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OVERVIEW OF RAILROAD BRIDGES AND ASSESSMENT OF METHODS TO MONITOR RAILROAD BRIDGE INTEGRITY

Office of Research and Development
Washington D.C. 20590

DOT/FRA/ORD-94/20

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Final Report

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13. ABSTRACT (Maximum 200 words)

This report provides background information on the numbers and types of railroad bridges existing in the U.S. The risk to these bridges is discussed including the initiating causes of accidents and their physical effects on bridges. Examples of railroad bridge train accidents are briefly presented. An assessment of existing and new technologies applied to the mission of monitoring railroad bridge integrity in order to prevent railroad accidents is made. Historical railroad bridge accident data is reviewed. Technologies applicable for monitoring railroad bridge structures are identified and discussed. The functional requirements and interfaces required by a bridge integrity monitor system are detailed. Candidate technologies are applied to three hypothetical railroad bridges to develop cost and performance estimates. The cost and performance of both simple and sophisticated bridge integrity monitor systems are compared.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
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ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
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lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
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m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
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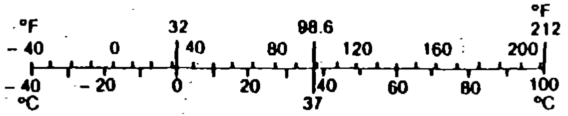
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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* SI is the symbol for the International System of Measurements

OVERVIEW OF RAILROAD BRIDGES AND ASSESSMENT OF METHODS TO MONITOR RAILROAD BRIDGE INTEGRITY

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Executive Summary

This report documents the results of an FRA-sponsored study to assess techniques and technology for automatic monitoring of railroad bridge integrity for the purpose of reducing the number of bridge-related train accidents.

The study focused on the following:

- Quantifying the risk of bridge-related accidents.
- Surveying technologies that may be applied to reduce risk.
- Preliminary evaluation of the costs of railroad bridge integrity monitoring.

Risk Evaluation

The numbers and types of railroad bridges and their specific vulnerability to natural and operational hazards was determined. There are approximately 100,900 railroad bridges in the U.S. with an average length of 120 feet. The number of bridge-related accidents was found to be very small in comparison to overall railroad accidents and to the number of bridges. In the last 10 years there has been an average of two railroad train accidents involving bridges per year. This is approximately 1/1000 of all railroad accidents each year. The low failure rates of railroad bridges can be attributed partly to the periodic inspection programs used by all railroads, and partly to the design standards and construction methods used for railroad bridges.

Monitor Technologies

Railroads have deployed automatic monitoring devices for hazards such as floods, rock slides, and fires since the 1930's. These proven methods and several modern technologies may be used to perform bridge integrity monitoring. This study addressed a range of technologies from simple mechanical devices to complex video and microprocessor based "smart" systems. Ultimately, 18 different technologies were evaluated.

Operational Issues

To accomplish its mission of warning trains to avoid bridge accidents, the bridge integrity monitor system must relay its alarm to crews by some interface. The most likely method of warning train crews is through an interface to the wayside signal system. This interface would have to be arranged to be a vital circuit, meaning that a failure of the integrity monitor system would cause the same restrictive signals as a true bridge integrity problem. The operational impacts from an integrity monitor alarm due to an internal failure were determined to include stopping of trains, inspection of the bridge, and inspection and repair of the bridge integrity monitor system if necessary. These actions cause a cost impact to the railroad. Thus to avoid cost and operational impacts from false alarms, the railroad bridge integrity monitor system must be extremely reliable.

Hypothetical Bridges

Three hypothetical bridges were modeled to provide a basis to compare various integrity monitoring technologies. A simple deck girder bridge, a timber trestle, and a multi-span truss bridge were specified. Bridge lengths ranged from 40 to 1020 feet. The number of spans monitored ranged from one to 16. A very adverse distribution history of hazardous events to these bridges was assumed over a 25-year interval, including impacts from highway vehicles, barges, and ships, in order to obtain estimates of integrity monitor performance. The different sensor technologies were used to design integrity monitors for each hypothetical bridge, primarily for detection of impacts or misalignment. Design details were used to estimate cost and reliability data for each system component. The probability of each sensor technology detecting events on the bridges was estimated in order to compare the performance of the systems. The 25-year life cycle period was used to illustrate and compare performance, cost and reliability estimates.

Results

The analysis found that the standard track signal circuit provides almost no warning of bridge misalignments or damage except in cases of complete collapse. Many of the technologies modeled had satisfactory technical performance. The high technology monitoring systems did not appear to have an advantage over simple electrical and mechanical monitor systems in terms of cost and performance. In some cases, high technology systems exhibited poor performance in the modeling due to excessive false alarms resulting from projected component failures.

Cost Estimates

The cost estimates developed from the hypothetical bridges showed that the majority of the installation costs would stem from interfacing to the railroad wayside signal system and from the initial cost of providing electric utility power to the integrity monitor. These cost estimates were used to project costs for installing and operating integrity monitors on other railroad bridges. The minimum projected cost to install an integrity monitor system on any bridge was found to range from $24,000 to $40,000. The minimum projected overall life cycle cost to install and operate a bridge integrity monitor over a 25-year period ranged from $40,000 to $55,000, including the sensor system, electricity, periodic maintenance, repair of failures, and cost of false alarms. From these minimum values, installation costs increased by approximately $9.00 per foot of bridge, and life cycle costs increased by approximately $17.50 per foot of bridge.

Using these figures, the cost in 1994 dollars to install integrity monitors on all U.S. railroad bridges and operate them for 25 years was projected to be $4.7-5.8 billion. Due to this high costs and the small number of railroad train accidents per year involving bridges, it would, therefore, appear that a methodology for ranking railroad bridges by vulnerability would be a necessary part of any program of bridge integrity monitoring.

INTRODUCTION

The purpose of this study was to assess means of providing automatic bridge integrity monitoring for railroads and rail transit using either existing or new technology in order to reduce the risk of railroad accidents on bridges. The assessment involved compiling railroad bridge information and postulating the use of new technologies for bridge integrity monitoring. The method of analysis followed these steps:

- Historical railroad bridge accident statistical data was examined.
- The number and types of railroad bridges were determined.
- Information on the history of railroad bridge safety was obtained.
- The risks involved with travel over railroad bridges were evaluated.
- Bridge failure scenarios were developed.
- Bridge failure detection technologies were identified both for existing systems and for postulated new systems.
- Three hypothetical bridges were suggested to illustrate practical concerns on detector installation and to provide a basis of comparison for detector technologies.
- The costs associated with detector systems on the hypothetical bridges were estimated for three areas: sensor system costs, signal interface costs, and recurring costs.
- The performance and value of each sensor system in terms of number of valid alarms, number of false alarms, number of alarms missed, installation cost, and life cycle cost, were compared for each of the theoretical bridges.
- The costs of four type of integrity monitor systems with similar performance were averaged and used as a basis for projecting costs for other span lengths of bridges.

1.0 BACKGROUND

Historically, railroad accidents on bridges have been a very small portion of the total railroad accident or derailment picture. A train accident has been defined by the Federal Railroad Administration (FRA) using a damage amount threshold that has been increased periodically to account for overall cost growth. The threshold use in 1994 is a minimum of $6,300.00 of damage to railroad property. A railroad bridge accident as used in this report is a railroad accident that occurs while a train is crossing or attempting to cross a railroad bridge.

A railroad bridge consists of a span or superstructure that carries the railroad or rail transit track and a substructure of bents, columns, or piers which support the span. The superstructure consists of the girders, beams, or masonry elements which carry the load of the bridge itself and the live load of the train on the railroad track. A bridge member is any single load carrying component of the bridge.

1.1 Railroad Bridge Accident Statistics

In the period from 1975 through 1992, there were a total of 48 railroad accidents reported to the FRA in which bridges were listed as playing a part in causing the accident. During this same time period, the total number of railroad train accidents of all causes was 99,656.[1]

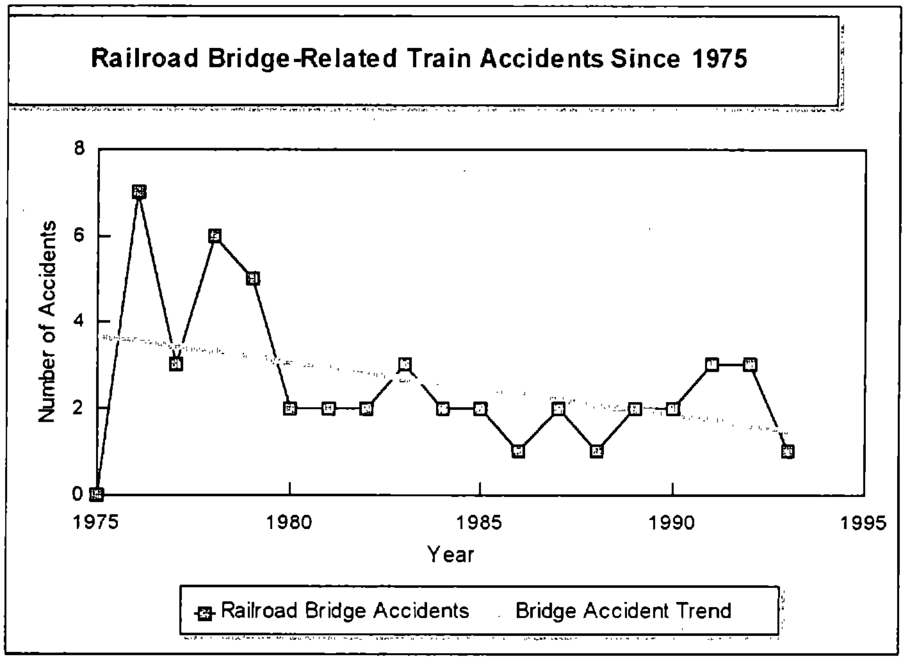

Figure 1.1 Railroad Accident Statistics

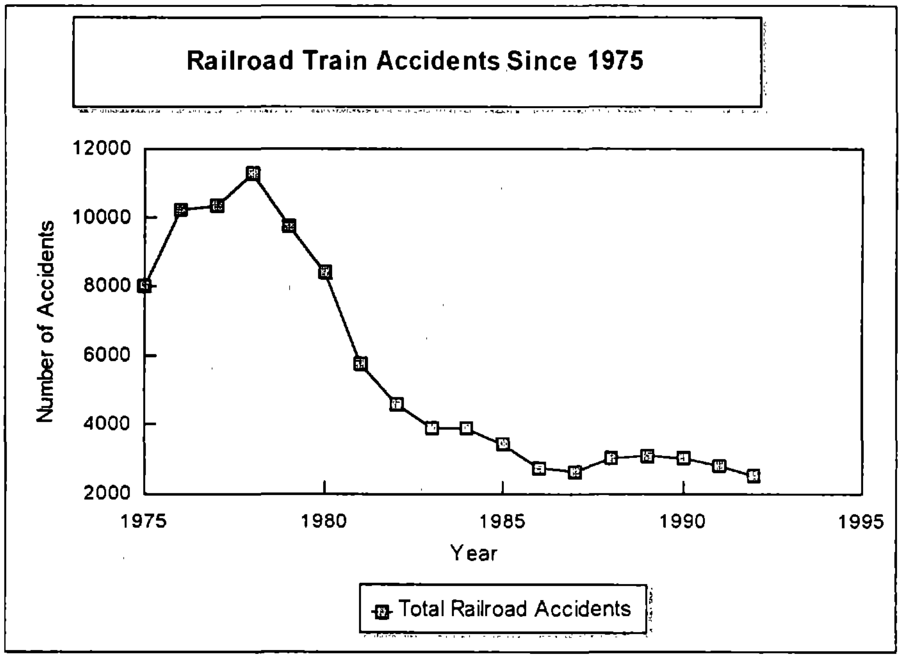

Figure 1.2 Total Railroad Accidents

As indicated in Figure 1.1, the number of reported railroad bridge accidents per year has decreased from a high of seven in 1976 to an average of two in the last 10 years. Part of this decrease may be due to a 1983 revision in FRA accident reporting methods that provided more specific accident cause codes. Comparing Figure 1.1 to the total railroad accidents in Figure 1.2 indicates that railroad bridge accidents constitute less than 1/1000th of all railroad accidents each year.

Despite the statistical insignificance of railroad bridge accidents, the overall public concern for decaying transportation infrastructure has led to increasing questions on the subject of railroad bridge condition and safety. Several instances of highway bridge collapse, such as the Mianus River Bridge on I-95 in Connecticut in 1983, have brought attention to railroad bridges as well, even though the loads and design criteria are much different for railroad bridges than for highway structures.

Current public perception is that many bridges in the U.S. are in poor condition and in need of repair or replacement. This perception may be accurate for highway bridges, since 200,000 of 500,000 bridges in the National Bridge Inventory database of the Federal Highway Administration rated as deficient[2]. However, the vast majority of railroad bridges, although many are old, are still quite capable of carrying trains safely. Railroad bridge inspection practices as noted in Section 1.3, have contributed to the low number of railroad bridge accidents.

1.2 Federal Government Bridge Safety Activity

Federal government involvement with any aspect of railroad safety began with the first Safety Appliance Act of 1893. Additional federal regulations followed including the Accident Reports Act of 1910, which required railroads to report accidents of certain types to the Interstate Commerce Commission (ICC) who regulated railroad safety at that time. In 1967, the FRA took over responsibilities from the ICC. In 1970, the Federal Railroad Safety Act gave the FRA specific authority over all railroad safety related matters. The Rail Safety Improvement Act of 1988 first addressed FRA involvement in the issue of bridge safety, in the specific area of workplace safety requirements for bridge workers and inspectors.[3]

The FRA has taken several steps to ensure the safety of the nation's railroad bridges. In 1971, the National Bridge Inspection Act was enacted which created a policy for the inspection and reporting of conditions on all highway bridges. Railroad bridges were not included in this code since railroads had been inspecting their bridges regularly for years. In 1980, as a result of the train accident at Devil's Slide UT, the National Transportation Safety Board issued safety recommendation R-80-36[4] that the FRA "study the feasibility of installing a mechanism which can be incorporated in the automatic block system to indicate when bridges are displaced." At that time, the FRA calculated that installation of railroad monitors was not cost effective, and the NTSB concurred by closing the safety recommendation with acceptable action status. The FRA Office of Safety began a study of railroad bridges in 1992. Its purpose was to determine and document whether or not there was any significant railroad bridge safety problem in the United States. [5] The survey was undertaken to provide a well-rounded basis for a national railroad bridge policy. The survey included the 19 Class I railroads (railroads with annual revenue over $96 million per year) at the time of the study, AMTRAK, and six other commuter and passenger railroads, 11 selected regional railroads, and 41 selected class III railroads.

In 1992, the FRA began to train its 48 track inspectors in bridge theory and inspection. The use of experienced track inspectors allowed the FRA to observe the bridge inspections being carried out by the railroad's own bridge inspectors and to allow the FRA Inspectors to note bridge conditions while performing their normal track inspection tasks.

1.3 Railroad Bridge Inspection and Maintenance

Railroad bridges are inspected by their owners to ensure the safety of each railroad's rail network and to detect the need for bridge maintenance and repair. By inspecting each bridge and maintaining a file of inspection results and bridge repairs or modifications, railroad bridge offices accurately determine the loads that can be safely carried on each bridge and prioritize preventive or corrective maintenance activities. As will be shown in Section 2, there are several external factors that over time can reduce the load carrying capacity (load rating) of any bridge. Periodic inspections document the extent of any reduction in strength and permit either re-rating the bridge or determining the type of repairs or modifications required to maintain the desired load rating. The American Railway Engineering Association (AREA) is an organization of railroad engineering professionals that promotes the advancement of knowledge pertaining to the scientific and economic location, construction, operation, and maintenance of railways.[6] The AREA has specific technical committees dealing with railroad timber structures, steel structures, and concrete structures and publishes recommended practices for their design, construction, inspection, and maintenance in the AREA Manual of Standards and Recommended Practices. In 1968 the Association of American Railroads (AAR) surveyed 600 railroads on their bridge inspection practices. At that time, 100% of the class I and 95% of the class II line-haul railroads inspected bridges periodically by at least the minimum AREA recommended practices and standards. Inspection periods varied from once a year to once a month.[7]

In addition to the scheduled bridge inspections performed by trained technicians or engineers, the track structure on each bridge is inspected by a railroad track inspector at frequent intervals. Main tracks carrying passenger or significant amounts of freight traffic are required to be inspected by the railroad twice weekly with at least one calendar day interval between inspections.[8] Train crews or other railroad employees crossing bridges also observe and report unusual conditions or bridge movement to the dispatchers for relay to the appropriate bridge office.

2.0 RISK EVALUATION

The actual risk to the public from a railroad bridge accident results from three catastrophic events: train derailment, bridge collapse, and collateral damage. Clearly, both a train derailment on a railroad bridge and a collapse of a railroad bridge cause risk to the passengers and crew involved. Collateral damage resulting from either a derailment or bridge collapse can also cause risk to nearby persons or vehicles and their occupants. Collateral damage can be worsened by fire or release of hazardous materials.

Direct public risk from railroad bridge accidents depends on the following:

- The amount and type of rail traffic over the bridge.
- The amount and type of nearby rail, highway, or other traffic.
- The nature and population density of the surrounding area.

The assessment of risk to the public resulting from train accidents on railroad bridges therefore cannot be generalized. Site-specific information is required for any meaningful risk assessment.

2.1 Generic Bridge Accident Scenario

In the first railroad bridge accident scenario, in order for a bridge-caused railroad accident to occur, all of the following circumstances must be present:

1. The bridge must become unsafe or placed into an unsafe condition.
2. The unsafe condition must remain undetected by railroad bridge inspectors, and by other persons, either by occurring between periodic inspections or by being in a location that is not visible or is inaccessible for inspection, or by being undetected by current inspection methods.
3. A train must attempt to travel over the bridge without its crew being aware of the hazardous bridge condition.

Each of these three circumstances is in itself a rare event, and all three must be present simultaneously for a railroad bridge-caused accident to result. In this case, real-time bridge integrity monitoring and warning of train crews could prevent an accident.

A second railroad bridge accident scenario is that a bridge in otherwise safe condition is damaged by impact from train contents, or from external forces while a train is immediately approaching or actually crossing the bridge, resulting in a train accident on the bridge. This type of accident cannot be prevented by any type of bridge inspection procedure or automated integrity monitoring of the bridge.

To discuss railroad bridge-caused accidents in a generic sense and to provide a basis for analysis, a railroad bridge accident model was developed:

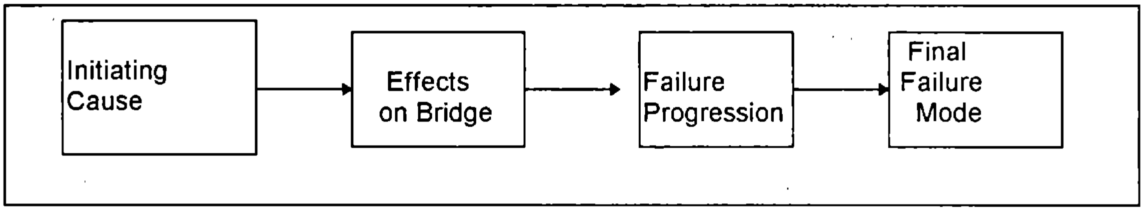

Figure 2.1 Generic Railroad Bridge Accident Model

In this study, a number of possible initiating causes and their detectable effects on bridges were identified based on historical bridge data. Engineering judgment was then used to identify possible bridge failure progression paths resulting from these effects. Finally, a railroad bridge accident was considered to occur if a train attempted to pass over a bridge with any condition of track misalignment, lack of support, or obstruction of the track. Any of the three defects may lead to a railroad accident if a train crossed the bridge with the bridge in those conditions. The actual accident could then be a bridge collapse or a train derailment on the bridge.

2.2 Numbers and Types of Railroad Bridges

In order to properly assess the potential scope of railroad bridge integrity monitoring the number of bridges and details on the different types were determined.

Preliminary results of the FRA 1992 Bridge Survey indicated that approximately 100,900 railroad bridges exist on all U.S. railroads.[9] Approximately 47% of the bridges are of metal construction, 35% are of wood or timber construction, and 18% are of masonry construction. U.S. railroads have an average of one bridge every 1.4 miles of track. The average length of bridge is 120 feet. In comparison, a 1987 survey of highway bridges by Better Roads Magazine indicated that there are approximately 590,000 highway bridges of all types in the U.S.[7]

There are three main types of railroad bridges in common use in the United States. These are truss bridges, girder bridges, and trestles. Each type of bridge has specific construction features and can be vulnerable to specific initiating causes of failure and resistant to other initiating causes. Each type of railroad bridge is sketched and discussed below.

Truss Bridges

A truss is a jointed structure designed so that the load carrying members are a series of triangles. Truss bridges are generally used to span long distances over streams, lakes, open water or large land areas where other types of spans would not be economical to construct. Truss bridges may be of several designs, usually named after their designer, or may be variations of these designs. Truss bridges may be one of three basic configurations:

1. A through truss with the track passing between the trusses on either side and boxed overhead by frames and portal members and underneath by the floor members.

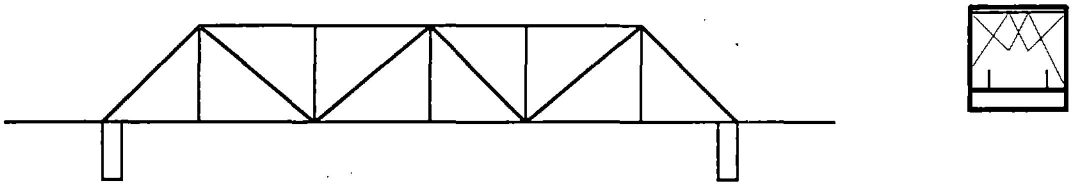

Figure 2.2 Through Truss Bridge

2. A deck truss, having the track on top of the truss and the lower portion of the truss supported at the ends of the bottom chord at an abutment or pier.

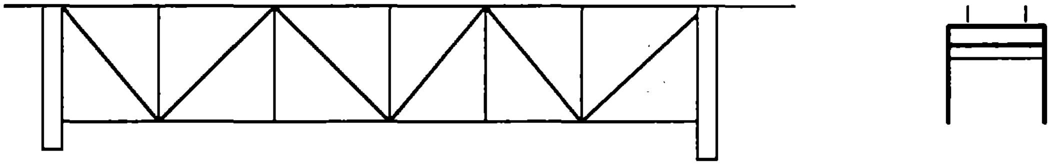

Figure 2.3 Deck Truss Bridge

3. A suspended or underslung deck truss with the track on top of the truss and the truss supported at the ends of the top chord with the inverted truss suspended underneath.

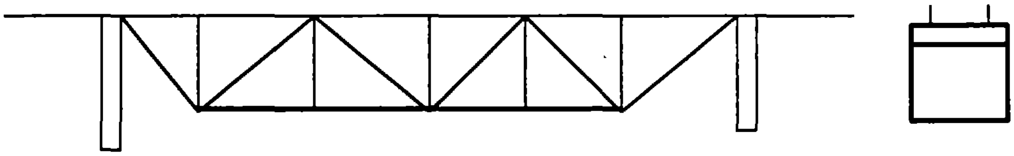

Figure 2.4 Suspended Deck Truss Bridge

Many small streams, highways and railroads are crossed using single span trusses up to 200 feet in length resting upon stone masonry or concrete abutments. The nation's navigable waterways are typically crossed by truss spans - some over 1,000 feet in length.

Plate Girder Bridges

There are two commonly used plate girder designs.

1. The through plate girder railroad bridge consists of a deep girder on either side of the track, with the track resting on a floor system similar to those used on the truss bridge. The two girders extend above the track level.

