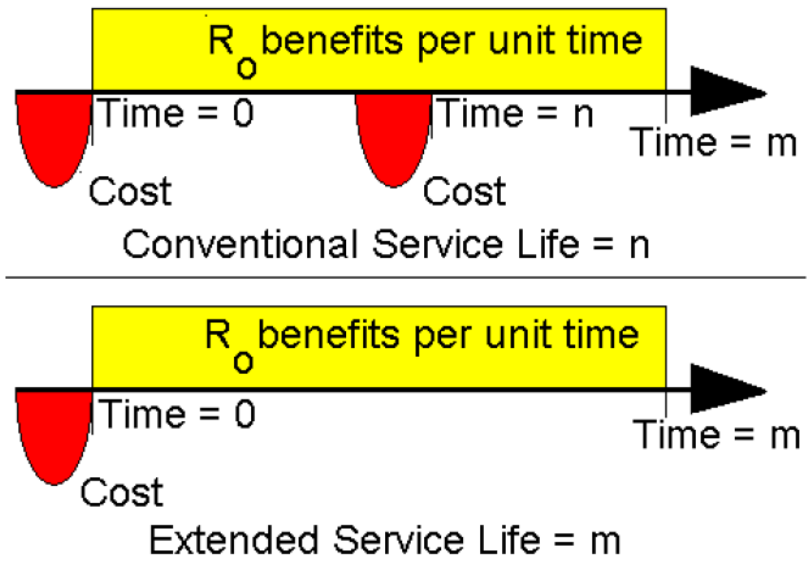

Figure X.1. Project Cash Flows, Conventional and Extended Service Life.

To obtain a simple model for service life extension, we compare two cases, as diagrammed in Figure X.1. The first case is a facility built with conventional materials and methods, which, due to environmental conditions, has an effective service life of *n* years. The second case is a facility in the identical location, but built in a more durable way using materials and methods based on research at the proposed Texas marine exposure test site. To compare these two cases, we need an expression for the net present worth of the uniform series of benefits. The concern here is with generic projects, and so in the absence of explicit information about a particular project's economic benefits, we assume the simplest possible case, one with uniform benefits per unit time. Thus R_o is a constant representing the rate, in as-spent dollars per unit time, of the net benefits due to the facility. Then the present worth, *PW*, of the amount R_o of benefits obtained in time interval (e.g., year) *k*, at some discount rate *r*, is, using the usual present value equation:

$$PW = \frac{R_o}{(1+r)^k} \qquad (1)$$

Then, for a discrete uniform series starting at time *a* and continuing through time *b*, the present worth of the benefit stream is the sum of the discounted benefits over all of the facility service life:

$$PW = \sum_{k=a+1}^{b} \frac{R_o}{(1+r)^k} = R_o\left[\frac{1}{(1+r)^{a+1}} + \frac{1}{(1+r)^{a+2}} + \ldots + \frac{1}{(1+r)^k} + \ldots + \frac{1}{(1+r)^b}\right] \quad (2)$$

Multiply this expression by (1 + r) to obtain:

$$(1+r)PW = \sum_{k=a+1}^{b} \frac{R_o}{(1+r)^{k-1}} = R_o\left[\frac{1}{(1+r)^{a}} + \frac{1}{(1+r)^{a+1}} + \ldots + \frac{1}{(1+r)^{k-1}} + \ldots + \frac{1}{(1+r)^{b-1}}\right] \quad (3)$$

Subtract the first expression from the second to obtain:

$$rPW = R_o\left[\frac{1}{(1+r)^a} - \frac{1}{(1+r)^b}\right] \quad (4)$$

Dividing by r (for r not zero) gives the present worth of a uniform series from a to b:

$$PW = \frac{R_o}{r}\left[\frac{1}{(1+r)^a} - \frac{1}{(1+r)^b}\right] \quad (5)$$

Consider the stream of net benefits shown in Figure X.1. Under the simplifying assumption that these net benefits are constant in time, with value \$$R_o$ per unit time, the present worth (at time 0) of the benefit stream, $PW_b(r, n)$, can be calculated by using the above formula, with a = 0 and b = n years:

$$PW_b(r,n) = \left(\frac{R_o}{r}\right)\left\{\left[\frac{1}{(1+r)}\right]^0 - \left[\frac{1}{(1+r)}\right]^n\right\} \quad (6)$$