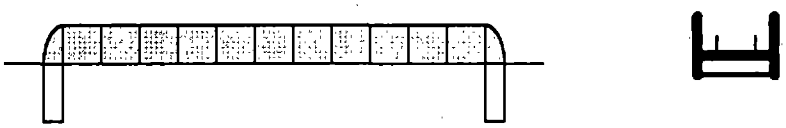

Figure 2.5 Through Plate Girder Bridge

These bridges may have an open deck with ties resting directly upon the stringers or a ballast deck with the crushed rock underlying the track structure resting upon a steel, timber or concrete deck. Through plate bridges are used where the under-clearance to a stream, highway, railroad, etc. will not permit deep girders. Through plate girder bridge span lengths vary from 40 - 150 feet.

2. The deck plate girder bridge consists of two girders located under the track. The height of the girders varies depending upon the span length.

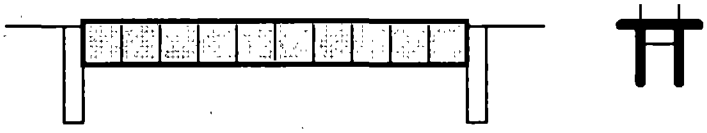

Figure 2.6 Deck Girder Bridge

These bridges may have an open deck with the track crossties resting directly upon the top flanges of the girders, or a solid deck made of steel, timber or concrete to carry the track ballast. The deck girder bridge is more economical than a through plate girder bridge since it does not have the additional floor system required by the through plate girder bridge. Deck girder span lengths vary from 10 feet to about 120 feet. Beyond that distance, the girder sections become too deep to continue to be an economical system and trusses are used.

3. A variation of the deck plate girder is a beam span. These bridges usually consist of one to four beams per rail or two to eight beams per span.

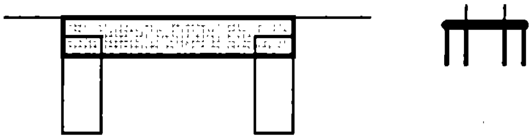

Figure 2.7 Beam Span

There are many beam span bridges with short spans of 10 to 50 feet in use today. Those constructed previous to the late 1940's are of built up sections - angles and plates riveted together. The more recent spans are constructed of rolled steel wide-flange beams. The deck is usually a reinforced concrete slab with a ballast track section.

Both through plate and deck plate girder bridges are a popular and economical design and continue to be used whenever new bridges are constructed on rail lines throughout the United States. This design lends itself well to the short spans crossing streams, highways and other railroads.

Timber Trestles

Timber trestles are generally constructed using a series of vertical supporting units called bents capped with a large timber. Timber stringer beams spanning a short 10-12 ft distance are laid between the bents. Crossties and rail are then attached to the stringers to form an open deck bridge. Alternatively, a solid deck structure filled with ballast can be used.

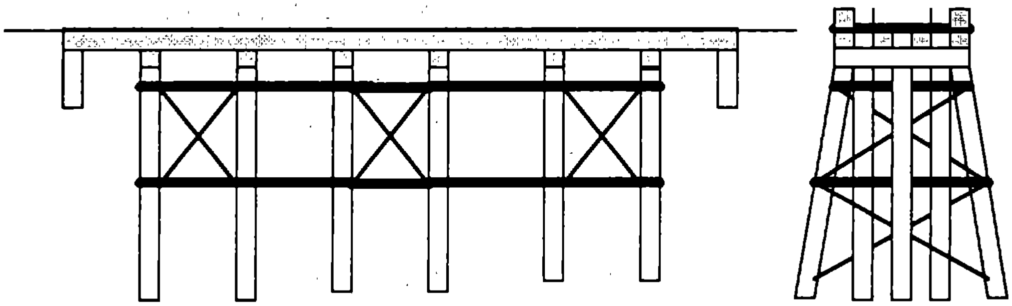

Figure 2.8 Seven-Span Timber Trestle

Over many navigable streams timber spans serve as approach spans to a truss, a girder span, or a moveable bridge at the navigable channel. Most timber trestles are three to five spans in length and cross small streams at heights of 5 - 15 feet. Longer timber trestles are used - several hundred feet in length and up to 200 feet high. Most of these are found in Western states, although there are a few located in the Southeastern U.S.

Concrete Spans

The early concrete structures built during the Federal Highway boom in the 1920's and 1930's are massive ornate reinforced structures. This same general design was used all over the United States. These structures are constructed with concrete encased steel columns and girder spans with a reinforced concrete ballast deck. In the case of a four lane highway underpass, there is a center island supporting the columns with a lane span to each side and a short sidewalk span at each end. Newer concrete structures consist of pre-cast, pre-stressed concrete slabs resting upon concrete piles or a poured concrete abutment and piers. These bridges are normally very stable.

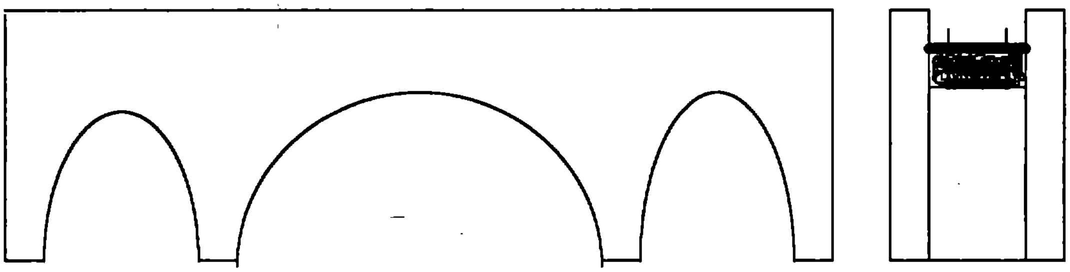

Figure 2.9 Concrete Span

Moveable Railroad Bridges

A moveable bridge has one or more spans than can be turned, raised, lifted, or otherwise moved from their normal position to allow for passage of marine cross traffic. The three most common types are: the vertical lift, the bascule, and the rotating or swing span. They are commonly constructed with limited clearance underneath for the navigable channel when in a position to handle rail traffic and are opened to allow vessels to pass. A moveable railroad bridge may normally be kept in either the closed or open position depending on the relative amount of rail and marine traffic. Moveable bridges are usually manned by a bridge tender, employed by the railroad, who controls the bridge and may also control railroad switching and signaling. Some moveable bridges are not manned and are operated by remote control, or automatically by sensing the approach of trains.

- **Vertical Lift Bridge**: The vertical lift span usually is a truss span connected at each end by large cables to two tall towers that act as guides for the span as it is being raised or lowered. The towers also contain large counterweights that support and balance the weight of the truss so it can easily be raised or lowered. The raising and lowering mechanism is usually electrically powered, although some type of engine is typically available in case of power failure. When in the raised position, a navigable channel equal to the length of the span is provided. Vertical lift spans usually are 200 - 300 feet in length, although a few spans approach 600 feet.

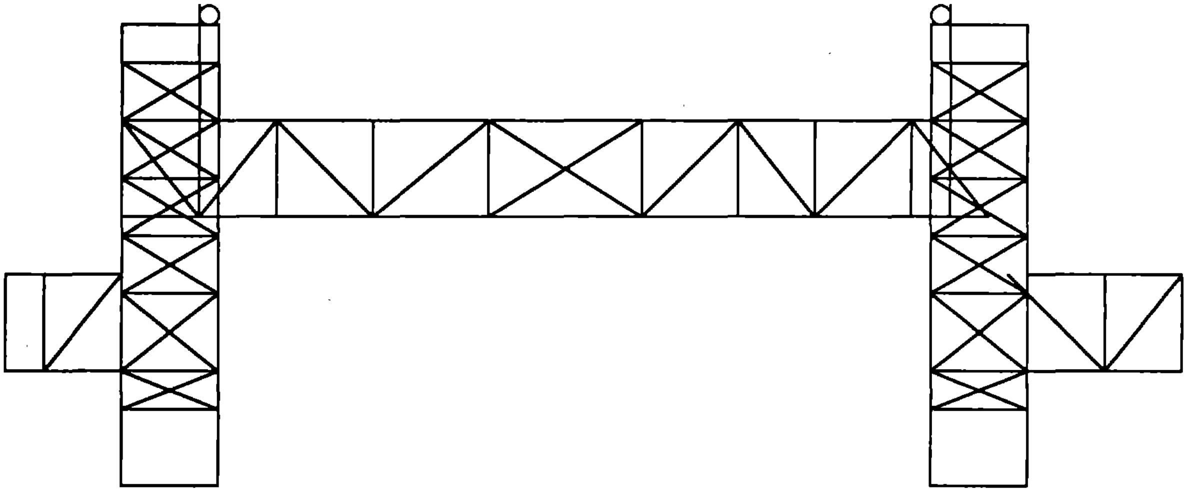

Figure 2.10 Vertical Lift Bridge

- **Bascule Bridge:** A Bascule bridge is usually a single span truss pivoted and counter-balanced at one end. This span is raised as the counter balance is lowered creating a channel opening. Bascule bridge spans are shorter than the vertical lift spans usually with channel widths of 150 - 200 feet. When in the raised position, the maximum navigable channel is equal in width to the length of the span. Vertical clearance for marine traffic will vary along the bascule span as a function of the angle that the span is raised. Bascule bridges for smaller navigable channels may use a through plate or deck plate structure to span channels up to 100 feet in width.

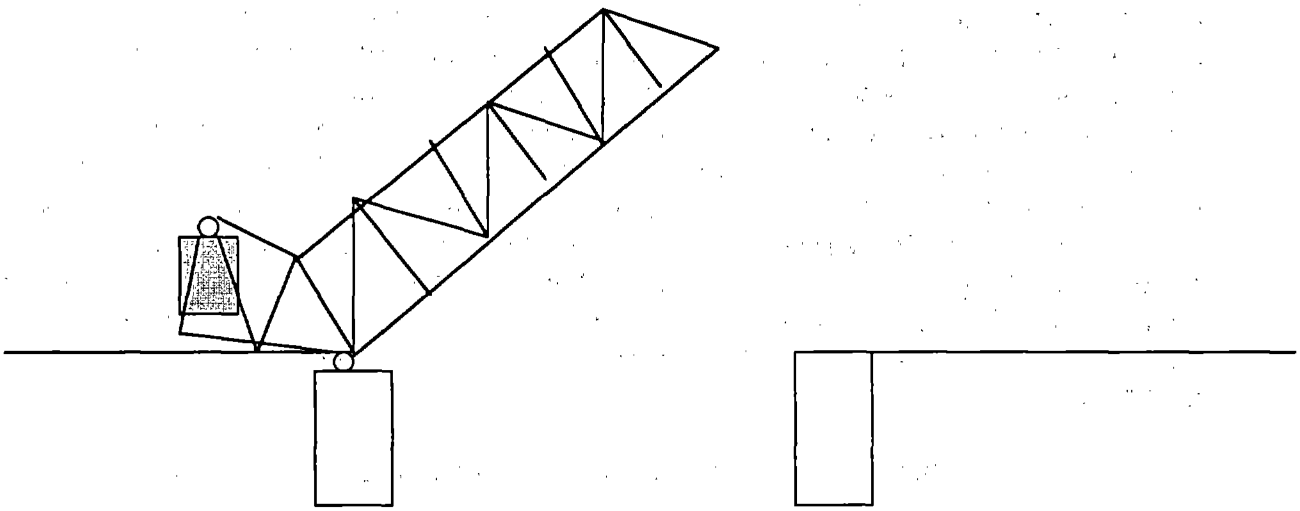

Figure 2.11 Bascule Bridge

- **Swing Bridge:** A swing bridge usually consists of two through truss spans connected at a center pivot point. When in position for rail traffic, it presents a two span truss bridge resting on piers or abutments at each end and a large pivot pier at the center. When opened, the bridge turns at right angles to the railroad and provides a navigable channel along one or both sides for the passage of vessels. Swing truss spans provide navigable openings equal to one of the span lengths, typically 75 - 150 feet in width. Vertical clearance for marine traffic is unlimited with the swing span open. Swing bridges may also use a swing girder span.

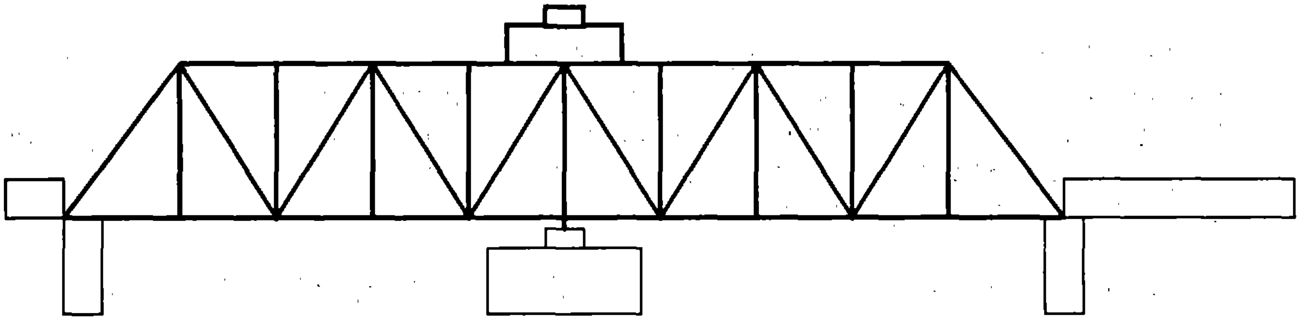

Figure 2.12 Swing Bridge

2.3 Initiating Causes of Accidents

An initiating cause for a bridge accident is defined in this report as the cause which first begins a progression of events in the bridge structure leading up to any of the three generic final failure modes. The amount of time between an initiating cause and a bridge accident could conceivably vary from hundreds of years to less than one second depending on the type and severity of the initiating cause and the type of bridge, the schedule of routine inspections, and the quality of maintenance of the bridge. Table 2.1 is a summary of initiating causes. Note that some types of initiating causes can be due to either naturally occurring events or due to human activity. Each is discussed in more detail below. The vulnerability of a railroad bridge to any particular initiating cause depends on many factors. Due to physical differences, the types of railroad bridges vary in their vulnerability to natural and operational initiating causes. Each of the major types of railroad bridges was assessed for its vulnerability to the initiating causes of railroad bridge accidents.

Table 2.1 Initiating Causes of Railroad Bridge Accidents

Natural Initiating Causes	Operational Initiating Causes
Corrosion	Impact
Flood	Fatigue
Earthquake	Fire
Intruding Object	Overload
Fire	Subsidence
Ice Buildup	Intruding Object
Wind	Explosion
	Improper Construction

2.3.1 Impact

Railroad bridges are subject to impacts both from vehicles of all types crossing under the bridge structure, and from the railroad train itself and its lading. Damage to railroad bridges has occurred from impacts from automobile or highway trucks and equipment being carried on the trucks. Ships, barges, and flood debris have impacted and damaged railroad bridges over waterways.

External impacts may cause minor denting, distortion of bridge elements without affecting load carrying ability, or can fracture, bend, or carry away bridge superstructure. Impacts can also affect the supporting elements of the bridge causing reduced strength or collapse of masonry, steel, or timber substructure. Bridge superstructure can be impacted by oversized railroad loads outside the normal clearance envelope, or by derailed cars in the consist. Bridge substructure can be impacted in the same manner by other railroad traffic crossing under the bridge.

Overhead railroad bridges that provide less than the highway standard 15-foot vertical clearance are particularly vulnerable to impacts. These impacts occur frequently in areas of the country where heavy machinery is being transported.

Some through truss bridges are constructed high enough above other railroads, highways, etc., that there is little danger for collision with the superstructure. There have been instances where the bridge's supporting piers and abutments have been struck and damaged to the extent that the bridge had to be temporarily closed until the support damage was repaired. Moveable truss bridges and those bridges located low to the water have been struck by barges or deep water vessels. Turn span trusses are particularly vulnerable: once in the open position, the bridge is parallel to the marine traffic flow leaving the ends exposed to impacts from the river traffic. These bridges have been struck at the exposed ends with enough force to move them off the center support pier. In most instances when barges collide with piers, only slight damage to the stone or concrete pier, is incurred. Bridges crossing navigable channels are well marked in accordance with Coast Guard regulations.

Through truss bridges are potentially vulnerable to derailments. A piece of derailed railroad equipment has close side clearance when passing through a truss bridge. If it impacts the bridge end post, the entire bridge can collapse. Serious damage can also occur to the internal vertical and diagonal members of the bridge necessitating the bridge's removal from service until repairs can be made. Lading carried on the train can shift in transit, becoming displaced far enough to impact bridge members.

Many of the railroad through and deck girder bridges were constructed the during 1920's and 1930's when necessary overhead highway clearance was much lower. As a result, today there are numerous girder bridges located over city streets, and federal, state and secondary roadways with less than 15 foot clearance between the bottom of the bridge and the roadway surface. Even though some may have been constructed to the 15 foot clearance, resurfacing the roadway several times may have reduced this distance.

It is not uncommon to see bridge girders with deformed bottom flanges as a result of being struck by a high load carried on the highway. Usually a slight deformation to the bottom flange does not render the bridge unsafe. More serious damage can occur if the impact is heavy enough to move the bridge laterally from the anchorage at the bridge seat and create misalignment to the track. The worst result is if an impact knocks the bridge completely off of its substructure support. Even though many of these bridges are struck repeatedly, there are few derailments as a result of these collisions since damage inspections are performed to assure the safety of the bridge.

Derailments have little effect on deck girder bridges. Since there is no lateral clearance problem, the track guardrails tend to keep the derailed equipment within the track structure. Other than damaging the wooden bridge ties and the outer guardrails, the bridge superstructure does not suffer. Through girder bridges may incur damage to bracing inside the girders or damage to the girder ends.

Timber bridges are not normally used to cross navigable channels of waterways, but they may be used as approach spans to a fixed or moveable steel span. They are susceptible to impact even when used as approach spans. A collision with a timber bridge by a commercial vessel often results in severe damage to the structure in the immediate area of the accident. Timber structures are susceptible to highway vehicle impacts. These highway collisions are usually reported and derailments are rare. Timber trestles, except for those with ballast decks, commonly have timber guardrails at the ends of the ties. In addition to holding the tie spacing, these guardrails function as guides to hold derailed equipment in the track structure. If a derailment occurs and the equipment goes off the side of the bridge, excessive damage will occur, possibly destroying the bridge. Otherwise, a derailed piece of equipment will typically gouge the bridge ties with little damage to the remaining structure.

The older concrete bridges constructed in the 1920's and 1930's were massive structures. The worst effects from impact to these bridge is removal of concrete at the point of impact. Many of these bridges crossing highways have a bent located in the roadway. This bent is usually protected by a large concrete island to prevent vehicular traffic from striking the bent. Newer concrete structures have a crash rail constructed next to the bent to deflect vehicular traffic. The overhead ballast deck spans usually provide more than 15 foot clearance and very few are struck by vehicular traffic. Damage, if any, is minor. In the few derailment cases involving concrete bridges, little damage is done to the structure, other than breaking a piece of the concrete ballast curb or cracking a back wall, both of which can be easily repaired with no effect to rail traffic.

2.3.2 Flood

Flooding can affect the substructure of bridges by either undermining the columns, bents, other supports, or by destroying the abutments on either end of the span. Flood waters can also carry large amounts of dead trees and other debris which can strike the bridge supports and cause failure by shock loading or by decreasing their load carrying ability. Floating debris collecting against the bridge structure may dam the flood waters, increasing the side load on the bridge supports. If the lateral force builds to the point where it overcomes the mass of the bridge, the bridge will "float" on the pile of debris and will be completely displaced downstream.

Flood waters can also rise above the bridge and its approach track causing washout of track structure or ballast leaving the track unable to retain its gage or support the weight of trains. During periods of flash flooding and heavy stream flow, piers and abutments can be undermined, allowing these support structures to tilt, dropping the spans into the stream. Even with good pile support under these structures, once the stream reaches the earthen fill behind an abutment or erodes deep enough to expose most of the pile length, the pier or abutment will fail. Few derailments occur as a result of flooding due to frequent track inspections during inclement weather or flooding conditions and increased vigilance by the railroads.

Truss bridges that are constructed high above streams are not usually damaged by floods. Since many plate girder bridges are constructed closer to water level, debris buildup against them can be more rapid and the breaching of the fill behind the bridge is more likely than with a truss bridge. Floods usually have little effect on concrete bridge structures resting upon concrete or steel piles with massive concrete caps supporting the deck structure, although the earthen fill behind the back wall is sometimes breached. Timber bridges are more affected by flood - especially flash floods - than steel structures. The vertical timber support bents are usually on 12 to 15 foot centers. Flood-driven debris building up against the bents can quickly generate intense side loads. The structure can be displaced laterally and/or washed out completely.

2.3.3 Fire

Fire can affect both timber structures such as trestles, and the structure of other types of bridges. The heat from a fire can melt, bend, or break metallic bridge members either by direct heating, increasing internal stresses due to thermal expansion, or by increasing loads on remaining pieces of the bridge structure. Fire can totally destroy a wooden bridge structure leaving the steel rails intact, or it may reduce the load carrying ability of the structure by decreasing the cross-section of the wood members. Fire can be due to natural causes such as wildfire, forest fires, and lightening strikes. Operational causes of fire include hot brakes or bearings on train cars, track or bridge maintenance activities including repair welding or cutting, and rail grinding, or other man-made fires.

Truss bridges are vulnerable only to extremely hot brush or forest fires beneath them or to a bridge deck fire. Members can become overheated and the weight of the bridge can warp and twist these members rendering the structure unsafe.

Girder bridges frequently have timber decking to support the ballasted track structure. If the decking catches fire, the heat can be devastating to the bridge steel and in the worst cases can require a bridge replacement.

Fires are more critical to timber structures, which if located in remote or inaccessible areas may totally burn without being detected or extinguished. If fires are extinguished before incurring excessive cross-section loss in the large-dimension timber, the load carrying ability of the bridge may not be appreciably decreased.

Concrete bridges are not affected by brush or forest fires. However, a major derailment at a bridge with large quantities of burning cargo such as propane, can destroy a concrete bridge.

2.3.4 Fatigue

Fatigue cracking of members of a bridge can be due to the accumulated load history of the bridge, the maintenance history of the bridge, or the design of the individual bridge members and resulting stress concentration. Increase in railroad traffic or weight of locomotives or cars can begin or accelerate the fatigue process, as can an increase in the speed of train traffic over the bridge. Conversely, bridges originally designed and used for freight trains that have been converted for light rail or transit use will have increased fatigue life due to decreased loading. Fatigue cracking can also result from internal defects, improper manufacturing or installation, or overloading. Fatigue affects primarily bridges of metallic construction.

There are many fracture critical members in truss bridges. There are also a number of redundant paths in which loads can be transferred. Lightly constructed trusses - especially pin connected trusses are vulnerable to fatigue failures of individual members.

The fatigue critical areas on through and deck girder bridges include the girder ends and floor beams.

Fatigue has little effect on timber bridges other than the normal mechanical wear to the timber's surface. Timber is a very forgiving material and unless it is overloaded it will continue to perform and safely carry a load for many years. Components of timber bridges, unless overloaded, usually deteriorate from mechanical wear, weathering and old age before becoming affected by fatigue.

The pre-cast/pre-stressed concrete structures in use today are constructed to adequately carry the current loads. The few incidents of fatigue that have surfaced are due to poor quality control when the slabs were constructed.

2.3.5 Corrosion

Corrosion of the bridge structural members can occur on steel bridges, or on the steel reinforcing bars in concrete bridge members or supports. Corrosion occurs slowly, but can in time significantly reduce the load capacity of the bridge. The corrosion may be caused by natural sources such as rain or stream water, ocean spray or salt water, or by chemicals or minerals leached from surrounding rock or soil. Corrosive agents may also be introduced from the ballast rock, spills from freight car or tank car lading, or construction or maintenance activity. The effect of corrosion is to slowly decrease the effective strength of bridge members or connections as the cross-sectional area of metallic parts is decreased by the corrosion process. Stress corrosion can also occur at areas of high internal stress.

There are many areas in truss bridges that are subject to corrosion. The structural members were sometimes fabricated in such a way as to retain water and air borne chemicals. Over a long period of time these areas can develop significant rust and loss of cross-sectional area. Girder bridges are susceptible to corrosion along the bottom flange of the girders. Rusting can also cause loss of web area above the bottom flange angle. Timber does not corrode, but does weather as a result of exposure to sunlight. This is only a surface effect and does not damage the wood internally. Timber survives chemical action well and other than freezing, thawing, and the leaching of preservative treatment material, is not generally affected by chemical action. Corrosion does not significantly affect concrete structures in the railroad environment.

2.3.6 Earthquake

All bridges can be vulnerable to earthquakes. The effect of an earthquake on a given bridge will depend on the proximity of the bridge to the center of the earthquake, the intensity of the earthquake, and the geometry of the bridge relative to the earthquake motion. Significant earth motion can cause immediate collapse of the bridge structure, bending or distortion of members, or lateral or vertical displacement of the entire bridge or sections of the bridge. The type of soil or terrain at the bridge site also will determine the extent of damage caused by an earthquake. The design standards used for bridges also effect the extent of damage from earthquake motion. In the 1994 earthquake in the Los Angeles, California, railroad bridges remained standing without damage, while several highway bridge structures collapsed.

Older structures supported on stone masonry piers and abutments are subject to more serious substructure damage from earth motion than those supported on reinforced concrete. Older stone structures may have lost continuity between joints if the mortar has weathered away, leaving the stones resting on, but not secured to each other. Stone masonry is subject to cracking across the grain of the stone when seriously disturbed. Earthquakes can tilt piers and abutments rendering them useless as load bearing devices. Lateral movement of the bridge can dislodge the bridge from its foundation or cause severe track misalignment.

Railroads have procedures to slow or stop trains after earthquakes to control the risk of accidents due to damaged or displaced tracks, bridges, or debris interfering with train passage. Earthquakes above a Richter Scale reading of 6.0 cause railroads to stop trains and engines within 100 miles of the epicenter. Rail traffic is not continued until a track, bridge and signal inspection can be made.[10]

2.3.7 Overload

Overloading can occur from excessive speed of trains, excessive car or locomotive weight, dynamic resonance (truck hunting or vehicle/track resonance), and excessive acceleration or braking of trains on bridges. Bridge members with undetected or hidden damage from any of the possible initiating causes listed above, can suffer an overload condition from otherwise normal weight trains and otherwise normal operation. Railroads have historically kept good records of the design and construction of bridges. The records include the structural repairs periodically made to bridges and whether or not they have been strengthened to carry higher loads. Every main line and branch line has a "load rating" which takes into account all of the structures located on that line. No load that exceeds the rating may be moved over a line without first communicating with the railroad's clearance/bridge office. However, there are instances, where railroad trackage has been sold to regional or short line operations and these records have not been forwarded to the new owner.

Truss bridges are vulnerable to overloads at the vertical members near the ends and some of the diagonal connections toward the center of the bridge.

Timber is normally a very forgiving material; however, it does not respond well to overloading. Cracking, bulging, and eventual collapse of overloaded members can occur if an overload condition is repeated enough.

Concrete railroad bridges in current use are not particularly vulnerable to overloading if the slabs are square and level. If the quality control is poor when the slabs are fabricated and the ends are not perfectly flat and in the same plane, the slabs will rock on the opposite uneven corners when placed upon the concrete cap. When this occurs, the slabs develop stress cracks at the bearing areas but even then, these slabs will support load for a long time before becoming dangerous.

2.3.8 Intruding Object

An intruding object is anything which violates the clearance envelope for a railroad bridge. Intruding objects can strike passing trains with varying effects. An example of an intruding object would be a tree trunk carried by flood waters which becomes lodged across the track on a bridge. Rock slides and avalanches are other intruding objects. Small light objects may be moved out of the way by the train with no effect. Larger or heavier objects may damage parts of the locomotive or cars. The largest and heaviest objects may cause a derailment.

2.3.9 Explosion

An explosion can occur from ignition of explosive lading either on a train crossing, a bridge, or on another type of transportation crossing under a bridge. An explosion could also be a deliberate act of sabotage using explosives.

2.3.10 Improper Construction or Maintenance

Improper construction or maintenance can reduce the load carrying capability of a bridge. This initiating factor can be in the form of improper selection of materials, incorrect stress analysis, errors during assembly or repair of bridge components, improper welding technique, manufacturing defects in bridge components, improper curing of concrete, unforeseen effects of paints and coatings, or other such construction problems.

2.3.11 Subsidence

The subsidence of the soil or rock under any of the bridge supports can damage, misalign, or undermine these supports and leave sections of the bridge either unsupported or misaligned. Bridges built in deep mining territory, or in areas where the local geology allows sinkhole formation can be subject to subsidence. The resulting misalignment can be in the vertical, lateral, or longitudinal directions, or a combination, depending upon the geometry of the bridge supports and the area of subsidence.

2.3.12 High Winds

Bridges are affected laterally by loads due to winds. The amount of force depends on wind velocity and the type of bridge and, therefore, the aerodynamic drag of bridge components. Some highway bridges, particularly suspension bridges, have been affected by dynamic wind effects including unstable oscillations leading to failure. Wind loading can cause distortion of the bridge or in the worst case collapse due to excessive side loads or dynamic effects. Such catastrophic effects are usually confined to suspension bridges, few of which carry railroad or transit traffic. All railroad bridges have a wind factor built into the design calculations. This factor is increased by adding the wind load on the side of a train crossing the bridge.

Damage to truss bridges from wind alone is generally negligible. It is doubtful that wind alone will dislodge a girder bridge. Timber bridges constructed along coastal tide plains may be seriously affected by hurricane-driven tides and the debris carried with them. If this situation occurs, the rail lines are closed to traffic and not reopened until a complete track, bridge, and signal inspection has been made. Wind has little effect on concrete bridges -

even those located along coastal waters subject to hurricane force winds and wind driven tides.

2.3.13 Ice Buildup

Buildup of ice on the water below a bridge can cause a damming effect and increase the lateral loads on the bridge supports or the bridge superstructure depending on the clearance distance from the water to the bridge deck. Heavy and thick ice formations in the water beneath the bridge can lift bridge spans from their mounts and can displace supporting bents or pilings.

2.3.14 Sabotage

The deliberate sabotage of railroad bridge structures has been rare in the U.S.

2.4 Mechanical or Physical Effects

As discussed above, damage or failure of bridge structural members can be due to many causes. In most cases, due to conservative railroad bridge design standards, failure of any one member does not necessarily lead to a dangerous condition or a collapse. Each of the causes has certain effects on the bridge structure or its supporting soil. The majority of the initiating causes result in similar effects. Six generic effects that can lead to bridge failure were considered in this study.

1. Disconnection of members.
2. Displacement of members.
3. Cracking of members.
4. Distortion of members.
5. Overstressing of members.
6. Undermined supports.
7. Direct Interference With Trains.

Each of these effects is discussed below.

2.4.1 Disconnection of Members

Disconnection of a member can occur due to improper fastening, cracking through a member, or sufficient displacement to allow connections and/or bearings to disconnect or fall out. Disconnection effectively removes that bridge member from the structure and, therefore, can increase the loads on other remaining members.

2.4.2 Displacement of Members

Displacement is considered to be a lateral, vertical, or horizontal movement of a bridge member which remains intact. Displacement may or may not decrease the load carrying capability of the bridge member or the bridge itself. If displacement of the bridge structure becomes severe enough to displace the railroad track itself, a derailment may occur.

2.4.3 Cracking of Members

Cracking of members is generally due to fatigue or impact. The tendency to crack can be affected by overloading of the member due to improper design or construction which allows stress concentration.

2.4.4 Distortion of Members

Distortion is the change of shape of a bridge member. This can include bending, twisting, or denting of the member. All of these effects tend to decrease the strength of the bridge member which can lead to further distortion. If distortion causes any displacement or distortion of the railroad track it can lead to a derailment. Overloading can lead to distortion if the load is sufficient to exceed the elastic limit of the material.

2.4.5 Overstress

Overstress is the effect of overloading. If locomotive or car weights exceed the design limits of the bridge, overstress of the bridge members can occur. Similarly, if corrosion or rot has decreased the effective cross-sectional area of bridge or support members, a standard weight train can result in an overstress condition. Overstress in the lateral plane can occur due to flood water, ice, or debris with the bridge acting as a dam to resist downstream flow. High winds also can overstress a bridge in the lateral plane or create high dynamic loads.

2.4.6 Undermined Supports

All types of bridges over waterways can be susceptible to undermining of their support substructure from natural causes. The scouring effect of flowing water is a function of the water speed, depth, angle of water flow in relation to the bridge supports and the type and composition of the subsoil below the waterway. Bridges over navigable waterways can also have their substructure damaged as a result of the impact of vessels. The substructure of bridges over roads or railroads can be damaged by the impact of vehicles. Undermined supports may slowly change position, causing distortion of the bridge structure, or may cause additional stresses in the bridge superstructure as their support is lessened or eliminated. Supporting structure may settle vertically or may shift horizontally, longitudinally, or in a combination of directions, depending on the site-specific geological and water flow conditions. Undermined supports can leave a bridge in its normal position but with decreased load carrying ability, or they can cause slow or rapid displacement of the bridge in both the vertical and lateral planes.

2.4.7 Direct Interference With Trains

Some initiating causes have direct effects on trains passing over bridges. These effects can cause an accident on a bridge that is structurally sound. Examples of direct interference include intruding objects and earthquakes.

Table 2.2 relates these effects to the initiating causes of bridge failure.

Table 2.2 Bridge Damage Effects Due to Initiating Causes

Initiating Cause	Disconnection of Members	Displacement of Members	Cracking of Members	Distortion of Members	Overstress of Members	Undermined Supports	Direct Interference With Trains
Flood		X			X	X	
Earthquake	X	X	X	X	X	X	X
Ice Buildup		X			X	X	X
Wind				X	X		X
Fire	X		X	X	X	X	
Explosion	X	X	X	X	X	X	
Intruding Object							X
Impact	X	X	X	X	X	X	X
Subsidence		X				X	
Fatigue			X				
Overload		X	X	X	X		
Corrosion	X				X	X	
Improper Construction	X		X		X		

2.5 Failure Progression

Failure progression is the gradual or rapid increase in the severity of the effects on the bridge. During the failure progression stage, each effect may become worse, or additional effects may result from abnormal distribution of internal loads. In the majority of cases, periodic bridge inspections detect slow failure progressions and the bridge may be removed from service for repair or replacement of damaged bridge members prior to a catastrophic failure.

2.6 Final Failure Modes

The final step in the railroad bridge failure progression was considered to be that point at which the bridge is no longer mechanically safe for the passage of trains. The final failure modes considered were:

- Misalignment.
- Obstruction.
- Derailment.

Misalignment can be improper lateral or vertical alignment of key bridge members or of the railroad track crossing the bridge. Obstruction can be fouling of the railway clearance area with either misaligned positions of the bridge structure or with external objects. For the purposes of this study, derailment was treated as the potential for derailment of the next train to pass over the bridge. Derailment can occur on a bridge still otherwise strong enough to support the weight of the train, or it can occur during collapse of a bridge no longer strong enough to support the train's weight. The final failure modes are interrelated since misalignment or obstruction can lead to derailment and derailment can cause misalignment and obstruction.

In this study, the potential for train derailment was treated as the basic final failure mode to be prevented by operation of a railroad bridge integrity monitor system. The mission of the railroad bridge integrity monitor is to detect these conditions and warn train crews of their existence.

2.7 Examples of Railroad Bridge Accidents

To illustrate some of the initiating causes of railroad bridge accidents and their effects on bridge structures, the following cases are briefly discussed. These accidents are not intended to be a complete list of railroad bridge accidents, nor to indicate a possible distribution of initiating accident causes.

2.7.1 AMTRAK Accident Alabama 1993

Current emphasis on railroad bridge safety is a result of the AMTRAK accident on September 22, 1993 at the Big Bayou Canot bridge near Mobile, Alabama in which 47 people died. The accident occurred because one span of the bridge had been knocked out of proper alignment by the impact of a barge tow. The bridge crossed a waterway that did not carry barge traffic. The misalignment of the bridge and track was enough both to derail the lead engine and to cause it to strike the girder of the through girder span. The impact of the train was enough to collapse the center span of the bridge. No special monitors were in place on the bridge other than the track signal circuit, and the amount of deflection caused by the barge impact force did not sever or short circuit the continuous-welded rails of the track. If the rails had been broken, or short circuited, the existing block signal system would have detected either the lack of electrical continuity, or the short circuit, and set a restrictive aspect on the nearest signal.[11]

2.7.2 Loma Prieta Earthquake California, 1989

On October 17, 1989, an earthquake of magnitude 7.1 on the Richter scale occurred with an epicenter near Santa Cruz, California. This earthquake caused major damage to highway bridges and buildings. Although railroad bridges in the area received damage, the extent of damage was much less than the damage to nearby highway structures. Committee 8, Concrete Structures and Foundations of the AREA, studied the effect of this earthquake on railroad bridges and reported their results. The railroads estimated that the repair costs for the six railroad bridges that were damaged would be approximately $100,000. The committee concluded that: "Damage to all railroad bridges in the area was relatively light by comparison to the damage sustained by its highway counterparts." The railroads noted that "the use of simple span structures with ample bearings and bearing seats as well as the high live loads used in their design provided a large reserve capacity and were a factor in the survival of the bridges."[12]

2.7.3 Flood/Washout AMTRAK Vermont 1984

On July 7, 1984, the northbound AMTRAK Montrealer passenger train derailed at a washed out section of gravel embankment on the main track of the Central Vermont Railway near Essex Junction Vermont. Two locomotives and the first seven cars of the train were derailed and destroyed or heavily damaged. Three passengers and two crew members were killed. Twenty-nine people were injured. Damage was estimated at $6,586,312. The probable cause of this accident was determined by the National Transportation Safety Board to be a flash flood which destroyed the railway support embankment over a small stream at culvert 105.97. The flash flood was caused by heavy rains and the sequential collapse of a series of beaver dams upstream of the culvert. The NTSB report also noted that "Although an 80 foot section of the track was totally unsupported, it apparently remained taut and straight enough to appear to the fireman and engineer of the Montrealer to be level and in completely normal alignment until they were close enough to see that there was no ballast stone under it. The existence of a signal system would not have prevented the accident, since there was no disturbance to the track that would have caused the shunting necessary to produce restrictive signal indications."[13]

2.7.4 Misalignment UP Utah 1979

On November 17, 1979, a Union Pacific freight train was derailed crossing a bridge at Devil's Slide, Utah. The bridge had been misaligned by 30 inches laterally by the impact of a large piece of construction equipment. Despite the misalignment, the rails remained intact and the railroad signal system displayed a clear aspect. The train crew observed the bridge damage but was unable to stop the train short of the bridge. The accident resulted in the damage or destruction of five locomotives, 56 railroad cars, and portions of the bridge structure.[4]

2.7.5 Impact, Struck by Barge Tow SP Louisiana 1978

On April 1, 1978, four barges being transported by a towing vessel, collided with the fixed eastern truss span of the Southern Pacific Railroad bridge over the Atchafalaya River near Berwick Bay Louisiana. The impact occurred at a speed of approximately one MPH and caused the 232-foot though truss span to move off its supporting piers and sink in 54 feet of water. The lift span of the bridge had been raised for passage of the tow but due to river conditions and an under-powered tow boat, the master was unable to properly align the tow to pass under the open span. Railroad traffic had been stopped by the interlocking signal system when the span was raised so there was no railroad train accident. The cost to the railroad for repairing the bridge and rerouting traffic for eight days was estimated at $1,400,000.00. The NTSB noted that between 1948 and 1978 this bridge or its protective fender system had been struck by vessels 534 times.[14]

2.7.6 Collapse, Timber Supports B&M, New Hampshire 1939

On September 10, 1939, a westbound passenger train of the Boston and Maine Railroad derailed on bridge 57.23 over the Piscataqua River. The train consisting of a steam engine, tender, three coaches and a combination baggage and smoking car was moving over truss #4 of the bridge at approximately 5-7 MPH when the truss collapsed beneath the engine. The engine, tender, and one coach fell into the river and two trainmen were killed. The Interstate Commerce Commission[15] investigated the accident and found that the wooden pile bents supporting one end of the truss span had been moved out of position by anchor cables attached to a nearby caisson. The caisson was part of equipment being used to build a replacement bridge just upstream and was drifting due to wind and tide effects when its cables fouled on the bents. The same train had passed over the bridge eastbound approximately two hours earlier without incident.

3.0 BRIDGE INTEGRITY MONITOR TECHNOLOGIES

The mission of any bridge integrity monitor system is to warn train crews of dangerous bridge conditions. All systems designed for this mission will share some common functions and components. Most systems designed using either existing or new technologies described in this section require the following functional modules:

1. Sensor,
2. Data acquisition,
3. Logic or processing,
4. Alarm Interface, and
5. Power supply.

Sensors

Sensor types are described in Sections 3.2 and 3.3. These sensors rely on mechanical, electrical, or electronic measurement of some parameter or changes in an input from a transducer. The sensors can be attached to the bridge structure (contact sensors) or may sense bridge parameters from a location not directly connected to the bridge structure (non-contact sensors).

Data Acquisition

Data acquisition is the function of transferring data from a sensor to the next functional device in an integrity monitor system. Data acquisition can be achieved via cables routed along the bridge structure to an enclosure containing the logic, interface, and power subsystems. Existing technologies may use mechanical means of data acquisition by directly sensing position or movement by rods. New technologies may use light-based fiberoptic cable rather than electrical cable. Some systems can accomplish the data acquisition function by using low powered radio transmitters to replace hard-wired cables. Some sensors will require the use of signal conditioning and analog to digital conversion before their output can be used in the logic and interface subsystems.

Logic

Any bridge integrity monitor system will require one of three levels of logic functions. The most simple is direct logic where the output of the sensor is used directly to break a circuit in the alarm/reporting subsystem. The second level of logic is comparison of an incoming signal to preset hard limits. This can be accomplished in hardware by using logic circuits, or in software by simple IF-THEN programming steps. The third level of logic requires higher level processing. This level may include fuzzy logic, pattern recognition, neural networks, or other software techniques operating on high speed sophisticated microcomputers.

Alarm/Reporting

In order to accomplish the mission of warning train crews, a railroad bridge integrity monitor system must indicate the status of the bridge to the train crew. The interface from the railroad bridge integrity monitor to the railroad crew does not depend on the type of sensor system or the logic required for a given system. The interface requirements are driven by the presence or lack of a signal system on the railroad.

One method for this interface is to use the existing wayside signal system. In the U.S. there are approximately 91,255 miles of track equipped with signal systems[16]. The railroad signal system is designated a "vital" system, because it directly affects the safe passage of trains. If a signal system displays improper clear indications, a serious train accident can easily result. Accordingly, all signal systems are designed to be fail-safe by displaying their most restrictive signal aspect if the signal system itself becomes inoperative for any reason. To interface a bridge integrity monitor to the railroad signal system the same philosophy must be used. Each bridge integrity monitor system must be designed to interface to the railroad signal system via a relay that requires a constant output from the integrity monitor to maintain clear signals. Either a valid alarm state or failure of the integrity monitor would then cause the signal system to display its most restrictive aspect.

The signal system interface method would be applicable only in those areas where wayside signals currently exist. Bridge integrity monitor systems in sections of railroad without signals ("dark territory") must use some other means to warn train crews. Train crews presently receive important operational information from dispatchers, wayside detectors, and other crew members by VHF voice radio transmissions. Some current wayside detector and alarm systems including hot box and dragging equipment detectors use synthesized VHF voice messages to provide train crews with information on the status of the individual detector system and the results of its scanning of the train. However, present VHF voice radio systems are not considered reliable enough to be termed vital systems.

Some current detectors for landslides, rock falls, high water, and burned trestles have stand-alone signals located well in advance of the detector location so that trains receive adequate warning time to stop short of the indicated hazardous condition.[17]

Moveable bridges and interlocking of signal appliances with bridge devices is covered under 49 CFR Part 236,[18] which requires that signal interlocking of moveable bridges be so connected with bridge devices that the bridge must be properly locked and the track properly aligned before a signal governing movements over the bridge can display an aspect to proceed.

Power Supply

All electrical and electronic bridge integrity monitor systems will need some source of electrical power either for operation of the sensor and logic subsystems, and/or to communicate to the train crews. The power supply must be continuously available to avoid false alarms and it must protect the bridge integrity monitor systems from lightning or power surges. If complete power failure does occur, the system should be designed so that the source of failure can be easily identified. Four sources of power are currently used on railroad equipment.

1. Commercial AC power with battery backup.
2. Railroad AC Power with battery backup.
3. Battery with Solar Charging.
4. Replaceable Batteries.

In this study, commercial AC with battery backup was used for all hypothetical bridges since it was thought to be the most common method used by the railroads.

3.1 Detectable Parameters

Hazard to a railroad bridge can stem from either external or internal initiating causes, listed in Section 2.3, and their resulting effects on the bridge. The hazards can be categorized into four main groups.

1. Natural forces.
2. Operational Activity.
3. Internal structural changes.
4. Changes in position of bridge members.

There are two basic approaches to railroad bridge integrity monitoring. The first approach is the detection of dangerous external causes. The second approach is the detection of dangerous internal conditions in the bridge structure. Generally, external cause detection alone is not enough to diagnose dangerous bridge conditions because the existence of the external cause may or may not result in a dangerous situation. For example, abnormally high water levels and rapid current may not affect the load carrying capacity of a bridge founded on solid rock. Direct detection of internal bridge conditions can be more reliable. However, technologies for direct monitoring of internal bridge conditions are relatively expensive, and some failure progressions can be detected only by periodic manual field inspection. Failure causes such as fatigue or corrosion are not easily measured or detected directly. Detection techniques for these causes must use indirect methods based on the detection of measurable physical parameters connected with the cause. These parameters can include sound, acceleration, and vibration. Causes that can be detected directly are flood, wind, earthquake, fire, intruding objects, displacement, collapse, and change of alignment.

Table 3.1 shows internal and external detectable parameters for bridges along with the initiating causes associated with them. This table contains only detectable parameters within the bridge structure itself.

Table 3.1 Bridge Failure Causes and Effects With Associated Detectable Parameters

	Acoustic emission	Light emission	Temperature change	Vibration	Impact	Movement	Stress	Change of shape	Lack of continuity	Intrusion
Flood				X		X	X	X	X	X
Strong Wind				X	X	X	X	X	X	
Earthquake	X			X	X	X	X	X	X	
Ice build-up				X	X	X	X	X	X	
Overloading	X			X		X	X	X	X	
Improper clearances	X			X	X	X	X	X	X	X
Collision of ship or vehicle	X			X	X	X	X	X	X	
Derailment	X			X	X	X	X	X	X	X
Explosion	X	X	X	X	X	X	X	X	X	X
Fire	X	X	X			X	X	X	X	X
Weakening of construction	X		X	X			X			
Cracking of members	X			X			X			
Disconnection of members				X			X		X	
Undermined support						X	X	X	X	
Displacement of members						X	X	X	X	
Distortion						X	X	X		
Change of alignment						X	X	X		
Intruding objects			X							X
Collapse	X			X	X	X	X	X	X	
Total Number	10	2	4	13	8	15	18	15	14	6
Percent of Causes	53	11	21	68	42	79	95	79	74	32

An" X" in a column indicates that the cause or effect may create that detectable parameter

Table 3.1 shows that there are several detectable parameters connected with a high percentage of the initiating causes of bridge failure and their effects on bridge structures. These parameters in descending order are:

1. stress,
2. changes of shape,
3. movement of bridge elements,
4. lack of continuity,
5. vibration,
6. acoustic emission, and
7. impact.