Where n = the project service lifetime;
r = the discount rate; and
$PW_b(r, n)$ = the present worth of the net benefits stream starting at time 0, at discount rate r. Note that, to simplify this formulation by using the minimum number of parameters, future quantities are discounted to time zero, the time in which the project is completed. To discount to the start of the project, apply the additional discount term $\frac{1}{(1+r)^{T_o}}$, where T_o is the project development time.

Equation 6 can also be expressed as:

$$PW_b(r,n) = \frac{R_o}{r}\left[1-(1+r)^{-n}\right] = \frac{R_o}{r}\left[\frac{(1+r)^n - 1}{(1+r)^n}\right] \quad (7)$$

If the discount rate, r, is 0, it can be shown that Equation 7 reduces to $PW_b(0, n) = nR_o$, which is just the undiscounted total of the net benefits over the project lifetime (the area of the benefits rectangle in Figure X.1).

From Equation 7 it is readily apparent that if the service life n were longer, other things remaining constant, the present value $PW_b(r, n)$ of the benefit stream would increase. That is, longer facility service life adds value, and this added value is then available to justify the research program to develop the technology to extend service life.

The derivation above concerns only the present worth of the project benefit stream. For any distribution of the project costs over time, we can determine the present value of the costs, at discount rate r as $PW_c(r)$. The total net present worth of the project is the algebraic sum of the present value of the net benefits less the present value of the costs (subscript b denotes the benefit side; subscript c denotes costs):

$$PW(r) = PW_b(r,n) - PW_c(r) \qquad (8)$$

Given a discount rate and a numerical value for the benefits, this formula can be used to find the net present value. Or, to find the internal rate of return, which is the value of the discount rate that actually applies to a given combination of costs and benefits, set the total net present value in Equation 3 to zero, and solve for r. Call this solution r_o. Then Equation 3 may be written as:

$$PW(r_o) = 0 = PW_b(r_o, n) - PW_c(r_o) \qquad (9)$$

or,

$$PW_c(r_o) = PW_b(r_o, n) \qquad (10)$$

That is, at the actual discount rate or internal rate of return r_o, the present worth of the project costs must exactly equal the present worth of the project's net benefits available to offset the capital costs over its economic lifetime. Conversely, one can say that r_o is the rate of return that just balances the present worth of the project's costs and the project's net benefits.

Consider now Figure X.2, which plots the net present worth of the benefit stream throughout the facility service life (years on the x axis), $PW_b(r_o, n)$, at the discount rate r_o, for all values of the project service life n. Suppose that r_o represents the decision maker's minimum acceptable rate of return on investment, and that the decision maker finds any project with this rate of return to be equally acceptable. Then any point on this curve has rate of return r_o and is therefore acceptable to the decision maker. This curve is called an *indifference curve* because a risk-neutral decision-maker, making decisions based entirely on rate of return, would be indifferent between any of the points on the curve.