Since these parameters are associated with many initiating causes of bridge failure, bridge monitoring technology that uses these parameters has the potential to detect many of the possible dangerous situations. Unfortunately, most of these parameters are always present in bridges at some magnitude, particularly during passage of trains, and are not necessarily connected with hazardous conditions. The level and distribution of these parameters may vary from bridge to bridge and change with time on a particular bridge. To set alarm limits for an integrity monitor system, safe limits for each of these parameters would need to be calculated for each individual bridge.

3.2 Current Detection Technologies

Railroads have used automatic detectors for protection against unusual conditions for many years. The AREA classifies detectors into two categories, Category 1 detectors monitor the condition of rolling stock and motive power, Category 2 detectors are systems to detect undesirable conditions along the railroad right-of-way that will endanger the safe operation of trains. Types of Category 2 detectors include bridge movement (alignment), earth movement (earthquake or shifting of subgrade or ballast), falling objects (earth, rocks, or trees on bridge decks), fire (bridge decks and snow sheds), high water, high wind, and snow slide or avalanche detectors. Since the Category 2 detectors are deployed to prevent potential accidents, the AREA recommends interconnection with the wayside signal system, use of an automated radio warning message, or an alert to a dispatcher as means or warning trains.[17]

The following estimate of detectors that are currently in use on U.S. railroads was obtained from the FRA Regional Safety Offices and from railroad timetables.[18]

Table 3.2 Current Railroad Automatic Detector Systems

Detector Type	Number in Use
High Water	184
Fire	14
High / Wide Car or Load	694
Dragging Equipment	2954
Highway Vehicle Collision With Bridge	13
Bridge Alignment	5
Hot Box / Dragging Equipment	1415
Slide Fences	607
Track Alignment	13
Hot Box	2177

Information on the design and operation of current detectors was obtained from a survey conducted by the Brotherhood of Railroad Signalmen. A brief description of each of the detection devices follows.

High water detectors provide a warning when the water level reaches a predetermined depth. They may be installed some distance upstream from the tracks to provide warning time for flash floods. Usually older devices are float type sensors and newer types contain two electrodes which are short-circuited by rising water.

Fire detectors are usually based on a closed loop principle with sections of wire soldered together, or low melting point aluminum wire that will melt and break the loop if exposed to high temperatures.

High/wide load detectors provide a warning when railroad car loads or any oversized or damaged item infringes on the measured clearance envelope. These devices can be based on the stringing of a conductor that will be broken by the out-of-tolerance loads or can utilize optical or microwave detectors that will produce an alarm when loads cross the beam.

Dragging equipment detectors signal the presence of broken, misplaced, or hanging mechanical parts that have dropped below a predetermined clearance line above and between rails or adjacent to and outside of the rails. They can be self-resetting after activation.

Highway underpass collision detectors provide alarms after collisions by highway users with the bridge structures. These detectors may sense either impact or displacement. Simple detectors have a wire stretched over the highway connected to a mercury switch.

Earthquake detectors usually contain a pendulum. Displacement of the pendulum beyond normal limits is monitored by an electronic circuit.

Bridge alignment detectors contain circuit controllers or wires that break a circuit on a minimal displacement of the bridge structure.

3.3 Potential Detection Technologies

The following discussion will cover methods and techniques that are most promising for automatic bridge integrity monitoring based on the parameters identified in Table 3.2

3.3.1 Stress Monitoring

Measurement of loads and stresses in structural elements is a well-known technique used to study various types of construction. In general, stress measurement systems consist of a number of strain gages installed at the critical points of the structure, and a data collection system with a data processing device. This system would need information on expected train loads and would require that temperature sensors be included in the system. One example of this technology is the bridge-research program, recently initiated by the Research and Test Department of the Association of American Railroads.[19] The field part of this program includes measurements of strains and deformations on primary and secondary bridge members under static and impact loads. These measurements will be used for prediction of the remaining bridge fatigue life under various load conditions. The individual sensors are relatively inexpensive and can be installed in several critical locations of the bridge. They are excellent for determination of local stress levels during short-term experiments. However, to provide sufficient information to assure failure detection, the number of sensors may be large, and their long-term stability especially under changing environmental conditions can be questionable.

For long-term stress monitoring, other types of force transducers are sometimes applicable. For example, British Rail Research Central Services[20] used wire strain gages to measure changes the in stress level within continuous-welded rails. These sensors were connected to a data logger and through telephone telemetry to a central office. The system provided civil engineers with continuous information about stress level and indirectly about possible changes in railway track geometry. Another system that monitors the new Sunshine Skyway highway bridge in Florida required 228 concrete strain meters and 306 temperature sensors that are connected to a microcomputer through eight remote signal processors.[21]. The initial cost of this system was about $500,000.

Advantages of this technology:

- System monitors a parameter that is associated with the majority of internal structural failures.
- The software required is relatively simple.

Disadvantages of this technology:

- Stress measurements are localized, strain gages must be installed on every critical structure element to assure failure detection.
- Long-term reliability of strain gage sensors in a railroad environment is questionable.

3.3.2 Movement and Change of Shape Monitoring

There are several technologies that sense these parameters and can be considered for railroad bridge monitoring.

Displacement

This method is based on contact displacement sensors that provide a signal when the distance between rails, or between rail and bridge structure, or between supports and bridge spans is changing. The sensors could be a closed loop wire detector, differential transformers, or potentiometers.

Advantages of this technology:

- It monitors actual conditions of the railway and directly detects situations that can cause derailment.
- It can be used to monitor bridge continuity, eliminating the need for separate bridge continuity monitoring.
- The equipment is simple, reliable, and generally available.

Disadvantages of this technology:

- Sensors provide only local measurements and probably would not activate an alarm if a pier and the bridge span changed their positions simultaneously.
- A large number of sensors may be necessary for large bridges.

Tilt Measurement

Tilt measurement is another simple method of detecting movement that can be applicable to subsidence or impact. The system could contain several tilt sensors installed at key points on the bridge. Tilt beyond a predetermined limit would cause an alarm.

Advantages of this technology:

- Simple and cheap sensors

Disadvantages of this technology:

- Some bridge movements and changes of shape can take place without altering the tilt angle of the structure.
- May not be sensitive enough for some span lengths.

Light or Laser Alignment

Light or laser alignment detectors have been used to detect relative movement of bridge members. These systems consist of transmitting and receiving stations suitably aligned so that, if the light or laser path is broken by bridge movement, the alarm signal is issued. The receiving stations incorporate a time delay unit or more complicated processing device to compensate for the light or laser path being occasionally interrupted by birds, animals, or people. A system of this type was used in Britain[20] to monitor the influence of mining on railroad infrastructure. In some configurations, such systems can provide not only detection, but also very accurate measurements of bridge deflections.

Advantages of this technology:

- Produces accurate data on bridge displacements.
- Provides intrusion detection capability.
- Equipment available from the surveying industry.

Disadvantages of this technology:

- System adversely affected by meteorological conditions including heavy rain, fog, or snow.
- May not be practical on bridges with curved decks.

Distance Measurement

Laser or microwave distance measurement systems can also be used to detect movement or change of shape. The system can continuously measure distance to some critical point on the bridge and, therefore, provide information about bridge displacements. The system consists of a transmitter/receiver and a passive target that reflects the signal. The time taken for the signal to reach the target and return is used to measure distance to the target. Accuracy can be very high.

Advantages of this technology:

- Very high degree of accuracy.
- Relatively easy installation.
- Produces accurate data on bridge displacements.

Disadvantage of this technology:

- System adversely affected by meteorological conditions including heavy rain, fog, or snow.
- System monitors the distance to only one or a few critical points on the bridge.

Video Systems

Close range photogrammetry has been used to measure various geometric parameters of bridge structures, including steel-beam deflection measurement, and deck deterioration. This method utilizes a close range camera at a distance of approximately 12 feet, that is used to take stereoscopic overlapping pairs of photographs. This technique could be adapted for automatic bridge integrity monitoring by using digital cameras connected to a computer with image processing software. This combination would provide a detailed picture of the bridge and its condition. The system could be used for actual measurements of bridge elements. Another opportunity is to transmit images to a central location for monitoring by railway personnel. These systems would provide detailed information about changes in bridge geometry and also provide images of external conditions. To provide monitoring during the night, an infrared camera could be used.

Advantages of this technology:

- Continuous monitoring of the entire bridge structure.
- Possibility of documenting collisions or trespassing incidents.
- Monitoring for multiple initiating causes and effects.

Disadvantages of this technology:

- Requires sophisticated software, if automated.

- Adversely affected by meteorological conditions including heavy rain, fog, or snow.
- Reliability of equipment is questionable in a railroad environment.

3.3.3 Acoustic Emission Monitoring

This method is based on measuring acoustic emissions in the range of 100-1000 KHz from structural steel bridge members. Evaluation, provided as a part of the Kentucky Transportation Research Program[22], showed that this technology has the capability of detecting growing cracks on the steel members of in-service highway bridges. Similar results have been obtained on railway bridge spans. The system consists of a number of piezoelectric transducers, amplifiers, microprocessor, and recorders. Strain-gage sensors may also be incorporated to correlate stresses in a structure with acoustic emission. Sophisticated pattern-recognition data processing is used to distinguish between defect-related acoustic emission and routine noise associated with the normal bridge service environment.

Every bridge has an individual and complicated acoustic signal pattern. The reliability of acoustic monitoring will depend on the software's capability to separate failure conditions from routine noise and may be limited in some situations. Sophisticated signature recognition methods such as fuzzy logic and neural networks may be needed to distinguish valid alarms from routine noise.

Advantages of this technology:

- A broad range of detectable dangerous phenomena.
- High sensitivity.
- Ability to detect, locate, and characterize flaws.
- Detects only active growing defects.
- Can determine location of defects.

Disadvantages of this technology:

- Applicable only to steel or perhaps concrete bridge elements.
- Covers only effects and failure modes involving cracking.
- Requires external excitation of flaws by vehicular, or other external loading.

3.3.4 Discontinuity Detection

The simplest technology to provide discontinuity detection is a closed wire loop that is routed through all critical elements of a bridge. Any discontinuity breaks the loop and produces an alarm. This type of system can also be used to detect rail displacement.

Advantages of this technology:

- Simple system with little processing or logic required.
- Closed loop may also provide fire detection capability.

Disadvantages of this technology include:

- System does not give the location of defects directly.
- Closed loop may be damaged by birds, animals, or trespassers.

One disadvantage of the closed loop method is that it can be difficult to locate a problem when the alarm signal is triggered. To find the location of a discontinuity several more sophisticated methods are available. One method is time domain reflectometry (TDR). The TDR method has been applied to test electrical cables and to locate points where the cables were damaged. The technology is based on the fact that any discontinuity or damaged point in a cable reflects a portion of any electromagnetic waves traveling down the cable. The time taken for electromagnetic waves to reach the discontinuity and return can be measured extremely accurately. Since the velocity of the traveling wave is known, this time indicates the position of the discontinuity. The TDR method is fundamentally similar to radar, but is applied within a wire or cable rather than in the atmosphere. Electrical or optical cable could be attached at points along the bridge and any damage to this cable would be detected and localized. This method would be more expensive than the simple closed loop detectors, but it would provide additional information about location of the discontinuity.

Advantages of this technology:

- Can provide location of defects
- Closed loop may also provide fire detection capability

Disadvantages of this technology:

- System requires sophisticated logic and processing of data.
- Closed loop may be damaged by birds, animals, or trespassers

3.3.5 Vibration and Shock Monitoring

Vibration measurement is a common technique in various structure studies. Usually such measurements are used to evaluate structural behavior under various dynamic loads and used to determine specific natural frequencies of the bridge. There have been attempts to use vibration measurements for detection of fatigue and cracks in structural elements[23] but these attempts so far were not very successful. Vibration measurements, especially combined with shock measurements, seem to be very promising for failure detection purposes. Both parameters can be measured by sensitive accelerometers. The difference is only in the type of signals (periodic or transient) and their amplitude. Several sensors distributed along the bridge would probably be necessary.

Accelerometers would be connected to amplifiers and then to a microcomputer, where signals from all the sensors would be processed. Pattern recognition software would be necessary to analyze the received signals. This software theoretically should be less complicated than acoustic monitoring software, and results should be more reliable. This increase in reliability of detection is because this monitoring technology is based on measurements of the parameters directly connected with the failure. Dangerous levels of vibration and shock impact for every bridge can be estimated in advance.

Advantages of this technology:

- Broad range of initiating causes are covered.
- Reliability of failure detection.
- Possibility to calculate actual displacements of the structure by double integration of signals from accelerometers.

Disadvantages of this technology:

- Does not monitor Internal structural causes of bridge failure.
- Vibration monitoring occurs only when the bridge is loaded.

3.3.6 Detection of Intruding Objects

There is a broad spectrum of intruding object detection technologies that are available. In general these technologies fall into contact and non-contact groups. Contact detectors include the previously discussed falling rock fences, dragging equipment detectors, high water detectors, and other mechanical devices that provide an alarm signal.

Advantages of this technology:

- Very simple system.
- Reliable.

Disadvantages of this technology:

- Limited to detection of intruding objects only.

Non-contact devices include laser or other optical systems as well as microwave sensors that produce a signal when their beam is interrupted or when any target moves in the detection zone. Active acoustic sensors can be used for the same purpose although they are not likely to be applicable for the noisy conditions during routine train passage over a railway bridge. There are also passive infrared detectors that provide an alarm when any object with a temperature different from the temperature of existing objects appears in the detection zone. However, in general, these as well as other passive intruder detectors (seismometers, microphones and so on) do not seem to have potential for the severe conditions on railroad bridges.

The most promising non-contact systems for detecting intruding objects on bridges are active emitting devices (optic, infrared, microwave). The emitting devices can be installed on the bridge or on the train.

Advantages of this technology:

- Continuous monitoring of the entire bridge structure.
- Provides monitoring for multiple initiating causes and effects.

Disadvantages of this technology:

- Requires sophisticated software.
- System adversely affected by meteorological conditions including heavy rain, fog, or snow.
- Reliability of detection in railroad environment is questionable.

4.0 COSTS OF DETECTOR TECHNOLOGY

The costs to implement some of the technologies applicable for railroad bridge integrity monitoring were estimated for two reasons. First as a means of determining the potential cost impact to railroads to install bridge integrity monitors, and second, to provide a basis for comparing the technologies on different types and sizes of bridges. Cost estimates were developed for system components, for interfaces to other railroad equipment, and for recurring costs. Cost data was estimated in 1994 dollars using inflation and cost of money figures as noted in Section 4.6.

All recurring and non-recurring costs associated with bridge integrity monitor systems were assumed to be borne by the railroads.

4.1 Signal System Interface Cost Estimates

Bridges integrity monitors located in signaled territory would probably be interfaced to the wayside signal system. Indication of an alarm condition on the bridge can be accomplished by using the standard restrictive aspect of the existing signals or it might involve addition of another indicator or light such as a rotating light, to notify train crews that the bridge integrity monitor was the cause of the restrictive signal. In this study, no additional indicators were assumed to be required. To be effective in preventing accidents, wayside signals would need to be placed far enough from each end of the bridge to allow distance to stop trains. Costs associated with installation of additional wayside signals were not included in this study. Determination of the number and location of additional wayside signals would require a site-specific analysis beyond the scope of this study.

4.1.1 Track Circuit Interface

A track circuit is a means of sensing the presence of trains and of hazardous conditions such as broken rails, and using this information to control signal aspects to protect an oncoming train. Interfacing a bridge integrity monitor to the track circuit was assumed to require two railroad-quality relays and a suitable enclosure. The relay costs were included in the system costs for each integrity monitor technology used on the hypothetical bridges in Section 5. Costs for splicing into the existing signal system would include trenching, cable, and labor costs. Estimates for these costs vary depending upon the specific type of signal system in use, the proximity of wayside signals to the bridge, and the number of tracks. For the purpose of this study, a cost of $25,000 was assumed to be an average figure for completing this interface.

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4.1.2 "Talking" VHF Interface

Many existing wayside detector systems for hot bearings and dragging equipment broadcast their status and results to train crews via VHF radio. This method may be acceptable for single bridges but could result in frequency congestion if many bridges were in close proximity. Since on the average a bridge is located every 1.4 miles of track, this method should probably be considered only on a site-specific basis. Radio equipment is approximately $5000.00 per installation.

4.1.3 Cellular Telephone Interface

Another possibility for interfacing the status and alarms from an integrity monitor is the use of a cellular telephone. Systems of this type are available for approximately $1500. The monitor can be periodically polled from the railroad dispatch office over the cellular telephone, and would immediately dial up the dispatcher if an alarm occurred. This type of interface might be cost-effective for bridges with small amounts of traffic or for bridges in non-signaled territory. Since this interface relies on the warning of train crews from a remote location, there would be a longer time from the detection of an unsafe condition until notification than in signaled territory.

4.2 Sensor System Cost Estimates

The costs for each type of sensor system were developed using off-the-shelf products as much as possible. Data on both cost and reliability were obtained from manufacturer's data if available. Equipment was specified to be of MIL-STD quality or the equivalent to provide a wide temperature range of operation. Detailed cost breakdowns for each technology on each hypothetical bridge are contained in the appendices.

4.2.1 Sensors

The costs for individual sensors were obtained from manufacturer's catalogs or sales offices. Costs for technologies not currently used were estimated based on similar equipment intended for use in other applications.

4.2.2 Processing

Processing hardware costs were based on the use of single-board computers. If required, the addition of a signal conditioning card and an A/D conversion card were also included. Systems using lower levels of logic used logic arrays instead of full computer boards.

4.2.3 Installation

Installation costs were estimated for each system using an assumed trip length of 75 miles one-way for a signal technician. The amount of time (days) required to assemble, calibrate, and test each sensor system was estimated based on the complexity of the system, number of individual sensors, length of cabling, and other aspects of each system. Two workers were assumed to be needed for installation of any system. Costs associated with delay of train passage during installation were not estimated for any system.

Systems requiring AC power were assumed to require a one-time charge of $10,000 for the utility to set up poles, transformers, and other equipment needed to make this power available at the bridge site. Moveable bridges were assumed to have AC power available without requiring a one-time charge.

4.3 Recurring and Maintenance Costs

All of the proposed railroad bridge integrity monitor systems would create a need for periodic maintenance, adjustment, testing, component replacement, and other maintenance activities. Systems requiring a power source would also incur charges for use of commercial AC power. A 25-year period was used to estimate the recurring costs.

4.3.1 Electric Power

Each system operating from electric power was assumed to use commercial AC power as the primary source of energy with batteries used during times of AC power outage to decrease the possibility of false restrictive signals due to outage of the bridge integrity monitor. Electric power consumption was estimated at 20 watts for basic battery charging and to hold relays open. Systems requiring logic circuits were estimated to require 25 watts. Systems requiring computers were estimated to require 25 watts for each computer. Systems using lasers or video cameras were estimated to use 300 watts for each laser or camera. Electricity was assumed to cost seven cents per Kilowatt-hour.

4.3.2 Communication

Any interfaces via leased line communications or cellular telephone would be assessed a charge for service over the life of the equipment. These costs were not estimated at this time, due to the assumption that wayside signals would be used for interfacing the alarm information to the railroad.

4.3.3 Inspection and Maintenance

Each integrity monitor system was assumed to require periodic maintenance of some type. Currently, railroads typically inspect signal equipment four times each year. Relays in the signal system are checked in the field on a yearly basis. Components of the system such as batteries and lasers have known lifetimes and must be replaced at certain intervals to assure proper function. Each inspection and periodic maintenance action was assumed to require one technician two hours at $14.00 per hour and a round trip distance of 150 miles at $0.25 per mile. An overhead charge of 128% was added to the technician's time.

4.4 False Alarm Cost Estimates

Any type of integrity detector system fielded will result in some false alarms. The vital requirements placed on interfacing with the railroad signal system mean that the signal system must display a restrictive aspect any time the integrity monitor either declares an unsafe bridge state, or if the integrity monitor experiences an internal failure. The latter case is termed a false alarm since the bridge can still be in a safe condition. The railroad would experience costs associated with these false alarms since inspectors or technicians or both would need to travel to the bridge to inspect the bridge and the integrity monitor system to determine if the alarm was true or false. If false, the technician would need to repair the integrity monitor to restore it to service.

The costs associated with the repair and return to service were estimated as four hours of a technicians time at $14.00 plus 150 miles round trip travel at $0.25 per mile. An overhead charge of 128% was added to the technician's time. The cost of one component with the lowest reliability was also added assuming that the false alarm was due to its failure. There also would be costs to the railroad if trains were stopped during the time required for the technician to examine the monitor and return it to service. These costs were estimated based on a 70-car train and a three hour delay.

The estimated costs were:

- Locomotive cost of $ 100 per hour per unit for three units.
- Train crew cost of $ 150 per hour.
- Maintenance and supplies at $100 per hour.
- Per diem cost at $0.50 per car per hour.
- Missed connection cost at $50. per car.

For the assumed three hour delay these costs amounted to $4,552.

4.5 Accident Cost Estimates

The mission of a railroad bridge integrity monitor is to prevent train accidents on that bridge. If the mission is successful, the railroad will experience a cost saving. The cost of a train accident on a bridge depends on several factors, including the following:

- Type of train (freight, passenger) and contents, (passengers, bulk material or high value goods).
- Injuries or fatalities to the public, passengers, and railroad employees.
- Speed of train at derailment.
- Damage to train locomotives and cars and damage to railway and bridge structure.
- Time and extent of disruption of service across the bridge.
- Existence of alternate routes around the wreck location.
- Labor and materials required for wreck cleanup.

Accident cost data as reported to the FRA includes only damage to railroad equipment and does not account for other items including costs to reroute traffic during wreck cleanup. As early as 1967, a figure of $250,000 was estimated to cover all costs associated with a typical railroad derailment. At that time the average reported cost of a railroad derailment was $25,000, yielding a factor of 10 correction to reported costs.[24] The average cost of the three accidents in 1992 attributed to FRA Accident/Incident Cause Code number T401, "Bridge misalignment or failure" was $25,250. Multiplying this figure by 10 yields an estimated total cost for a bridge accident of $252,500.

The $252,200 cost can be considered a minimum value. Total accident cost data from NTSB investigations of major railroad bridge and culvert and culvert accidents as noted in Section 2 ranged from $1.4 million to $14 million.