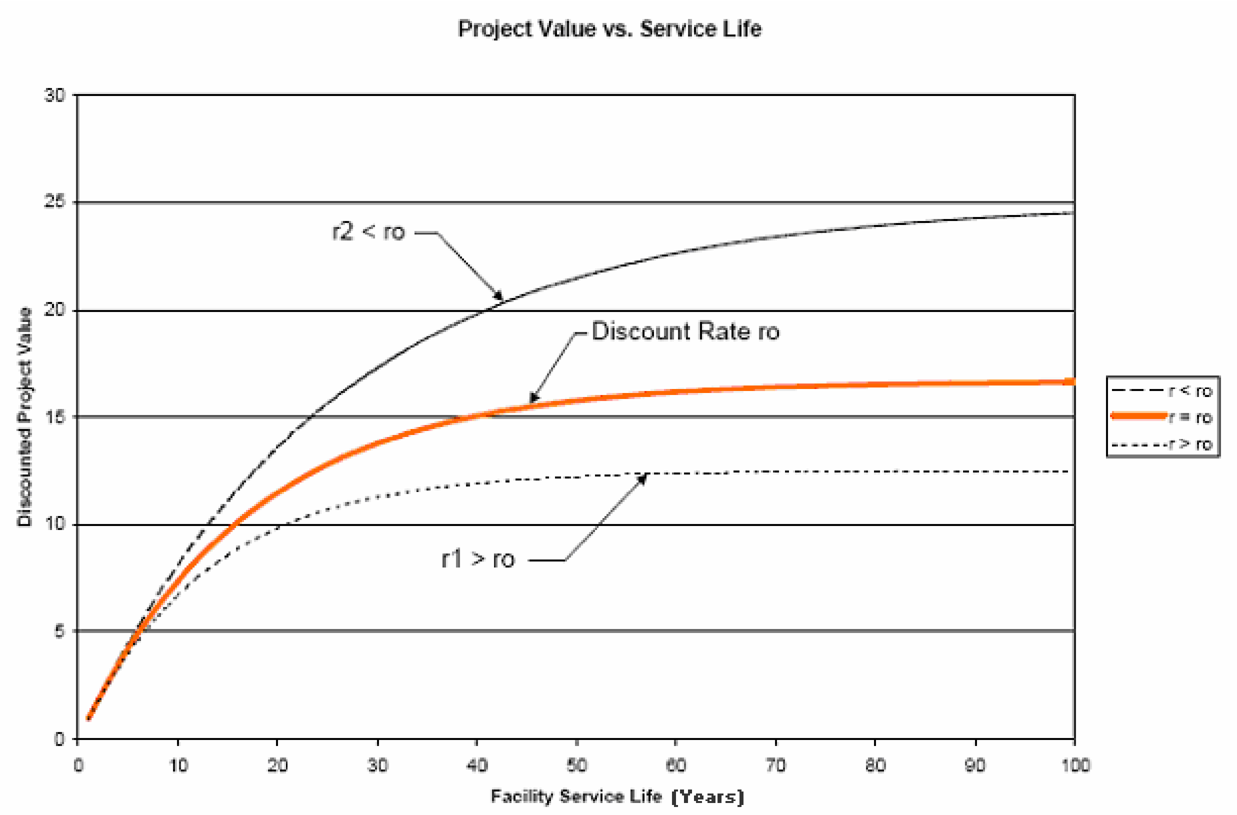

Figure X.2. Indifference Curves for Rate of Return.

Also shown in Figure X.2 is the indifference curve for discount rate $r_1 > r_o$. Because the decision-maker will accept any project with discount rate r_o, any project with discount rate $r_1 > r_o$ indicates a better return and is preferable. Conversely, the indifference curve for discount rate $r_2 < r_o$ is not acceptable to the decision-maker if r_o is his minimum rate of return.

Now, the question is, what is the present worth of the benefit stream for projects that are the same except one has a longer service life, $m > n$? The difficulty of comparing alternatives that have different periods or service lives is well known in engineering economics. Here a typical simplification is used, in which two alternatives are compared; one, the *conventional project*, with service life n; and the other, the *quality project*, with service life m, where $m = 2n$. That is, we assume that the need for the facility will exist through at least year m, where m is an integer multiple of n, and this need can be met by one of two alternatives:

- Two *conventional projects* in series, the first completed in year 0 and the second built at year *n*, to replace the first facility after it reaches the end of its service life. It is also assumed that the second project is built while the first is still functional, so there is no gap in service, no loss of user benefits during construction, and no need to consider the second project delivery time. This assumption is conservative in that deterioration of the first facility at the end of its service life, and the construction of the follow-on project, may well reduce user benefits.
- One *quality project*, built in year 0, with service life $m = 2n$. It is assumed that *m* is large enough that events beyond this time do not have a significant effect on the decision needed now.

In this way both alternatives cover identical periods, of length *m*. Therefore, both have the exact same benefit streams. Hence the present value of the benefits is identical for both alternatives. The difference is that the conventional approach must build two projects in series.

The present value of the benefits for the two conventional projects can be obtained by substituting the appropriate durations in the general equation above. Then, for the first conventional project, in service from time 0 to time *n*, from Equation 6, with $r = r_o$, $a = 0$, and $b = n$:

$$PW_b(1, r_o, n) = \left(\frac{R_o}{r_o}\right)\left\{\left[\frac{1}{(1+r_o)}\right]^0 - \left[\frac{1}{(1+r_o)}\right]^n\right\} \quad (11)$$

This can be rewritten as

$$PW_b(1, r_o, n) = \left(\frac{R_o}{r_o}\right)\left\{\frac{(1+r_o)^n - 1}{(1+r_o)^n}\right\} \quad (12)$$

The second conventional project is in service from time *n* to time 2*n*, so Equation 6 becomes:

$$PW_b(2, r_o, n) = \left(\frac{R_o}{r_o}\right)\left\{\left[\frac{1}{(1+r_o)}\right]^n - \left[\frac{1}{(1+r_o)}\right]^{2n}\right\} \quad (13)$$

This expression can be rewritten as:

$$PW_b(2, r_o, n) = \left(\frac{R_o}{r_o(1+r_o)^n}\right)\left\{\frac{(1+r_o)^n - 1}{(1+r_o)^n}\right\} \quad (14)$$

As these values are fully discounted, the present value of the two conventional projects to provide service life out to time *2n* is simply the sum of the two, or:

$$PW_b(1+2,r_o,n)=\left(\frac{R_o}{r_o}\right)\left\{\frac{(1+r_0)^n-1}{(1+r_o)^n}\right\}+\left(\frac{R_o}{r_o}\right)\left(\frac{1}{(1+r_o)^n}\right)\left\{\frac{(1+r_0)^n-1}{(1+r_o)^n}\right\}$$
$$PW_b(1+2,r_o,n)=\left(\frac{R_o}{r_o}\right)\frac{\left[(1+r_o)^{2n}-1\right]}{(1+r_o)^{2n}} \tag{15}$$

For the single quality project with service life $m = 2n$, the same analysis is done. From Equation 6,

$$PW_b(r_o,m)=\left(\frac{R_o}{r_o}\right)\left\{\left[\frac{1}{(1+r_o)}\right]^0-\left[\frac{1}{(1+r_o)}\right]^m\right\}$$
$$PW_b(r_o,m)=\frac{R_o}{r_o}\left\{1-\frac{1}{(1+r_o)^m}\right\}=\left(\frac{R_o}{r_o}\right)\frac{\left[(1+r_o)^m-1\right]}{(1+r_o)^m} \tag{16}$$
$$PW_b(r_o,m)=\left(\frac{R_o}{r_o}\right)\frac{\left[(1+r_o)^{2n}-1\right]}{(1+r_o)^{2n}}$$

Comparison of Equations 15 and 16 demonstrates that the present worth of the benefits stream over the future period *m* is identical for the two alternatives considered; the convention project with service life *n*, and the quality project with service life $m = 2n$.

However, the quantity of interest here is the project cost. Let C_o be the cost of the first conventional project, discounted to the project completion date at time zero. Then the present worth of the second conventional project, making the conservative assumption that the cost at time *n* is the same as that at time 0, is:

$$PW_c(C_o,r_o,n)=\frac{C_o}{(1+r_o)^n} \tag{17}$$

Then the total present value of the two conventional projects is the sum of them both:

$$PW_c(2C_o,r_o,n)=\left[1+\frac{1}{(1+r_o)^n}\right]C_o \tag{18}$$

Let C' be the cost of the quality project at completion at time 0, so $PW_c(C') = C'$. From the above derivations, it was seen that:

- if r_o is the rate of return on the conventional project, then the project sponsor is indifferent to the quality project compared to the conventional project if the rate of return on the quality project is also r_o, or greater;
- at the rate of return r_o, the present worth of the net cost is equal to the present worth of the net benefits; and
- the present worth of the net benefits is the same for the conventional approach and the quality project.