4.6 Life Cycle Cost Corrections

The cost for bridge integrity monitor components, interfaces, and installation were assumed to occur in 1994. Recurring costs occur over the 25-year life cycle. In order to correct these costs to the baseline year of 1994, the following procedure was used:

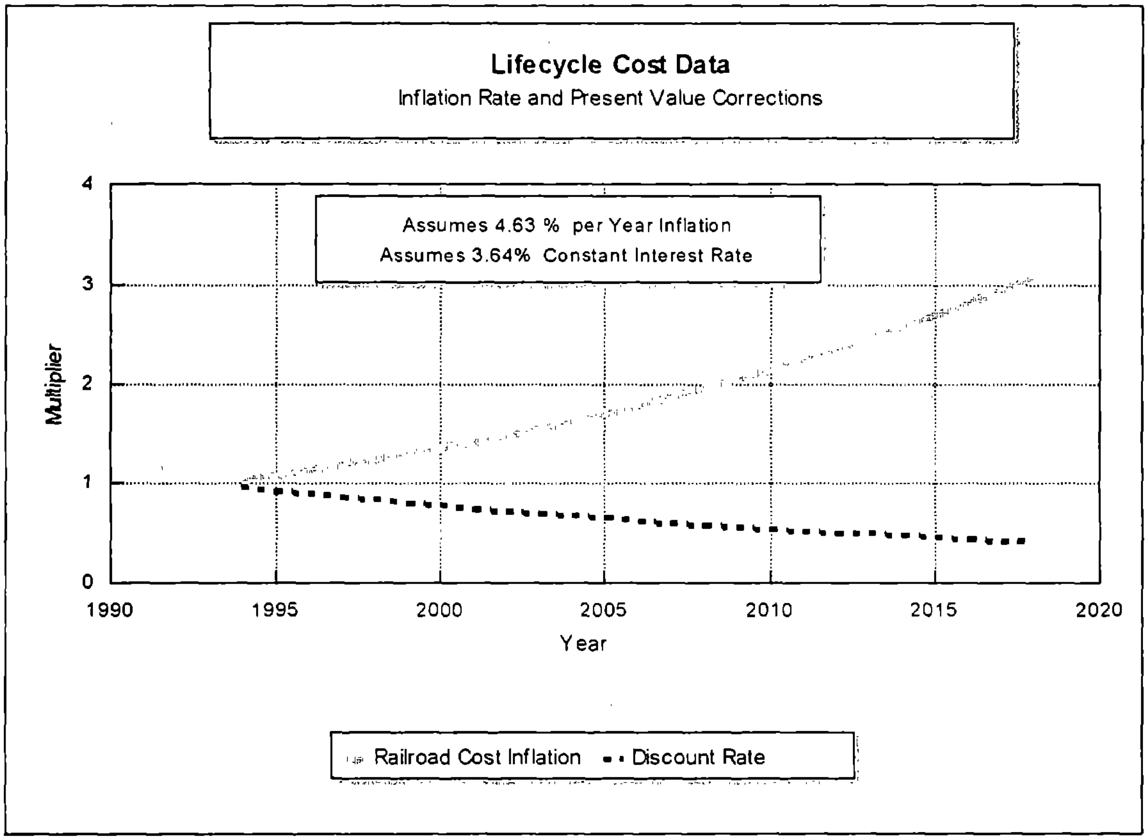
1. Historical data on the inflation of railroad costs was obtained from the 1992 edition of Railroad Fact Book[25], published by the Association of American Railroads. This publication contains a Rail Cost Adjustment Factor (RCAF) which is determined by the ICC. The factor is corrected quarterly to reflect actual price level growth experienced by railroads. The average value of the corrected RCAF was determined to be 1.0463 for the last four years. This 4.63% factor was assumed to be constant and used to inflate costs over the next 25 years.

2. The current interest rate for 30-year Treasury Bills was 3.64% on April 17, 1994.[26] This figure was used as a constant to discount costs in future years.

3. The inflation and discount rates were calculated for each of the 25 years.

4. Any costs incurred in future years were then multiplied by that year's inflation and discount factors to correct them to the baseline year.

Figure 4.1 shows the inflation factors and discount rates used in the life cycle cost analysis.



5.0 HYPOTHETICAL EXAMPLES

In order to adequately compare some of the existing and new technologies for railroad bridge integrity monitoring, the systems must be applied to a specific bridge. To determine details about a monitor system, the size, type and construction details of a bridge must be known along with an estimate of the numbers and types of initiating causes that may affect the bridge. Details on numerous existing railroad bridges were reviewed and used as a basis to create three hypothetical bridges. The hypothetical bridges are a simple deck girder span, a multi-span truss bridge with a moveable span, and a timber trestle. These bridges were chosen to illustrate application of monitoring technology to simple and complex railroad bridges of varying types. Each bridge was assumed to carry a single-track railroad line with both passenger and freight traffic at track speeds of 79 mph for passenger and 60 mph for freight (FRA class 4 track). A 25-year time period was used to estimate the number of different initiating causes the bridge would be exposed to and the recurring costs for the integrity monitor system.

The hypothetical bridges were identified using standard railroad terminology. Each bridge was assigned a number corresponding to the milepost location on the hypothetical railroad line. For example, bridge 125.20 is located two-tenths of a mile beyond milepost 125.

5.1 Method of Analysis

Assumptions were made for each bridge for the following parameters:

1. Initiating causes that the bridge would be exposed to.
2. Frequency of occurrence of each initiating cause.
3. Detailed effects on the bridge from each initiating cause.
4. Frequency of occurrence of each detailed effect (F_e).
5. Criticality of the hazard resulting from each detailed effect.

The frequencies of occurrence of the initiating causes were deliberately exaggerated in order to better illustrate the operation of the integrity monitor systems. Engineering estimates for each bridge integrity monitor system were made for the following:

1. Detection probability for each detailed effect.
2. System reliability and failure rate.

5.1.1 Criticality of Effects

The susceptibility of each bridge to each of the initiating causes was postulated based on the design of the bridge and the location and cross traffic modes involved. The exposure and risk to the bridge from each of the identified causes was assessed by breaking the risk into the frequency of occurrence of each initiating cause and the criticality of the effects resulting from each initiating cause. The specific sighting of each hypothetical bridge was used to allow a variety of causes to be discussed. The design details of each bridge allowed the effects of each initiating cause to be broken down into disconnection, displacement, distortion, cracking, overloading, or undermining of specific bridge structure members. These were called detailed effects. The hazard caused by each detailed effect was estimated for each bridge. Then each critical effect was assigned a numerical value for its probability of causing an accident estimated using engineering judgment and input from railroad and bridge experts. Table 5.1 indicates the probability of accident assumed for each level of criticality:

Table 5.1 Weighting of Hazard Levels of Effects on Railroad Bridges

Criticality	**Probability of Accident (P_A)**
No hazard to train or bridge occurs. Effect cannot derail the train or affect the bridge or track structure strength.	0.0
Hazard is Improbable. Effect has a very minor chance of derailment or of decreasing bridge or track structure strength.	0.1
Hazard is Remote. Effect has a minor chance of causing a derailment or of decreasing bridge or track structure strength.	0.3
Hazard is Likely. Effect may be capable of causing a derailment or of decreasing bridge or track structure strength.	0.7
Hazard is Highly Likely. Effect most likely can result in a derailment or definitely decreases bridge or track structure strength.	0.9
Hazard is Assured. Derailment is assured, or effect results in bridge collapse or track structure is destroyed.	1.0

In this analysis, a P_A of 0.0 should be interpreted as "very close to 0.0" and a P_A of 1.0 should be interpreted as "very close to 1.0."

The frequency of accidents (F_A) due to bridge failure or train derailment was calculated for each effect by multiplying the estimated frequency of effects in the 25-year period (F_e) by the probability of that effect causing a failure or derailment. Frequency of accidents was calculated as:

$$F_A = F_e * P_A$$

The frequency of non-accident causing effects F_{NA} was calculated by multiplying the frequency of effects by the probability that the effect would not cause a failure or derailment. Thus, F_{NA} was calculated as:

$$F_{NA} = F_e * (1-P_A)$$

The sum of the failures/derailments from all of the detailed effects was the expected number of bridge failures/train derailments resulting from a given initiating cause. The sum of the bridge failures/train derailments from all assumed initiating causes gave the expected total number of accidents for that bridge over the 25-year time period.

5.1.2 Detection Effectiveness

Detection effectiveness was evaluated assuming that each integrity monitor system was 100% operational. Failures within the integrity monitor systems were accounted for under false alarms in Section 5.1.3. The effect of meteorological conditions on non-contact sensors was factored into their detection effectiveness. The sensor systems were examined for their ability to detect the detailed effects assumed to result from the potential failure causes. The ability of each sensor system to detect each detailed effect was estimated using engineering judgment. Each detection probability (P_d) was scored from 0.0 to 1.0. The probability of detecting and alarming on a non-hazardous effect was also estimated. The actual detection probabilities used on each hypothetical bridge are included in the discussion of each bridge later in this section.

5.1.3 Definition of Alarms

The mission of a railroad bridge integrity monitor system is to warn trains of unsafe bridge conditions in order to stop passage of trains over the bridge and thereby avoid an accident. Output from an integrity monitor that causes the signal system to display a restrictive aspect was termed an alarm. The number of alarms generated by a given technology of integrity monitoring was calculated by multiplying the number of specific effects by the probability of detection of that effect and summing over all effects.

$$\text{Alarms } A = \Sigma F_{ei} * P_{di}$$

Where F_{ei} is the frequency of occurrence of the ith effect on the bridge and P_{di} is the probability of detection of the ith effect.

Depending on the operating costs of a bridge integrity monitor system, an alarm may represent a substantial cost saving to the railroad, its customers, and the general public by preventing an accident, by eliminating damage to the railroad track and structures and adjoining property, by preventing injury to train crews passengers and nearby persons, and by avoiding extended disruption of service during bridge repair and wreck clearing activities.

If the alarm condition was due to either failure of the integrity monitor, or detection and alarm on a non-hazardous effect, the alarm was termed a "false" alarm (A_f). A false alarm always represents cost to the railroad for stopping of trains, for inspection of the bridge and integrity monitor system to determine if the alarm was true or false, and for possible disruption of service or rerouting of trains while the alarm and bridge are out of service. False alarms are therefore a waste of the installation cost of an integrity monitor system. A railroad bridge integrity monitor system which produces numerous false alarms will be unacceptable to railroads. False alarms due to the detection technology ($A_{FT)}$) were calculated by determining the number of times the integrity monitor would issue an alarm on detection of a non-accident causing effect:

$$A_{FT} = \Sigma F_{NAi} * P_{di}$$

These are false alarms that occur with the integrity monitor system operating normally. The number of false alarms due to system failure was calculated by using estimated failure rates per one million hours calculated using MIL-HDBK-217F techniques.[27] These failure rates were adjusted to the hours in 25 years to give the expected number of failures of each system. Each system failure was assumed to create an alarm situation and was, therefore, counted as a false alarm (A_{FE}). The total number of false alarms over the 25-year period for each technology was then calculated by adding the sum of false alarms due to the technology and false alarms due to equipment failure or:

$$A_F = A_{FT} + A_{FE}$$

A "missed alarm" (A_m) situation occurs when a bridge integrity monitor system did not generate an alarm state when true hazardous conditions existed. Missed alarms are the worst case for cost impact to the railroad. In this case, the railroad had incurred the costs of installing and operating the monitor and did not avoid the costs associated with a railroad accident. Missed alarms indicate that a system has not performed its mission of warning trains. The number of missed alarms were calculated for each technology by summing the probability of not detecting an accident-causing effect times the number of accident-causing effects:

$$A_m = \Sigma F_{Ai} (1\text{-}Pd_i)$$

Where F_{Ai} is the frequency of actual bridge failures assumed to occur in 25 years due to the ith effect on the bridge.

The number of alarms (A) generated in the 25-year period was compared to the frequency of accidents that would have occurred without integrity monitoring (F_A). A value of A less than F_A indicated a tendency for that technology to miss alarms. A value of A greater than F_A indicated a tendency for false alarms.

The total, false, and missed alarms for each type for each specific integrity monitor system were determined to compare the relative performance of the technologies.

5.1.4 Sensor System Designs

Candidate systems for instrumenting each bridge were designed for the assumed initiating causes of failure. Since impact from vehicles crossing below each bridge was considered to be the most likely risk to the bridges, sensor systems were designed primarily to detect this initial cause. The ability of the sensor systems to protect against other assumed initiating causes such as fire and subsidence and were also examined as a secondary mission. Design details for integrity monitors on the 40-foot girder bridge, 125.20, are found in Section 5.2.2. Monitor design details for the multi-span truss bridge, 5.07 are found in Section 5.3.2. Monitor design details for the timber trestle, bridge 44.53 are found in Section 5.4.2.

Eighteen bridge integrity monitor systems based on technologies likely to sense either impacts or their effects on the bridges were developed for comparison. The technologies studied are shown in table 5.2.

Table 5.2 Sensor Technologies Applied to Hypothetical Bridges

Lateral Impact Sensor
Frangible Wire
Laser Alignment System
Fiber-optic Displacement System (TDR)
Pyrotechnic Impact Sensor
Mechanical Displacement Sensor
Brittle Bar
Laser Displacement System
Stereo Video Image Processing System
Self contained Impact Sensor (Transmitter)
Strain Gage System
Acoustic Emission Sensor
Accelerometers
Electromechanical Switch Movement Detector
Laser Occulting Target Alignment System
Piezo-electric Movement System
Pyrotechnic Displacement Sensor
Track Circuit

5.2 Hypothetical Bridge No. 1 Bridge 125.20, 40-Foot Deck Girder Bridge

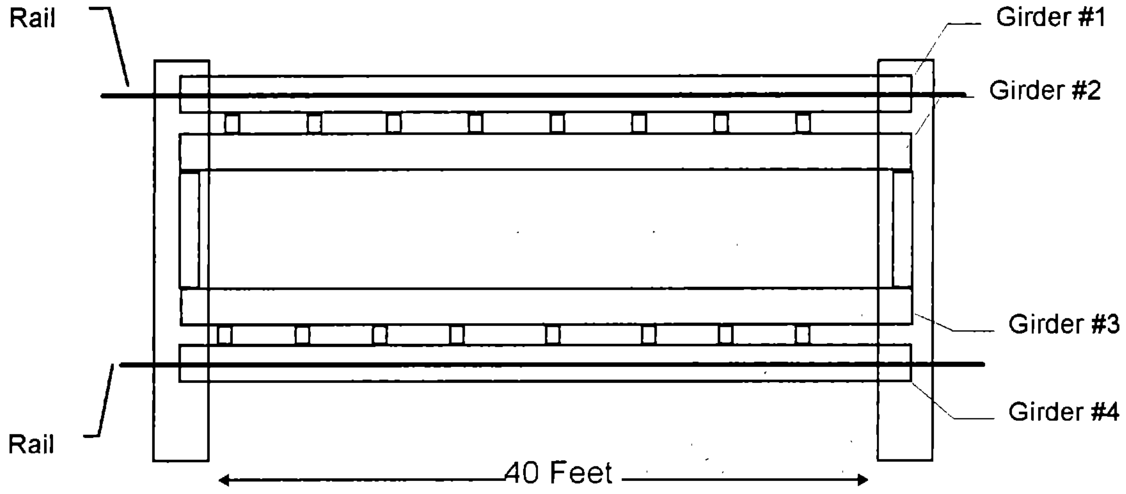


Figure 5.1 Top view of bridge 125.20 structure, track crossties removed for clarity

The design of this bridge is representative of a large number of girder bridges on U.S. railroads. This bridge is a 40-foot span deck girder bridge crossing a highway with 14 ft vertical clearance between the lowest point on the bridge superstructure and the highway pavement. The railroad is a single track line carrying freight and passenger service. A track circuit is in place on the bridge and a signal cable runs beside the track. Commercial AC power is available from a pole line along the highway. A two-lane highway passes under the bridge with a 55 mph speed limit.

The main hazard to the bridge is impacts from large trucks which pass beneath the bridge. Coal field equipment and large garbage trucks travel on the highway under the bridge regularly. Due to coal mining activity, there is a possibility of subsidence in the area. There is also a possibility of fire on the bridge deck from hot brake shoes or rail grinding activity. The following distribution of initiating causes was assumed.

5.2.1 Initiating Causes Bridge 125.20

Table 5.3 details the initiating causes assumed for this bridge along with the frequency of occurrence of each. Initiating causes that can occur but are normally identified by periodic bridge inspections were not considered in the integrity monitor analysis, since such conditions will be corrected by railroad maintenance crews before creating a hazard to the bridge.

Table 5.3 Initiating Causes and Frequencies of Occurrence for Bridge 125.20

Initiating Cause	Comments	No. in 25 Years *
Impact/Shock	Considered to be the most likely threat to this bridge. Probability of occurrence of significant impacts from highway vehicles set at 5 in 25 years.	5
Fire	Considered at low frequency of occurrence 1 fire per 25 years	1
Subsidence	Considered at a low frequency of occurrence of 1 case in 25 years	1

* Note: Likelihood of events is exaggerated for study purposes

The three most likely initiating causes for failure for this bridge were assumed to be impact, fire, and subsidence. Specific configurations of each candidate sensor system were then chosen to maximize the detection capability for impact.

To design the integrity monitor systems the bridge was simplified into its main components. The main components of bridge 125.20 are four wide flange girders placed two under each rail. The condition and position of these girders were considered to be the key parameters for integrity monitoring of this bridge.

Failure Progression

The failure progression associated with the major initiating causes was postulated based on engineering judgment. The effects on key portions of the bridge and track structure were proposed based on field experience and past bridge inspection results. The following tables summarize the detailed effects thought to occur after the initiating causes of impact, fire, and subsidence.

Impact

On bridge 125.20, the four main girders were assumed to be able to be moved laterally by severe impacts accompanied by shearing of restraining bolts at the fixed or bearing end as appropriate. Movement of a single main girder was discounted due to the strength of the diaphragm connection to the adjoining main girder. The most likely result of a typical vehicle impact was denting of the lower flange of an outer main girder. Separate movement of a pair of main girders on one side of the bridge was considered to be possible. Movement of all four main girders was considered in the lateral impact case only at a very low frequency of occurrence. The likelihood of a highway vehicle impacting the bridge with enough energy to completely collapse the span was considered to be so low that it could be eliminated. The locations of lateral movement considered in order of likelihood of occurrence were:

1. Movement of one end of two main girders on one side,
2. Movement of one end of all four main girders,
3. Movement of both ends of two main girders, or
4. Movement of both ends of all four main girders.

Table 5.4 contains the detailed effects, their criticality, and the number of bridge failures or derailments assumed to occur from each effect.

Table 5.4 Detailed Effects on Bridge 125.20 From Vehicle Impact

DETAILED EFFECTS	No of Occurrences per 100 Impacts	Number of Detailed Effect in 25 Years (5 Total Impacts)	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
FLANGE OF ONE GIRDER BENDS	80	4	0	0
TWO GIRDERS MOVE AT ONE END	13	0.65	0.9	0.585
FOUR GIRDERS MOVE AT ONE END	6	0.3	0.9	0.27
BOTH ENDS OF ALL GIRDERS MOVE	1	0.05	1	0.05
COLLAPSE	0	0	1	0

Movement of any of the main girders on one end of the bridge was considered to cause a kink in both of the track rails at that end of the bridge sufficient to cause a derailment. Movement of girders at both ends of the bridge was considered to cause similar rail kinks at both ends of the bridge. Sufficient lateral movement to cause the bridge to lose contact with its bearing seats was considered unlikely due to the weight of the bridge compared to the cross traffic vehicle weights.

Fire

Due to the steel construction of bridge 125.20, the most likely significant effect of fire was assumed to be limited to damaging bridge ties. The likelihood of derailment was considered to increase with larger numbers of damaged ties. Derailment was considered remote if only two ties in a row were damaged. A derailment after damaging three ties in a row was considered highly likely. Derailment was estimated to be probable after a fire had damaged or destroyed four ties in a row. A serious fire capable of destroying more than four ties in a row was considered to definitely cause a derailment. Fires damaging four or more ties were also considered to cause buckling of main girders, cross bracing, and diaphragm components, thereby weakening both the track and bridge structure.

Table 5.5 Detailed Effects on Bridge 125.20 From Fire on Bridge Deck

DETAILED EFFECTS	No of Occurrences per 100 Fires	Number of Detailed Effect in 25 Years (one fire in 25 years)	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
<= 1 TIE BURNS	70	0.7	0	0
2 TIES BURN	20	0.2	0.1	0.02
3 TIES BURN	5	0.05	0.7	0.035
4 TIES BURN	3	0.03	0.9	0.027
50% OF TIES BURN	1	0.01	1	0.01
75% OF TIES BURN	0.5	0.005	1	0.005
100% OF TIES BURN	0.5	0.005	1	0.005

Subsidence

Three cases of subsidence were considered. Due to the simple support of the short span bridge, the two abutments support all of the loads. Subsidence was considered to cause a vertical drop or an angular tilt of either the east, west, or both abutments. A derailment after movement of one abutment was considered highly likely. A derailment after movement of both abutments was considered assured.

Table 5.6 Detailed Effects on Bridge 125.20 From Subsidence

DETAILED EFFECTS	No of Occurrences per 100 Cases of Subsidence	Number of Detailed Effect in 25 Years (one subsidence)	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
EAST END OF BRIDGE MOVES	49	0.049	0.9	0.441
WEST END OF BRIDGE MOVES	49	0.049	0.9	0.441
BOTH ENDS OF BRIDGE MOVE	2	0.002	1	0.02

The assumptions used in these tables are discussed for each initiating cause. given below:

5.2.2 Integrity Monitor Systems and Detection Probabilities Bridge 125.20

This short deck girder bridge was considered to be a laterally stiff structure. The reaction of the bridge components to impact from highway vehicles was estimated to consist of either bending of the lower flange of the main girder that was struck or movement at the bearings by the ends of pairs or the ends of all four main girders. The bending of the lower flange was not considered to be hazardous. The movement at bearings was considered to be hazardous if it reached 0.5 inches. All systems were designed to be able to detect 0.5 inches of movement.

Lateral Impact Sensors

Two mercury switches are installed on the inner surface of the outer girders #1 and #4. Any impact against the girders from highway traffic above a specified magnitude will cause the switches to lose electrical continuity momentarily and cause a latching relay to cause a restrictive aspect on the local railroad signal system. The system is electrical and requires a latching relay but no logic circuits or processor. The sensor output is transient unless impact results in enough tilting of the girder to keep the switch open. The lateral impact G switch sensor was assumed to be set at a magnitude of acceleration above that normally found during train passage. Due to its simplicity, this sensor was considered to always trip if accelerations at its mounting location exceeded the limit. Mounting the sensor in approximately the area that would be struck by oversize vehicles created the possibility of a local acceleration or shock exceeding the threshold while causing only bending damage to the lower flange. Fire detection capability was considered as the probability that a connecting wire would burn in two at some point on the bridge during the fire. This probability was assumed to increase with the number of ties involved in a deck fire.

Table 5.7 Lateral Impact System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.2	Leads to false alarm
Two girders move at one end	1.0	Exceeds G limit
Four girders move at one end	1.0	Exceeds G limit
Four girders move at both ends	1.0	Well exceeds G limit
One tie burns or partially burns	0.01	Basic assumption for wired systems, detection from fault due to damage to wire
Two ties burn	0.02	Basic assumption for wired systems, detection from fault due to damage to wire
Three ties burn	0.05	Basic assumption for wired systems, detection from fault due to damage to wire
Four ties burn	0.10	Basic assumption for wired systems, detection from fault due to damage to wire
50% of ties on bridge burn	0.20	Basic assumption for wired systems, detection from fault due to damage to wire
75% of ties on bridge burn	0.75	Basic assumption for wired systems, detection from fault due to damage to wire
100% of ties on bridge burn	1.00	Basic assumption for wired systems
East end of bridge moves	0.01	Subsidence not likely to cause shock
West end of bridge moves	0.01	Subsidence not likely to cause shock
Both ends of bridge move	0.01	Subsidence not likely to cause shock

Accelerometers

Accelerometers oriented with their sensitive axis along the direction of highway travel are attached to the inner top surface of the bottom flange of each outer girder. Impact against the girder will cause a large acceleration in that member which will be sensed by the accelerometer. Depending on the magnitude of the impact, each accelerometer may also sense impacts on the opposite side of the bridge. The output of each accelerometer is monitored continuously and a processor decides if alarm thresholds are exceeded. The system must not alarm during normal train passage. The sensors are also able to detect major twisting or distortion in the outer main girders. The accelerometer system was assumed to operate with the same detection probability as the impact sensors. The added complexity of the computer system needed to analyze the accelerometer signals was accounted for in the failure rate calculations for false alarms. No degradation in detection probability was assumed due to software since the simple software needed to declare alarms was IF-THEN type logic. Due to the simplicity of the sensor and software, this system was considered to always trip if accelerations at its mounting location exceeded the limit. Mounting the sensor in approximately the area that would be struck by oversize vehicles created the possibility of a local acceleration or shock exceeding the threshold while causing only bending damage to the lower flange.

Table 5.8 Accelerometer System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.2	Leads to false alarm
Two girders move at one end	1.0	Exceeds G limit
Four girders move at one end	1.0	Exceeds G limit
Four girders move at both ends	1.0	Well exceeds G limit
Fire Detection		Basic assumption for wired systems
East end of bridge moves	0.02	Longitudinal tilt not likely to be sensed by lateral accelerometer
West end of bridge moves	0.02	Longitudinal tilt not likely to be sensed by lateral accelerometer
Both ends of bridge move	0.02	Longitudinal tilt not likely to be sensed by lateral accelerometer

Brittle Bar Sensors

Four brittle metallic bars are anchored to the bridge abutments and to the ends of the two outer girders. Excessive movement of the girders relative to the abutments will cause the bar at that end to fracture and open an electrical circuit that controls a relay in the track signal system. Rigging of the system must permit normal vibration under train passage and thermal expansion of the bridge and the sensor components without fracturing the brittle bars. The brittle bar system was designed to have breakable bars or wires attached to girder ends and to the bridge abutments in such a manner that relative lateral movement in excess of 0.5 inch would break the bar or wire. The brittle bars provided a degree of redundancy due to the assumptions of multiple girder movement from hazardous impacts. The detection probability of this simple system was therefore very high. The probability of breaking a bar or wire due to denting impact was considered to be small but non-zero.

Table 5.9 Brittle Bar System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.05	Leads to false alarm
Two girders move at one end	1.0	One or two bars break at 0.5 inch movement
Four girders move at one end	1.0	One to four bars break at 0.5 inch movement
Four girders move at both ends	1.0	One to four bars break at 0.5 inch movement
One tie burns or partially burns	0.02	Possibility of detection from thermal expansion
Two ties burn	0.05	Basic assumption for wired systems plus thermal expansion
Three ties burn	0.1	Basic assumption for wired systems plus thermal expansion
Four ties burn	0.2	Basic assumption for wired systems plus thermal expansion
50% of ties on bridge burn	0.4	Basic assumption for wired systems plus thermal expansion
75% of ties on bridge burn	0.9	Thermal expansion and wire burn through likely
100% of ties on bridge burn	1.00	Thermal expansion assured and wire burn through assured
East end of bridge moves	0.05	Possibility of twisting bars, little relative motion in lateral or vertical planes
West end of bridge moves	0.05	Possibility of twisting bars, little relative motion in lateral or vertical planes
Both ends of bridge move	0.05	Possibility of twisting bars, little relative motion in lateral or vertical planes

Frangible Wire

A loop of breakable wire conducting an electric current is attached to the east bridge abutment, along the outer bottom flange of girder #1 to the west abutment, across the abutment to the outer flange of girder #4, along the outer lower flange of girder #4 to the east abutment, and connected to a power supply and latching relay. If there is excessive relative movement between the bridge girders and the abutments, or between the bottom flanges of the outer girders, the wire will part and the relay in the signal system will cause a restrictive signal. Rigging of the system permits normal vibration under train passage and thermal expansion. The frangible wire provided a degree of redundancy due to the assumptions of multiple girder movement from hazardous impacts and the possibility of more than one break in the wire loop. The detection probability of this simple system was therefore very high. The probability of breaking the wire from a denting impact was considered to be small but non-zero. Fire detection probability was assumed to be higher for this system due to the fragile nature of the wire loop.

Table 5.10 Frangible Wire System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.05	Leads to false alarm
Two girders move at one end	1.0	One or two sections of wire break at 0.5 inch movement
Four girders move at one end	1.0	One to four sections of wire break at 0.5 inch movement
Four girders move at both ends	1.0	One to four bars sections of wire break at 0.5 inch movement
One tie burns or partially burns	0.02	Basic assumption for wired system plus possibility of detection from thermal expansion
Two ties burn	0.05	Basic assumption for wired systems plus thermal expansion
Three ties burn	0.1	Basic assumption for wired systems plus thermal expansion
Four ties burn	0.4	Basic assumption for wired systems plus thermal expansion
50% of ties on bridge burn	0.8	Basic assumption for wired systems plus thermal expansion
75% of ties on bridge burn	0.95	Thermal expansion and wire burn through likely
100% of ties on bridge burn	1.00	Thermal expansion assured and wire burn through assured
East end of bridge moves	0.05	Possibility of wire break from small relative motion in lateral or vertical planes
West end of bridge moves	0.05	Possibility of wire break from small relative motion in lateral or vertical planes
Both ends of bridge move	0.05	Possibility of wire break from small relative motion in lateral or vertical planes

Electromechanical Switches

Four snap action switches are mounted on the east and west abutments. They are mechanically connected to girders #1 and #4 at each end of the bridge. Lateral movement in excess of 0.5 inch of the girders relative to the abutment causes the switches to open the electrical circuit and a latching relay in the signal system to cause a restrictive signal. Rigging of the system must permit routine vibration under train passage and thermal expansion. The switches provided a degree of redundancy due to the assumptions of multiple girder movement from hazardous impacts. The detection probability of this simple system was therefore very high. The probability of opening a switch due to denting impact was considered to be small but non-zero.

Table 5.11 Electromechanical Switches

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.05	Leads to false alarm
Two girders move at one end	1.0	One or two switches open at 0.5 inch movement
Four girders move at one end	1.0	One to four switches open at 0.5 inch movement
Four girders move at both ends	1.0	One to four switches open at 0.5 inch movement
One tie burns or partially burns	0.02	Basic assumption for wired systems plus thermal expansion
Two ties burn	0.05	Basic assumption for wired systems plus thermal expansion
Three ties burn	0.1	Basic assumption for wired systems plus thermal expansion
Four ties burn	0.2	Basic assumption for wired systems plus thermal expansion
50% of ties on bridge burn	0.4	Basic assumption for wired systems plus thermal expansion
75% of ties on bridge burn	0.9	Thermal expansion and wire burn through likely
100% of ties on bridge burn	1.00	Thermal expansion assured and wire burn through assured
East end of bridge moves	0.05	Possibility of twisting girders opening one or more switches, little relative motion in lateral or vertical planes
West end of bridge moves	0.05	Possibility of twisting girders opening one or more switches , little relative motion in lateral or vertical planes
Both ends of bridge move	0.05	Possibility of twisting girders opening one or more switches, little relative motion in lateral or vertical planes

Acoustic Emission

Four sensors for detection of acoustic emission are bonded to the inner surface of the four main girders. Signals are sent via electrical cables to a processor for analysis. If software recognizes the acoustic signature of a crack above an established threshold, an alarm is sent. The processor must also recognize and ignore the range of sounds associated with train passage. The acoustic emission system senses the formation and growth of cracks. It would therefore alarm if crack growth exceeded predetermined limits. Its detection efficiency then depends on whether or not cracks would occur during the detailed effects on the bridge.

Table 5.12 Acoustic Emission System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.3	Leads to false alarm. System might detect cracking in flange and alarm.
Two girders move at one end	0.9	System would alarm if movement led to cracking.
Four girders move at one end	0.9	System would alarm if movement led to cracking.
Four girders move at both ends	0.9	System would alarm if movement led to cracking.
One tie burns or partially burns	0.01	Basic assumption for wired systems plus thermal expansion.
Two ties burn	0.02	Basic assumption for wired systems.
Three ties burn	0.05	Basic assumption for wired systems.
Four ties burn	0.15	Basic assumption for wired systems.
50% of ties on bridge burn	0.25	Basic assumption for wired systems plus possibility of thermal cracking.
75% of ties on bridge burn	0.75	Wire burn through likely plus possibility of thermal cracking.
100% of ties on bridge burn	1.00	Wire burn through assured plus possibility of thermal cracking.
East end of bridge moves	0.3	System would alarm if movement led to cracking.
West end of bridge moves	0.3	System would alarm if movement led to cracking.
Both ends of bridge move	0.3	System would alarm if movement led to cracking.

Laser Displacement

Laser reflectors are mounted on the center of the bridge on both the outer main girders. Laser transmitter/receivers are mounted on concrete pads offset to the north and south of the bridge and beam laser energy toward the reflectors. A processor in each receiver computes the distance from the laser source to each reflector and an alarm condition is set if that distance changes by a pre-established amount. The system's sensitivity is reduced by heavy rain, fog, or snow. A sustained interruption of the laser beam by animals, birds, insects, etc., can cause a false alarm. The processor must recognize and ignore bridge motion during train passage.

Table 5.13 Laser Displacement System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.3	Leads to false alarm. System might detect bend at center of girder and alarm.
Two girders move at one end	0.95	End movement of one outer girder most likely detectable, however the displacement of the center of the girder is being measured so the detection is not 100%.
Four girders move at one end	0.95	End movement of one outer girder most likely detectable, however the displacement of the center of the girder is being measured so the detection is not 100%.
Four girders move at both ends	0.95	End movement of one outer girder most likely detectable, however the displacement of the center of the girder is being measured so the detection is not 100%.
One tie burns or partially burns	0.0	Single tie would not affect lower girder flange area.
Two ties burn	0.01	Slight possibility of lower flange movement.
Three ties burn	0.02	Slight possibility of lower flange movement.
Four ties burn	0.05	Possibility of lower flange movement.
50% of ties on bridge burn	0.25	Possible flange movement or smoke interruption of beam.
75% of ties on bridge burn	0.75	Possible flange movement or smoke interruption of beam.
100% of ties on bridge burn	1.00	Flange movement and/or smoke interruption assured.
East end of bridge moves	0.95	Change in angle of girder detected at midpoint.
West end of bridge moves	0.95	Change in angle of girder detected at midpoint.
Both ends of bridge move	0.95	Change in angle of girder detected at midpoint.

Laser Alignment Mid Span Detector

Lasers are mounted on each side of the east abutment and beam laser energy down the length of the outer girders just above the bottom flange. A target with a photo diode detector is mounted in the center of each outer girder. Vertical or lateral movement of the laser image point on the detector is sensed and a processor sets an alarm state if a pre-established value is exceeded. The system's sensitivity is reduced by heavy rain, fog, or snow. A sustained interruption of the laser beam by animals, birds, insects, etc., can cause a false alarm. The processor must recognize and ignore bridge motion during train passage. The laser alignment system must have built in a tolerance to account for thermal effects and vibration during train passage.

Table 5.14 Laser Alignment Mid-span Detector System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.2	Leads to false alarm. System might detect bend at center of girder and alarm.
Two girders move at one end	0.95	End movement of one outer girder most likely detectable, however the alignment at the center of the girder is being measured so the detection is not 100%.
Four girders move at one end	0.95	End movement of one outer girder most likely detectable, however the alignment at the center of the girder is being measured so the detection is not 100%.
Four girders move at both ends	1.00	End movement of one outer girder most likely detectable, however the alignment at the center of the girder is being measured so the detection is not 100%, however system has redundancy one of two main girder movement will be detected.
One tie burns or partially burns	0.02	Single tie would not affect lower girder flange area.
Two ties burn	0.05	Slight possibility of lower flange movement.
Three ties burn	0.1	Slight possibility of lower flange movement.
Four ties burn	0.2	Possibility of lower flange movement.
50% of ties on bridge burn	0.65	Possible flange movement or smoke interruption of beam. or wire burn-through.
75% of ties on bridge burn	0.95	Possible flange movement or smoke interruption of beam or wire burn through.
100% of ties on bridge burn	0.95	Flange movement and/or smoke interruption detected.
East end of bridge moves	0.95	Change in angle of girder detected at midpoint.
West end of bridge moves	0.95	Change in angle of girder detected at midpoint.
Both ends of bridge move	0.95	Change in angle of girder detected at midpoint.

Laser Alignment Occulting Targets

Lasers are mounted on each side of the east abutment and beam laser energy down the length of the outer girders just above the bottom flange. A photo diode detector is mounted on the opposite abutment. A series of targets are mounted at intervals along the bottom flanges of the outer girders. Each target has a small hole or slot. Movement of the bridge girders beyond normal limits established by the hole and slot dimensions cause one or more of the targets to interrupt the laser beam. Movement of the two abutments relative to each other, vertical or lateral movement of the outer girders relative to either abutment, or bending or twist of the girders may be sensed. A processor sets an alarm state if the laser beam does not reach the detector. The system's sensitivity is reduced by heavy rain, fog, or snow. A sustained interruption of the laser beam by animals, birds, insects, etc., can cause a false alarm. The targets must be designed to allow normal bridge motion during train passage without occulting the laser beam.

Table 5.15 Laser Alignment Occulting Targets System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.2	Leads to false alarm. System might detect bend at center of girder and alarm.
Two girders move at one end	0.95	End movement of one outer girder most likely detectable.
Four girders move at one end	0.95	End movement of one outer girder most likely detectable.
Four girders move at both ends	1.00	End movement of one outer girder most likely detectable, system has redundancy one of two main girder movements will be detected.
One tie burns or partially burns	0.0	Single tie would not affect lower girder flange area.
Two ties burn	0.01	Slight possibility of lower flange movement.
Three ties burn	0.02	Slight possibility of lower flange movement.
Four ties burn	0.05	Possibility of lower flange movement or smoke interrupting laser beam.
50% of ties on bridge burn	0.25	Possible flange movement or smoke interruption of beam.
75% of ties on bridge burn	0.75	Possible flange movement or smoke interruption of beam.
100% of ties on bridge burn	1.00	Flange movement and/or smoke interruption assured.
East end of bridge moves	0.95	Change in angle of girder likely to be detected.
West end of bridge moves	0.95	Change in angle of girder likely to be detected.
Both ends of bridge move	0.95	Change in angle of girder likely to be detected.

Stereo Video

Two video cameras operating in either the visible or infrared spectrum are mounted in a raised enclosure offset from the end of the bridge viewing the bridge. The images produced by the cameras are processed and compared to previously stored images to determine if the bridge has moved or changed. The processor would have to account for the different appearance of the bridge during train passage and not cause alarms due to trains sitting on or moving across the bridge. An alarm state would occur if the bridge moved laterally or vertically beyond preset limits or if obstructions were found on the bridge itself. This system's sensitivity would be decreased by rain, snow, and fog. Animals or people crossing the bridge might also trigger the alarm unless the system's alarm threshold was lowered. The stereo video system is a noncontact system that senses changes in the bridge structure by comparing images of the bridge to that of an undisturbed bridge. It must be desensitized enough to not alarm during train passage.

Table 5.16 Stereo Video System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.3	Leads to false alarm. System might detect bend at center of girder or detect vehicle in contact with bridge and alarm.
Two girders move at one end	1.00	End movement of one outer girder detected plus may alarm on vehicle contact.
Four girders move at one end	0.95	End movement of both outer girders detected plus may alarm on vehicle contact.
Four girders move at both ends	0.95	End movement of both outer girders detected plus may alarm on vehicle contact.
One tie burns or partially burns	0.2	System may sense smoke or flame.
Two ties burn	0.3	System may sense smoke or flame.
Three ties burn	0.4	Slight possibility of lower flange movement or have smoke interruption of laser beam.
Four ties burn	0.65	Possibility of lower flange movement, or system may sense smoke or flame.
50% of ties on bridge burn	0.80	Possible flange movement or twist , or system may sense smoke or flame.
75% of ties on bridge burn	0.95	Possible flange movement or twist , or system may sense smoke or flame.
100% of ties on bridge burn	0.95	Possible flange movement or twist , or system may sense smoke or flame.
East end of bridge moves	0.95	Change in position of girder most likely detected.
West end of bridge moves	0.95	Change in position of girder most likely detected.
Both ends of bridge move	0.95	Change in position of girder most likely detected.

Fiber Optic Displacement Sensor

A fiber optic cable is attached to the east abutment and routed across girder #1. The cable is attached to the girder at intervals. At the west abutment, the cable is attached to the abutment and routed under the track to girder #4. The cable is attached to girder #4 at intervals and attached to the east abutment. A light signal is pulsed down the cable and the reflected and transmitted signals are processed to determine if there is any change from the previous pulse. Movement of the structure sufficient to damage or bend the cable will change the characteristics of the returning signals. Alarms can be set to predetermined levels of movement. The processor must recognize and ignore signal changes from normal bridge movement under trains and from expansion and contraction of the bridge structure due to temperature effects.

Table 5.17 Fiber Optic Displacement System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.2	Leads to false alarm. System might detect bend at center of girder.
Two girders move at one end	1.00	End movement of one outer girder detected.
Four girders move at one end	1.00	End movement of both outer girders detected.
Four girders move at both ends	1.00	End movement of both outer girders detected.
One tie burns or partially burns	0.02	Single tie would probably not affect lower girder flange area.
Two ties burn	0.05	Slight possibility of lower flange movement or thermal effects on fiberoptic cable.
Three ties burn	0.1	Slight possibility of lower flange movement or thermal effects on fiberoptic cable.
Four ties burn	0.2	Possibility of lower flange movement and thermal effects on fiberoptic cable.
50% of ties on bridge burn	0.4	Possibility of lower flange movement and thermal effects on fiberoptic cable.
75% of ties on bridge burn	0.9	Flange movement or twist and fiberoptic cable damage likely.
100% of ties on bridge burn	1.00	Flange movement or twist and fiberoptic cable damage likely.
East end of bridge moves	0.80	Change in position of girder most likely detected.
West end of bridge moves	0.80	Change in position of girder most likely detected.
Both ends of bridge move	0.80	Change in position of girder most likely detected.

Piezo-electric Movement Sensor

A cable or rod of piezo-electric material is attached to the east abutment and routed across girder #1. The cable or rod is attached to the girder at intervals. At the west abutment, the cable or rod is attached to the abutment and routed under the track to girder #4. The cable or rod is attached to girder #4 at intervals and attached to the east abutment. Any movement of the piezo-electric material causes a signal to be generated while the motion is taking place. A processor monitors the output of the material and sets an alarm if a predetermined level is exceeded. The processor must recognize and ignore signal changes from normal bridge movement under trains and from expansion and contraction of the bridge structure due to temperature effects.

Table 5.18 Piezo-electric Movement System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.3	Leads to false alarm. System might detect movement at center of girder.
Two girders move at one end	1.00	End movement of one outer girder detected.
Four girders move at one end	1.00	End movement of both outer girders detected.
Four girders move at both ends	1.00	End movement of both outer girders detected.
One tie burns or partially burns	0.02	Single tie probably would not affect lower girder flange area.
Two ties burn	0.05	Slight possibility of lower flange movement.
Three ties burn	0.1	Slight possibility of lower flange movement or thermal effects on piezo-electric material.
Four ties burn	0.2	Possibility of lower flange movement or thermal effects on piezo-electric material.
50% of ties on bridge burn	0.4	Possible flange movement or twist and thermal damage to piezo-electric material.
75% of ties on bridge burn	0.9	Possible flange movement or twist and thermal damage to piezo-electric material.
100% of ties on bridge burn	1.00	Possible flange movement or twist and thermal damage to piezo-electric material.
East end of bridge moves	0.8	Change in position of girder most likely detected if movement is rapid enough.
West end of bridge moves	0.8	Change in position of girder most likely detected if movement is rapid enough.
Both ends of bridge move	0.8	Change in position of girder most likely detected if movement is rapid enough.

Strain Gages

A total of eight strain gages are placed on the main girders. A processor monitors the output of the strain gages and compares it to predetermined stress limits. Detection of impacts would also be possible by determining strain rate. An alarm level is set at predetermined limits which account for thermal stresses and the passage of trains.

Table 5.19 Strain Gage System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.3	Leads to false alarm. System might detect bend at center of girder or detect vehicle in contact with bridge and alarm.
Two girders move at one end	.8	End movement of one outer girder detected if stress occurs at a gage location.
Four girders move at one end	.8	End movement of both outer girders detected if stress occurs at a gage location.
Four girders move at both ends	.8	End movement of both outer girders detected if stress occurs at a gage location.
One tie burns or partially burns	0.02	Single tie probably would not affect lower girder flange area.
Two ties burn	0.05	Slight possibility of lower flange movement.
Three ties burn	0.1	Slight possibility of lower flange movement or thermal stresses.
Four ties burn	0.2	Possibility of lower flange movement and thermal stresses.
50% of ties on bridge burn	0.4	Possibility of lower flange movement, thermal stresses and wire burn-through.
75% of ties on bridge burn	0.9	Possibility of lower flange movement, thermal stresses and wire burn-through.
100% of ties on bridge burn	1.00	Possibility of lower flange movement, thermal stresses and wire burn-through.
East end of bridge moves	0.8	Change in position of girder most likely detected if stresses occur near sensor.
West end of bridge moves	0.8	Change in position of girder most likely detected if stresses occur near sensor.
Both ends of bridge move	0.8	Change in position of girder most likely detected if stresses occur near sensor.

Self-Contained Impact

Two impact sensors (mercury switches) are mounted on the bottom flanges of girders #1 and #4 at the 1/3 span points. The impact sensors are contained in sealed containers. If impact to these girders exceeds a preset value the sensor activates a small radio transmitter and deploys an antenna. A nearby receiver detects the signal and opens a relay in the railroad signal system. No wiring on the bridge is required. This technology is currently used to detect overheated journal roller bearings on railroad cars. An adaptation from a thermal to an impact sensor is postulated.

Table 5.20 Self Contained Impact System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.2	Leads to false alarm
Two girders move at one end	1.00	Exceeds G limit
Four girders move at one end.	1.00	Exceeds G limit
Four girders move at both ends	1.00	Well exceeds G limit
One tie burns or partially burns	0.	No impact, no wires to burn through
Two ties burn	0.	No impact, no wires to burn through
Three ties burn	0	No impact, no wires to burn through
Four ties burn	0.05	No impact slight possibility of thermal effect
50% of ties on bridge burn	0.1	Slight possibility of shock from thermal expansion
75% of ties on bridge burn	0.2	Slight possibility of shock from thermal expansion
100% of ties on bridge burn	0.4	Possibility of shock from thermal expansion
East end of bridge moves	0.01	Subsidence not likely to cause shock
West end of bridge moves	0.01	Subsidence not likely to cause shock
Both ends of bridge move	0.01	Subsidence not likely to cause shock

Pyrotechnic Displacement

Displacement (firing pin) sensors are connected to a sodium azide supply in a sealed container, similar to the “air bags” used to protect occupants in automobiles. Movement of the structure activates the system causing the sodium azide to ignite and provide a high-energy supply of hot gas. This energy is used to transmit a signal to a nearby receiver which then opens a relay in the railroad signal system. Four displacement sensors are deployed to monitor movement of both ends of girders #1 and #4. No wiring on the bridge is required.

Table 5.21 Pyrotechnic Displacement

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.3	Leads to false alarm.
Two girders move at one end	1.00	One or two switches open at 0.5 inch movement.
Four girders move at one end	0.95	One to four switches open at 0.5 inch movement.
Four girders move at both ends	0.95	One to four switches open at 0.5 inch movement.
One tie burns or partially burns	0	No movement at girder ends, no wires to burn through.
Two ties burn	0	No movement at girder ends, no wires to burn through.
Three ties burn	0	No movement at girder ends, no wires to burn through.
Four ties burn	0.1	Slight possibility of thermal expansion.
50% of ties on bridge burn	0.2	Slight possibility of thermal expansion.
75% of ties on bridge burn	0.3	Thermal expansion likely.
100% of ties on bridge burn	0.4	Thermal expansion likely.
East end of bridge moves	0.05	Possibility of twisting girders opening one or more switches, little relative motion in lateral or vertical planes.
West end of bridge moves	0.05	Possibility of twisting girders opening one or more switches , little relative motion in lateral or vertical planes.
Both ends of bridge move	0.05	Possibility of twisting girders opening one or more switches, little relative motion in lateral or vertical planes.

Pyrotechnic Impact

Impact sensors are connected to a sodium azide supply in a sealed container, similar to the "air bags" used to protect occupants in automobiles. Acceleration of the structure beyond limits activates the system causing the sodium azide to ignite and provide a high-energy supply of hot gas. This energy is used to transmit a signal to a nearby receiver which then opens a relay in the railroad signal system. Two impact sensors are placed at the 1/3 span points on the bottom outer flange of girders #1 and #4. No wiring on the bridge is required.