The conclusion then is that the present worth of the cost of the quality project can be as large as the present worth of the conventional project and still achieve the rate of return r_o. Consequently, the quality project is to be preferred if:

$$\begin{aligned} &PW(C') \le PW_c(2C_o, r_o, n) \\ &C' \le C_o\left[1 + \frac{1}{(1+r_o)^n}\right] \end{aligned} \tag{19}$$

Therefore, the maximum percentage increase in initial cost such that the quality project is preferred to the conventional project is:

$$\begin{aligned} &C' \le C_o\left[1 + \frac{1}{(1+r_o)^n}\right] = C_o\left[1 + \frac{1}{(1+r_o)^n}\right] \\ &\frac{C'}{C_o} \le \left[1 + \frac{1}{(1+r_o)^n}\right] \\ &\frac{C'-C_o}{C_o} \le \frac{1}{(1+r_o)^n} \\ &100\left(\frac{C'-C_o}{C_o}\right) \le \frac{100}{(1+r_o)^n} \end{aligned} \tag{20}$$

That is, if the research program at the proposed Texas marine exposure test site can extend the facility service life from *n* to *2n* years, and the percentage increase in the initial cost for the quality project compared to the conventional project, including research costs, is less than or equal to $\frac{100}{(1+r_o)^n}$, then the extended service life project is economically superior. Because of the assumptions made in the derivation of this result, the equation has only two parameters, conventional service life and discount rate, and is not dependent on information about specific costs or benefits.

For example, assuming that $n = 25$ years, then Equation 20 reduces to:

$$\text{Maximum percentage increase } = 100\left[\frac{1}{(1+r_o)^{25}}\right] \tag{21}$$

If $r_o = 0.04$ *per annum*, then Equation 21 gives the maximum percentage increase in project initial cost for a longer service life as:

$$\text{Maximum percentage increase} = \frac{100}{(1.04)^{25}} = 38\% \tag{22}$$

That is, when the internal rate of return on investment r_o is 4 percent, the owner should be willing to invest up to 38 percent more than the cost of the conventional project in research, advanced materials, new methods, and other technology costs in order to extend the service life of the facility from 25 years to 50 years. Note that these costs are discounted costs, not current dollars. In other words, $0.38C_o$ is the present value of savings made by *not* needing to replace the facility in year 25. Obviously an increase in service life from 25 years to 50 years is a large improvement, but is not necessarily out of the question for facilities located near the gulf coast.

If, for example, a project such as a highway bridge is expected to cost $1,000,000 using conventional materials in the gulf coast zone, with an expected service life of 25 years in this environment, then the equation states that one could spend up to $1,380,000 on the initial construction if the research program provided confidence that a replacement would not be needed for 50 years.

Obviously, one project does not justify a research program. Suppose that research into new materials and methods to extend the service life as in the example above is anticipated to cost $2,000,000, and the full cost (discounted) of a marine exposure test site to perform the research is $1,250,000. Suppose that 25 bridges are to be built in the aggressive environment of the coastal zone. Then the initial cost of these 25 bridges with conventional materials and 25-year service lives would be $25,000,000. The maximum initial cost of a bridge using advanced materials and methods to obtain a 50-year service life would, by Equation 21, be $1,380,000. (Note that this maximum initial cost increase is a percentage of the total project cost, not just the materials alone.) Suppose that the cost of these bridges built with advanced materials is expected to be at most 25 percent more than the cost with conventional materials. Allocating the $2,000,000 research cost and the $1,250,000 capital cost of the marine exposure test facility to these 25 bridges only, and not any other projects, the totals would be:

Initial cost of conventional projects with 25-year service lives — $25,000,000

Initial cost premium for more durable materials for 50-year service lives — $6,250,000

Allocated cost of entire research program and exposure test site — $3,250,000

Total — $34,500,000

Average cost per project for 25 projects — $1,380,000

Under this scenario, the full cost of research to extend service life in the gulf coast zone could be recovered on these projects alone, even if the improved materials increased the initial costs of these projects by 25 percent compared to current projects. And insofar as the cost premium is less than 25 percent, and/or the research cost is less than $3,250,000, the initial cost increase would be less than 38 percent, which would translate into a higher rate of return on TxDOT's investment.