Table 5.22 Pyrotechnic Impact System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.2	Leads to false alarm.
Two girders move at one end	1.00	Exceeds G limit.
Four girders move at one end	1.00	Exceeds G limit.
Four girders move at both ends	1.00	Well exceeds G limit.
One tie burns or partially burns	0	No impact. No wire burn-through.
Two ties burn	0	No impact. No wire burn-through.
Three ties burn	0	No impact. No wire burn-through.
Four ties burn	0.1	Slight possibility of impact from sudden thermal expansion.
50% of ties on bridge burn	0.2	Slight possibility of impact from sudden thermal expansion.
75% of ties on bridge burn	0.3	Possibility of impact from sudden thermal expansion.
100% of ties on bridge burn	0.4	Possibility of impact from sudden thermal expansion.
East end of bridge moves	0.01	Subsidence not likely to cause shock.
West end of bridge moves	0.01	Subsidence not likely to cause shock.
Both ends of bridge move	0.01	Subsidence not likely to cause shock.

Mechanical Displacement

A standard railroad switch circuit controller is mounted on each abutment. A switch circuit controller is basically a rugged form of leaf switch enclosed in a weather resistant case. The west controller is mechanically connected to outer main girder #1 and the east controller is mechanically connected to outer main girder #4. Lateral movement of the girders relative to the abutment causes the switch circuit controller to open the electrical circuit and a relay in the signal system to display a restrictive signal. Rigging of the system must allow normal vibration under train passage and thermal expansion.

Table 5.23 Mechanical Displacement System

Detailed Effect	Detection Probability	Comments
Flange of Girder Bends	0.3	Leads to false alarm
Two girders move at one end	1.00	One or two circuit controllers open at 0.5 inch movement
Four girders move at one end	0.95	One to four circuit controllers open at 0.5 inch movement
Four girders move at both ends	0.95	One to four circuit controllers open at 0.5 inch movement
One tie burns or partially burns	0.02	Basic assumption for wired systems
Two ties burn	0.05	Basic assumption for wired systems
Three ties burn	0.1	Basic assumption for wired systems
Four ties burn	0.2	Basic assumption for wired systems
50% of ties on bridge burn	0.4	Basic assumption for wired systems
75% of ties on bridge burn	0.9	Basic assumption for wired systems
100% of ties on bridge burn	1.00	Basic assumption for wired systems
East end of bridge moves	0.05	Possibility of twisting girders opening one or more circuit controllers, little relative motion in lateral or vertical planes
West end of bridge moves	0.05	Possibility of twisting girders opening one or more circuit controllers , little relative motion in lateral or vertical planes
Both ends of bridge move	0.05	Possibility of twisting girders opening one or more circuit controllers, little relative motion in lateral or vertical planes

Track Circuit

The standard railroad track signal circuit will cause a restrictive signal indication any time either rail continuity is broken or if an electrical short circuit exists between the two rails. The track circuit only will cause a restrictive signal to be displayed if the two rails are either shorted together or if either rail is broken to form an open circuit. The only conditions assumed likely to cause either of these conditions on this bridge other than total collapse were during the deck fire. None of the other specific effects were given a non-zero detection probability.

Table 5.24 Track Circuit System

Detailed Effect	Detection Probability	Comments
50% of ties on bridge burn	0.1	Slight probability of short to rails from deck damage.
75% of ties on bridge burn	0.2	Slight probability of short to rails from deck damage or open circuit on one rail.
100% of ties on bridge burn	0.3	Possibility of short to rails from deck damage or open circuit on one or both rails.

5.2.3 Performance Comparison

The candidate integrity monitor systems were compared on the basis of actual alarms (mission success), number of missed alarms (mission failure), and number of false alarms (system reliability). The expected number of bridge failures or train accidents in the 25-year life cycle period was 1.909, resulting from the extremely adverse distribution of initial causes assumed for the purposes of this analysis. Fractions of a failure were retained solely for the purposes of comparing the different systems over the short 25-year period. Therefore, integrity monitor systems operating in this scenario with fewer than two alarms indicated a tendency to miss hazardous conditions, while systems with greater than two alarms indicated a tendency toward false alarms whether from the technology or from internal failures. Figures 5.2-5.3 compare the alarm performance of the systems.

All systems except the track circuit generated alarms in the 25-year period. The laser displacement, laser alignment, laser occulting, stereo video, and piezo-electric movement systems generated more alarms than the other technologies. The brittle bar, frangible wire, spring switch movement, and mechanical displacement systems performed similarly with slightly more alarms than the actual number of potential accidents. Sensors using displacement did not perform as well as impact sensors on this bridge.

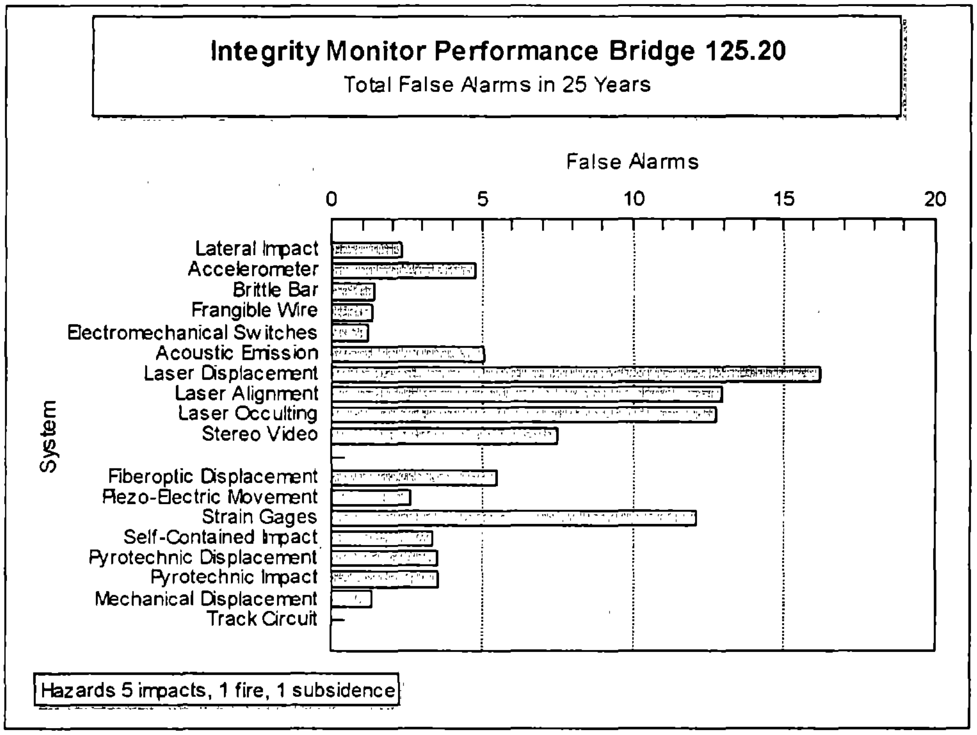


Figure 5.2 False Alarm Performance Bridge 125.20

The non-contact laser and video systems, the fiber optic movement, and the strain gage sensor systems created over five false alarms in the 25-year period. Displacement sensor systems had fewer false alarms than impact sensor systems. The track circuit had no false alarms.

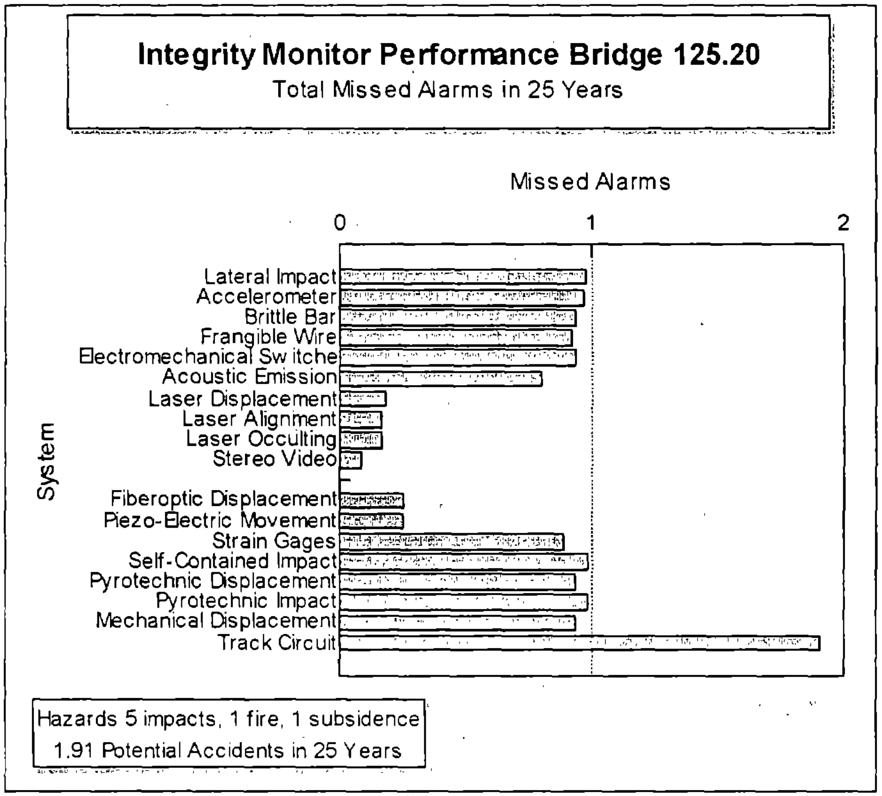


Figure 5.3 Missed Alarm Performance Bridge 125.20

The track circuit missed all alarms during the 25-year period. The impact sensors missed one alarm on the average. The non-contact laser and video sensors, along with the fiber-optic displacement and the piezo-electric movement sensors missed less than one alarm. The remaining sensor systems missed approximately one hazardous condition in the 25-year period.

5.2.4 Cost Comparison

The technologies were compared on the basis of installation cost and life cycle cost. Installation costs included $10,000 electrical and $25,000 signal system interface costs for each system. Figures 5.4-5.5 summarize the cost data for the 40-foot girder bridge.

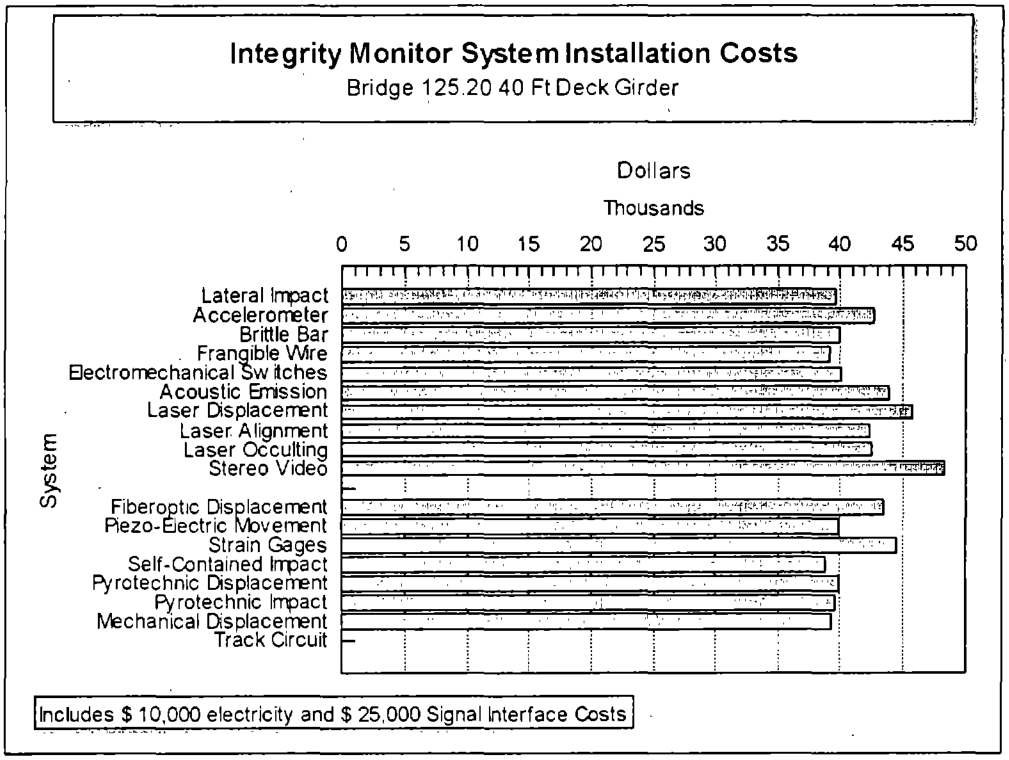


Figure 5.4 Installation Costs Bridge 125.20 (1994 Dollars)

The majority of the systems cost approximately $40,000 to install on this simple bridge. The high technology systems, and those with a large number of individual sensors cost more to install than the simple systems.

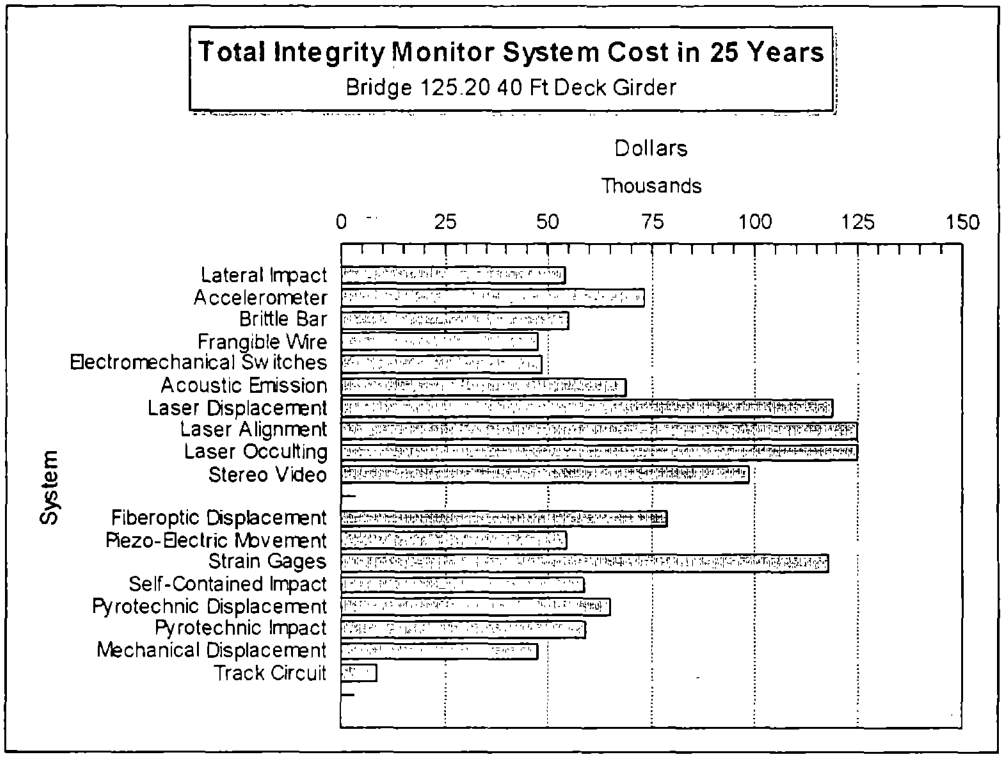


Figure 5.5 Total Costs During 25-Year Period Bridge 125.20 (1994 Dollars)

The influence of false alarms is evident in the total life cycle cost data. The non-contact systems with high false alarm rates had much higher life cycle costs than the simple systems. The simpler systems cost $50,000-$55,000 to install and operate over the 25-year time period. All costs were adjusted to 1994 dollars using the procedure explained in Section 4.6. See Section 6.0 for a summary of costs for all three hypothetical bridges.

5.3 Bridge 5.07 Three 240-Foot Deck Trusses with 300-Foot Through Truss Turn Span

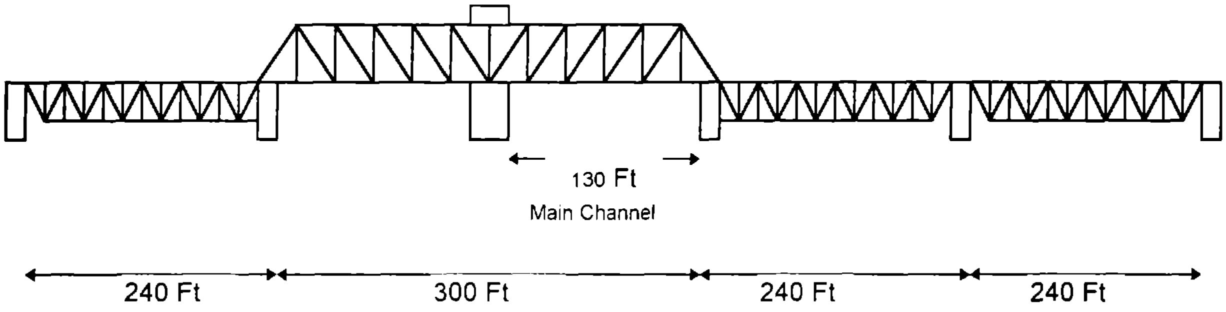


Figure 5.6 Bridge 5.07 Multi-span Truss Bridge

This bridge spans a navigable waterway with both barge and ocean-going ship traffic. The bridge consists of four total spans, three fixed and one turn span. The fixed spans are 240-foot pin-connected Warren deck trusses. The turn span is a 300-foot pin-connected Pratt truss. The deck trusses have 6-feet of clearance and the turn span when closed has 40-feet of clearance above the normal river level. The bridge is normally opened only for ocean-going vessels which transit the bridge infrequently, once or twice per year. The bridge is not required to be opened for barge traffic and towing vessels, and is unmanned unless a large ship is expected. Fender systems are in place to protect the turn span in the open position and the piers on either side of the turn span. The piers of the other spans are not protected by fenders. An ocean-going vessel would ground before hitting one of the approach spans from either upstream or downstream. Barges could, however, reach the approach spans without grounding. The railroad is a single track line operating with both freight and passenger service. Automatic block signals are in place on the track with signal circuits carried by cable. The moveable span is protected by home signals at either end of the bridge that are interlocked with the turn span locks.

Because of the infrequent operation of the turn span, the rails at the ends of the turn span are joined with common six-hole joint bars that are removed by track maintenance personnel when the bridge must be opened. Track circuit current through these joints is carried by track wires connected to each rail at the joint, and through a connector that engages after placement of the bridge locks.

5.3.1 Initiating Causes

The main hazards to the bridge are impact from barges and ships. Fire on the bridge decks from hot brake shoes or rail grinding is possible. The following distribution of initiating causes appropriate for bridge 5.07 was chosen:

Table 5.25 Initiating Causes for Bridge 5.07 Multi-Span Truss

Initiating Cause	Comments	No. in 25 Years*
Impact	Considered to be the most likely threat to this bridge. Possibility of occurrence of significant impacts from ocean going vessels and barges. A ship impact could occur on the closed turn span due to improper coordination with railroad bridge operator or due to mechanical problems on approaching ship. Barges could impact piers or lower chords of approach spans.	1 ship 1 barge every 10 years
Fire	Considered at low frequency of occurrence 1 fire per 25 years	1

* Note: Likelihood of events is exaggerated for study purposes

The detailed effects on bridge 5.07 from the above initiating causes are summarized in the tables below:

Table 5.26 Detailed Effects on Bridge 5.07 From Collision with Oceangoing Vessel

DETAILED EFFECTS	No of Occurrences per 100 Impacts	Number of Detailed Effect in 25 Years	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
LOWER CHORD OF TURN SPAN STRUCK, ONE SIDE SHORTENED STILL ON BEARINGS	5	0.05	0.7	0.035
ONE END OF TURN SPAN MOVED LATERALLY ON BEARINGS	60	0.6	0.9	0.54
BOTH ENDS OF TURN SPAN MOVED LATERALLY ON BEARINGS	30	0.3	1	0.3
PIER STRUCK AND TILTED OR DAMAGED	4	0.04	0.9	0.036
CHORD DEFLECTED ONE SIDE SHORTENED OFF BEARINGS TURN SPAN TRUSS TILTS OFF PIERS	1	0.01	1	0.01

Table 5.27 Detailed Effects on Bridge 5.07 From Collision with Single Loose Barge

DETAILED EFFECTS	No of Occurrences per 100 Impacts	Number of Detailed Effect in 25 Years	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
LOWER CHORD ON DECK TRUSS STRUCK ONE SIDE SHORTENED STILL ON BEARINGS	60	0.6	0.7	0.42
ONE END OF SPAN MOVED LATERALLY ON BEARINGS	30	0.3	0.9	0.27
BOTH ENDS OF SPAN MOVED LATERALLY ON BEARINGS	6	0.06	1	0.06
PIER STRUCK AND TILTED OR DAMAGED	4	0.04	0.9	0.036
CHORD DEFLECTED ONE SIDE SHORTENED OFF BEARINGS TRUSS TILTS OFF PIERS	0	0	1	0

Table 5.28 Detailed Effects on Bridge 5.07 From Fire on Bridge Deck

DETAILED EFFECTS	No of Occurrences per 100 Fires	Number of Detailed Effect in 25 Years	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
<= 1 TIE BURNS	70	0.7	0	0
2 TIES BURN	20	0.2	0.1	0.02
3 TIES BURN	5	0.05	0.7	0.035
4 TIES BURN	3	0.03	0.9	0.027
25% OF TIES BURN	0.5	0.005	1	0.005
50% OF TIES BURN	0.5	0.005	1	0.005
100% OF TIES BURN	0	0	1	0

5.3.2 Integrity Monitoring Systems and Detection Probabilities Bridge 5.07

This long truss bridge was considered to be less laterally stiff than the deck girder bridge. The large amounts of energy to be dissipated from the massive marine vessels lead to much larger reactions in the bridge structure that are more easily distinguished from train passage by the sensor systems. The detection of deck fires was assumed to be identical to that on bridge 125.20 for each system.

Lateral Impact Sensors

Four sensors were placed the lower chords of each 240-ft span. Six sensors were placed on the lower chords of the 300-ft turn span. The total number of sensors for the bridge was 18. Any impact against the girders from marine traffic above a specified magnitude will cause the switches to lose electrical continuity momentarily and cause a latching relay to cause a restrictive aspect on the local railroad signal system. The system is electrical and requires a latching relay but no logic circuits or processor. The sensor output is transient unless impact results in enough tilting of the girder to keep the switch open. The lateral impact G switch sensor was assumed to be set at a magnitude of acceleration above that normally found during train passage. Due to its simplicity, this sensor was considered to always trip if accelerations at its mounting location exceeded the limit. Fire detection capability was considered as the probability that a connecting wire would burn in two at some point on the bridge during the fire. This probability was assumed to increase with the number of ties involved in a deck fire.

Table 5.29 Lateral Impact Sensors

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.99	Exceeds G limit
One end of span moved laterally on bearings	0.99	Exceeds G limit
Both ends of span moved laterally on bearings	1.00	Exceeds G limit may break wires
Pier struck and tilted or damaged	1.00	Exceeds G limit may break wires
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Exceeds G limit, wires broken, system destroyed.
Fire Detection		Basic assumption for wired systems

Accelerometers

Four sensors were placed on the lower chords of each 240-ft span. Six sensors were placed on the lower chords of the 300-ft turn span. The total number of sensors for the bridge was 18. Accelerometers oriented with their sensitive axis along the direction of marine travel are attached to the inner bottom surface of the bottom flange of the lower chord girders. Impact against the girder will cause a large acceleration in that member which will be sensed by the accelerometer. Depending on the magnitude of the impact, each accelerometer may also sense impacts on the opposite side of the bridge. The output of each accelerometer is monitored continuously and a processor decides if alarm thresholds are exceeded. The system must not alarm during normal train passage. The sensors are also able to detect major twisting or distortion in the outer main girders. The accelerometer system was assumed to operate with the same detection probability as the impact sensors. The added complexity of the computer system needed to analyze the accelerometer signals was accounted for in the failure rate calculations for false alarms. No degradation in detection probability was assumed due to software since the simple software needed to declare alarms was IF-THEN type logic. Due to the simplicity of the sensor and software, this system was considered to always trip if accelerations at its mounting location exceeded the limit.

Table 5.30 Accelerometer System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.99	Exceeds G limit
One end of span moved laterally on bearings	0.99	Exceeds G limit
Both ends of span moved laterally on bearings	1.00	Exceeds G limit may break wires
Pier struck and tilted or damaged	1.00	Exceeds G limit may break wires
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Exceeds G limit, wires broken, system destroyed.
Fire Detection		Basic assumption for wired systems

Brittle Bar Sensors

Brittle bars were placed on each pier and connected to each lower chord girder. A total of 16 bars were used. Excessive movement of the girders relative to the abutments will cause the bar at that end to fracture and open an electrical circuit that controls a relay in the track signal system. Rigging of the system must permit normal vibration under train passage and thermal expansion of the bridge and the sensor components without fracturing the brittle bars. The brittle bars provided a degree of redundancy due to their location on either end of the chord girders. The detection probability of this simple system was therefore very high.

Table 5.31 Brittle Bar Sensors

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	1.00	Movement at bearings breaks one bar.
One end of span moved laterally on bearings	1.00	Movement at bearings breaks one or more bars.
Both ends of span moved laterally on bearings	1.00	Movement at bearings breaks one or more bars.
Pier struck and tilted or damaged	1.00	Movement at bearings breaks one or more bars.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Movement at bearings breaks all four bars on span.
One tie burns or partially burns	0.02	Possible thermal expansion breaks one bar.
Two ties burn	0.05	Possible thermal expansion breaks one bar.
Three ties burn	0.10	One bar broken by thermal expansion of span.
Four ties burn	0.20	One bar broken by thermal expansion of span.
50% of ties on bridge burn	0.80	One or more bars broken by thermal expansion.
75% of ties on bridge burn	0.90	One or more bars broken by thermal expansion.
100% of ties on bridge burn	1.00	Thermal expansion breaks bars.

Frangible Wire

Three frangible wire loops were used, one on the turn span, and one on each of the two fixed portions of the bridge. The fixed-span loops were attached to the lower chords and also to the piers. The moveable span loop ran along the lower chords and the end floor beams. Each of the wire loops was connected to a power supply and latching relay. If there is any excessive relative movement between the bridge girders and the abutments, or between the bottom flanges of the outer girders, the wire will part and the relay in the signal system will cause a restrictive signal. Rigging of the system permits normal vibration under train passage and thermal expansion. The frangible wire provided a degree of redundancy due to the assumptions of multiple girder movement from hazardous impacts and the possibility of more than one break in the wire loop. The detection probability of this simple system was therefore very high.

Table 5.32 Frangible Wire System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	1.00	Wire broken from impact or bridge movement.
One end of span moved laterally on bearings	1.00	Wire broken from impact or bridge movement.
Both ends of span moved laterally on bearings	1.00	Wire broken from impact or bridge movement.
Pier struck and tilted or damaged	1.00	Wire broken from impact or bridge movement.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Wire broken from impact or bridge movement.
One tie burns or partially burns	0.02	Possible wire burn through.
Two ties burn	0.05	Possible wire burn through.
Three ties burn	0.10	Possible wire burn through.
Four ties burn	0.40	Possible wire burn through.
50% of ties on bridge burn	0.80	Wire burn through likely or thermal expansion of span breaks wire.
75% of ties on bridge burn	0.95	Wire burn through likely or thermal expansion of span breaks wire.
100% of ties on bridge burn	1.00	Wire burn through assured.

Electromechanical Switches

Displacement switches were placed on each pier and connected to each lower chord girder. A total of 16 switches were used. Relative lateral movement of the girders relative to the abutment causes the switch to open the electrical circuit and a latching relay in the signal system to cause a restrictive signal. Rigging of the system must permit routine vibration under train passage and thermal expansion. The switches provided a degree of redundancy due to the assumptions of multiple girder movement from hazardous impacts. The detection probability of this simple system was therefore very high.

Table 5.33 Electromechanical Switch System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	1.00	Switch activated from impact or bridge movement.
One end of span moved laterally on bearings	1.00	Switch activated from impact or bridge movement.
Both ends of span moved laterally on bearings	1.00	Switch activated from impact or bridge movement.
Pier struck and tilted or damaged	1.00	Switch activated from impact or bridge movement.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Switch activated from impact or bridge movement. Wires destroyed.
Fire Detection		Basic assumption for wired systems

Acoustic Emission

Four sensors were placed on each 240-ft span. Six sensors were placed on the 300-ft turn span. A total of 18 sensors were used. Signals are sent via electrical cables to a processor for analysis. If software recognizes the acoustic signature of a crack above an established threshold, an alarm is sent. The processor must also recognize and ignore the range of sounds associated with train passage. The acoustic emission system senses the formation and growth of cracks. It would therefore alarm if crack growth exceeded predetermined limits. Its detection efficiency then depends on whether or not cracks would occur during the detailed effects on the bridge. The energy of the impacts from marine traffic were assumed to cause cracking in one or more of the bridge members.

Table 5.34 Acoustic Emission

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.80	Detected by impact sound in structure or if crack location is near sensor.
One end of span moved laterally on bearings	0.90	Detected by impact sound in structure or if crack location is near sensor.
Both ends of span moved laterally on bearings	0.95	Detected by impact sound in structure or if crack location is near sensor.
Pier struck and tilted or damaged	1.00	Detected by impact sound in structure or if crack location is near sensor, wires may be broken.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Detected by impact sound in structure or if crack location is near sensor, wires broken, system destroyed.
One tie burns or partially burns	0.01	Basic assumption for wired systems.
Two ties burn	0.02	Basic assumption for wired systems.
Three ties burn	0.05	Basic assumption for wired systems.
Four ties burn	0.15	Basic assumption for wired systems plus detection of thermal cracking.
50% of ties on bridge burn	0.50	Basic assumption for wired systems plus detection of thermal cracking.
75% of ties on bridge burn	0.80	Wire burn through likely.
100% of ties on bridge burn	1.00	Wire burn through assured.

Laser Displacement

Two systems were used on towers displaced laterally from the bridge. Each system monitored the position of targets on the mid-point of two spans. Laser reflectors are mounted on the center of each of the bridge spans on both lower chord girders. Laser transmitter/receivers are mounted on concrete pads offset from the bridge and beam laser energy toward the reflectors. A processor in each receiver computes the distance from the laser source to each reflector and an alarm condition is set if that distance changes by a pre-established amount. The system's sensitivity is reduced by heavy rain, fog, or snow. A sustained interruption of the laser beam by birds, insects, etc., can cause a false alarm. The processor must recognize and ignore bridge motion during train passage.

Table 5.35 Laser Displacement System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.95	Lower chord motion detected.
One end of span moved laterally on bearings	0.95	Lower chord motion detected.
Both ends of span moved laterally on bearings	0.95	Lower chord motion detected.
Pier struck and tilted or damaged	1.00	Lower chord motion detected.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Lower chord motion detected, target out of laser beam.
One tie burns or partially burns	0.00	Does not affect lower chord.
Two ties burn	0.01	Possibility of smoke interrupting laser beam.
Three ties burn	0.02	Possibility of smoke interrupting laser beam.
Four ties burn	0.05	Possibility of smoke interrupting laser beam.
50% of ties on bridge burn	0.50	Lower chord motion or smoke effects.
75% of ties on bridge burn	0.80	Lower chord motion or smoke effects.
100% of ties on bridge burn	0.95	Lower chord motion or smoke effects.

Laser Alignment Mid Span Detector

Four lasers were used each mounted on a pier and illuminating a target at the mid span of each span. Lasers are mounted on each side of the east abutment and beam laser energy down the length of the lower chord girders just above the bottom flange. A target with a photo diode detector is mounted in the center of each span's lower chord girder. Vertical or lateral movement of the laser image point on the detector is sensed and a processor sets an alarm state if a pre-established value is exceeded. The system's sensitivity is reduced by heavy rain, fog, or snow. A sustained interruption of the laser beam by animals, birds, insects, etc., can cause a false alarm. The laser alignment system must have built in a tolerance to account for thermal effects and vibration during train passage.

Table 5.36 Laser Alignment Mid-span Detector System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.95	Lower chord motion detected.
One end of span moved laterally on bearings	0.95	Lower chord motion detected.
Both ends of span moved laterally on bearings	0.95	Lower chord motion detected.
Pier struck and tilted or damaged	1.00	Lower chord motion detected.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Lower chord motion detected, target out of laser beam.
One tie burns or partially burns	0.02	Does not affect lower chord.
Two ties burn	0.05	Possibility of smoke interrupting laser beam.
Three ties burn	0.10	Possibility of smoke interrupting laser beam.
Four ties burn	0.20	Possibility of smoke interrupting laser beam.
50% of ties on bridge burn	0.65	Lower chord motion or smoke effects.
75% of ties on bridge burn	0.95	Lower chord motion or smoke effects.
100% of ties on bridge burn	0.95	Lower chord motion or smoke effects.

Laser Alignment Occulting Targets

Four lasers were used, each mounted on a pier with their beams illuminating a single span. Lasers are mounted on each side of the piers and beam laser energy down the length of the lower chord girders just above the bottom flange. A photo diode detector is mounted on the opposite pier. A series of targets are mounted at intervals along the bottom flanges of the outer girders. Each target has a small hole or slot and the targets are mounted and aligned so that the laser beam passes through the slots in each target from the laser to the photo diode detector. Movement of the bridge girders beyond normal limits established by the hole and slot dimensions cause one or more of the targets to interrupt the laser beam. Movement of the two piers relative to each other, vertical or lateral movement of the outer girders relative to either pier, or bending or twist of the girders may be sensed. A processor sets an alarm state if the laser beam does not reach the detector. The system's sensitivity is reduced by heavy rain, fog, or snow. A sustained interruption of the laser beam by animals, birds, insects, etc., can cause a false alarm. The targets must be designed to allow normal bridge motion during train passage without occulting the laser beam.

Table 5.37 Laser Alignment Occulting Target System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.95	Lower chord motion detected.
One end of span moved laterally on bearings	0.95	Lower chord motion detected.
Both ends of span moved laterally on bearings	0.95	Lower chord motion detected.
Pier struck and tilted or damaged	1.00	Lower chord motion detected.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Lower chord motion detected, target out of laser beam.
One tie burns or partially burns	0.02	Does not affect lower chord.
Two ties burn	0.05	Possibility of smoke interrupting laser beam.
Three ties burn	0.10	Possibility of smoke interrupting laser beam.
Four ties burn	0.20	Possibility of smoke interrupting laser beam.
50% of ties on bridge burn	0.70	Lower chord motion or smoke effects.
75% of ties on bridge burn	0.95	Lower chord motion or smoke effects.
100% of ties on bridge burn	0.95	Lower chord motion or smoke effects.

Stereo Video

Eight cameras were used. They were located on towers on piers between the span 1 and 2 and between spans 3 and 4. Each pair of cameras monitored one span. The images produced by the cameras are processed and compared to previously stored images to determine if the bridge has moved or changed. The processor would have to account for the different appearance of the bridge during train passage and not cause alarms due to trains sitting on or moving across the bridge. An alarm state would occur if the bridge moved laterally or vertically beyond preset limits or if obstructions were found on the bridge itself. This system's sensitivity would be decreased by rain, snow, and fog. Animals or people crossing the bridge might also trigger the alarm unless the system's alarm threshold was lowered.

Table 5.38 Stereo Video System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.95	Detection of movement or of ship/barge in contact with bridge.
One end of span moved laterally on bearings	0.95	Detection of movement or of ship/barge in contact with bridge.
Both ends of span moved laterally on bearings	0.95	Detection of movement or of ship/barge in contact with bridge.
Pier struck and tilted or damaged	1.00	Detection of movement or of ship/barge in contact with bridge.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Detection of movement or of ship/barge in contact with bridge.
One tie burns or partially burns	0.20	Detection of smoke or flame.
Two ties burn	0.30	Detection of smoke or flame.
Three ties burn	0.40	Detection of smoke or flame.
Four ties burn	0.65	Detection of smoke, flame and movement.
50% of ties on bridge burn	0.80	Detection of smoke, flame and movement.
75% of ties on bridge burn	0.95	Detection of smoke, flame and movement.
100% of ties on bridge burn	0.95	Detection of smoke, flame and movement.

Fiber Optic Displacement Sensor

Three fiber-optic loops were used, one on the turn span, and one on each of the two fixed portions of the bridge. A fiber optic cable is attached to each pier and routed across the span on the lower chord girder. The cable is attached to the girder at intervals. At the next pier, the cable is attached to the pier and routed under the track to the lower chord girder on the opposite side of the bridge. The cable is attached to this girder at intervals and attached to the pier at the end of the span. A light signal is pulsed down the cable and the reflected and transmitted signals are processed to determine if there is any change from the previous pulse. Movement of the structure sufficient to damage or bend the cable will change the characteristics of the returning signals. Alarms can be set to predetermined levels of movement. The processor must recognize and ignore signal changes from normal bridge movement under trains and from expansion and contraction of the bridge structure due to temperature effects.

Table 5.39 Fiber Optic Displacement System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.99	Detection of movement between chord and pier likely.
One end of span moved laterally on bearings	1.00	Detection of movement between chord and pier.
Both ends of span moved laterally on bearings	1.00	Detection of movement between chord and pier.
Pier struck and tilted or damaged	1.00	Detection of movement between chord and pier.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Detection of movement between chord and pier.
Fire Detection		Basic assumption for wired systems.

Piezo-electric Movement Sensor

Three fiber-optic loops were used, one on the turn span, and one on each of the two fixed portions of the bridge. The loops were attached to the lower chords and the piers of the fixed span and the lower chords and the end beams of the moveable span. Any movement of the piezo-electric material causes a signal to be generated while the motion is taking place. A processor monitors the output of the material and sets an alarm if a predetermined level is exceeded. The processor must recognize and ignore signal changes from normal bridge movement under trains and from thermal expansion and contraction of the bridge structure.

Table 5.40 Piezo-electric Movement System

Detailed Effect	**Detection Probability**	**Comments**
Lower chord struck, one side shortened, still on bearings	0.99	Detection of movement between chord and pier likely.
One end of span moved laterally on bearings	0.99	Detection of movement between chord and pier.
Both ends of span moved laterally on bearings	1.00	Detection of movement between chord and pier.
Pier struck and tilted or damaged	1.00	Detection of movement between chord and pier.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Detection of movement between chord and pier.
Fire Detection		Basic assumption for wired systems.

Strain Gages

One-hundred strain gages were attached to key structural members on all four spans. A processor monitors the output of the strain gages and compares it to predetermined stress limits. An alarm level is set at predetermined limits which account for thermal stresses and the passage of trains.

Table 5.41 Strain Gage System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.80	End movement of chord girder detected if stress occurs at a gage location.
One end of span moved laterally on bearings	0.90	Stress detection during movement..
Both ends of span moved laterally on bearings	0.95	Stress detection during movement.
Pier struck and tilted or damaged	1.00	Stress change in truss components.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Stress changes and interruption of system wiring.
Fire Detection		Basic assumption for wired systems

Self-Contained Impact

Impact type sensors were distributed on the lower chords; four per 240-foot span and six on the 300-ft turn span. A total of 18 sensors were used. If impact to these girders exceeds a preset value the sensor activates a small radio transmitter and deploys an antenna. A nearby receiver detects the signal and opens a relay in the railroad signal system. No wiring on the bridge is required.

Table 5.42 Self Contained Impact System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.99	Exceeds G limit
One end of span moved laterally on bearings	0.99	Exceeds G limit
Both ends of span moved laterally on bearings	1.00	Exceeds G limit
Pier struck and tilted or damaged	1.00	Exceeds G limit
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Exceeds G limit, system destroyed.
One tie burns or partially burns	0	No impacts to sense
Two ties burn	0	No impacts to sense
Three ties burn	0	No impacts to sense
Four ties burn	0.05	Slight possibility of falling structure creating impact
50% of ties on bridge burn	0.10	Possibility of falling structure creating impact
75% of ties on bridge burn	0.20	Possibility of falling structure creating impact
100% of ties on bridge burn	0.40	Possibility of falling structure creating impact

Pyrotechnic Impact

Impact sensors were distributed on the lower chords; four per 240-foot span and six on the 300-ft turn span for a total of 18 sensors. Acceleration sensors are connected to a sodium azide supply in a sealed container, similar to the "air bags" used to protect occupants in automobiles. Impact to the structure activates the system causing the sodium azide to ignite and provide a high-energy supply of hot gas. This energy is used to transmit a signal to a nearby receiver which then opens a relay in the railroad signal system. No wiring on the bridge is required.

Table 5.43 Pyrotechnic Impact System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	0.99	Exceeds G limit.
One end of span moved laterally on bearings	0.99	Exceeds G limit.
Both ends of span moved laterally on bearings	1.00	Exceeds G limit.
Pier struck and tilted or damaged	1.00	Exceeds G limit.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Exceeds G limit, system destroyed.
One tie burns or partially burns	0	No impact to detect.
Two ties burn	0	No impact to detect.
Three ties burn	0	No impact to detect.
Four ties burn	0.10	Slight possibility of falling structure creating impact.
50% of ties on bridge burn	0.20	Possibility of falling structure creating impact.
75% of ties on bridge burn	0.30	Possibility of falling structure creating impact.
100% of ties on bridge burn	0.40	Possibility of falling structure creating impact.

Pyrotechnic Displacement

Pyrotechnic displacement sensors were used on each pier to monitor the chord girders at the piers. A total of 16 displacement sensors were used. Movement sensors are connected to a sodium azide supply in a sealed container, similar to the "air bags" used to protect occupants in automobiles. Movement of the structure beyond limits activates the system causing the sodium azide to ignite and provide a high-energy supply of hot gas. This energy is used to transmit a signal to a nearby receiver which then opens a relay in the railroad signal system. No wiring on the bridge is required.

Table 5.44 Pyrotechnic Displacement System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	1.00	Detection of movement between chord and pier likely.
One end of span moved laterally on bearings	1.00	Detection of movement between chord and pier.
Both ends of span moved laterally on bearings	1.00	Detection of movement between chord and pier.
Pier struck and tilted or damaged	1.00	Detection of movement between chord and pier.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Detection of movement between chord and pier.
One tie burns or partially burns	0	Displacement below activation range.
Two ties burn	0	Displacement below activation range.
Three ties burn	0	Displacement below activation range.
Four ties burn	0.05	Slight change of displacement.
50% of ties on bridge burn	0.50	Detection of displacement of lower chords.
75% of ties on bridge burn	0.90	Detection of displacement of lower chords.
100% of ties on bridge burn	1.00	Detection of displacement of lower chords.

Mechanical Displacement

Circuit controllers and mechanical links were used on each pier to monitor the position of the lower chord girders. Lateral movement of the lower chord girders relative to the pier causes the switch circuit controller to open the electrical circuit and a relay in the signal system to display a restrictive signal. Rigging of the system must allow normal vibration under train passage and thermal expansion. A total of 16 circuit controllers were used.

Table 5.45 Mechanical Displacement System

Detailed Effect	Detection Probability	Comments
Lower chord struck, one side shortened, still on bearings	1.00	Movement detected at pier.
One end of span moved laterally on bearings	1.00	Movement detected at pier.
Both ends of span moved laterally on bearings	1.00	Movement detected at pier.
Pier struck and tilted or damaged	1.00	Movement detected at pier.
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Movement detected at pier.
Fire Detection		Basic assumption for wired systems

Track Circuit

The standard railroad track signal circuit will cause a restrictive signal indication any time either rail continuity is broken or if an electrical short circuit exists between the two rails. The track circuit only will cause a restrictive signal to be displayed if the two rails are either shorted together or if either rail is broken to form an open circuit. The only conditions assumed likely to cause either of these conditions on this bridge other than total collapse were during the deck fire. None of the other specific effects were given a non-zero detection probability.

Table 5.46 Track Circuit System

Detailed Effect	Detection Probability	Comments
Chord deflected, one side shortened off bearings, truss tilts off pier	1.00	Open circuit created after collapse, possibility of short circuit during failure.
50% of ties on bridge burn	0.1	Slight probability of short to rails from deck damage.
75% of ties on bridge burn	0.2	Slight probability of short to rails from deck damage or open circuit on one rail.
100% of ties on bridge burn	0.3	Possibility of short to rails from deck damage or open circuit on one or both rails.

5.3.3 Performance Comparison

The candidate integrity monitor systems were compared on the basis of number of true alarms (mission success), number of missed alarms (mission failure), and number of false alarms (system reliability). The expected number of bridge failures or train accidents in the 25-year life cycle period was 2.99, resulting from the extremely adverse distribution of initial causes assumed for the purposes of this analysis. Fractions of a failure were retained solely for the purposes of comparing the different systems over the short 25-year period. Therefore, integrity monitor systems operating in this scenario with fewer than three alarms indicated a tendency to miss hazardous conditions, while systems with greater than three alarms indicated a tendency toward false alarms wither from the technology, or from internal failures. All of the technologies performed nearly the same on this large bridge in sensing and alarming on the high energy impacts from ships and barges. Figures 5.7-5.8 compare the alarm performance of the systems.

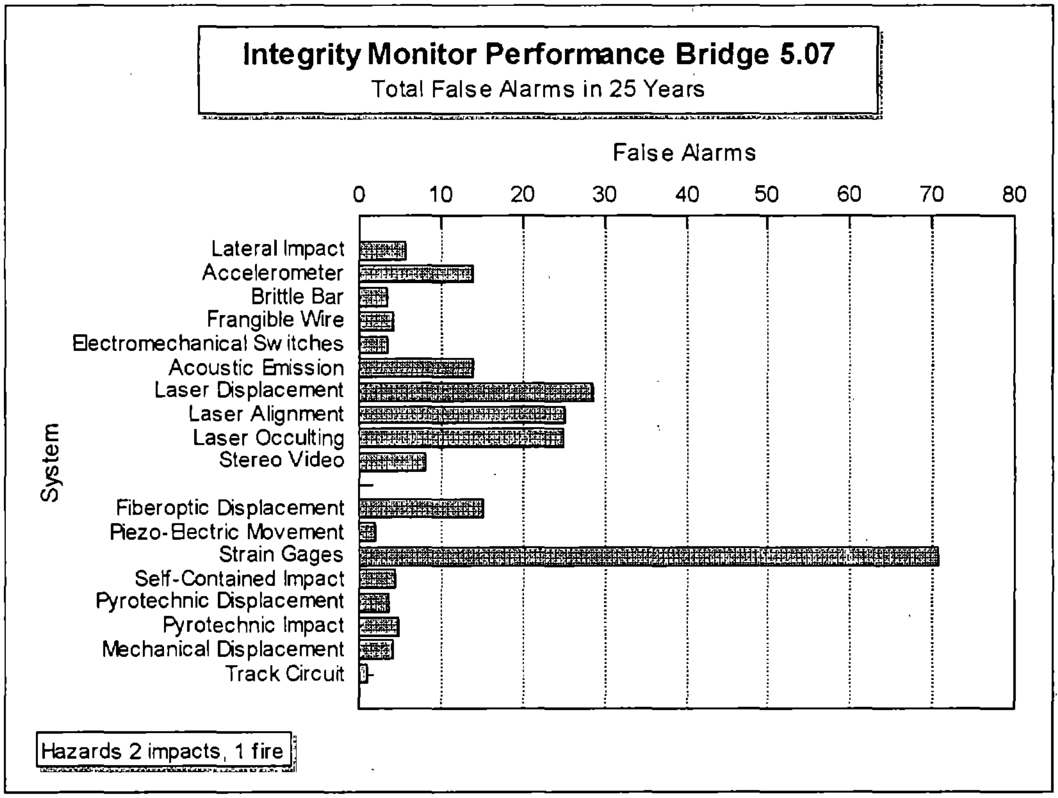


Figure 5.7 False Alarm Performance Bridge 5.07

The simple impact and displacement sensor systems performed best with three to five false alarms in the 25-year period. The fiber optic and acoustic emission systems were next best in performance with approximately 15 false alarms. The laser systems had between 20-30 false alarms, and the strain gage system created over 70, an excessive number of false alarms.

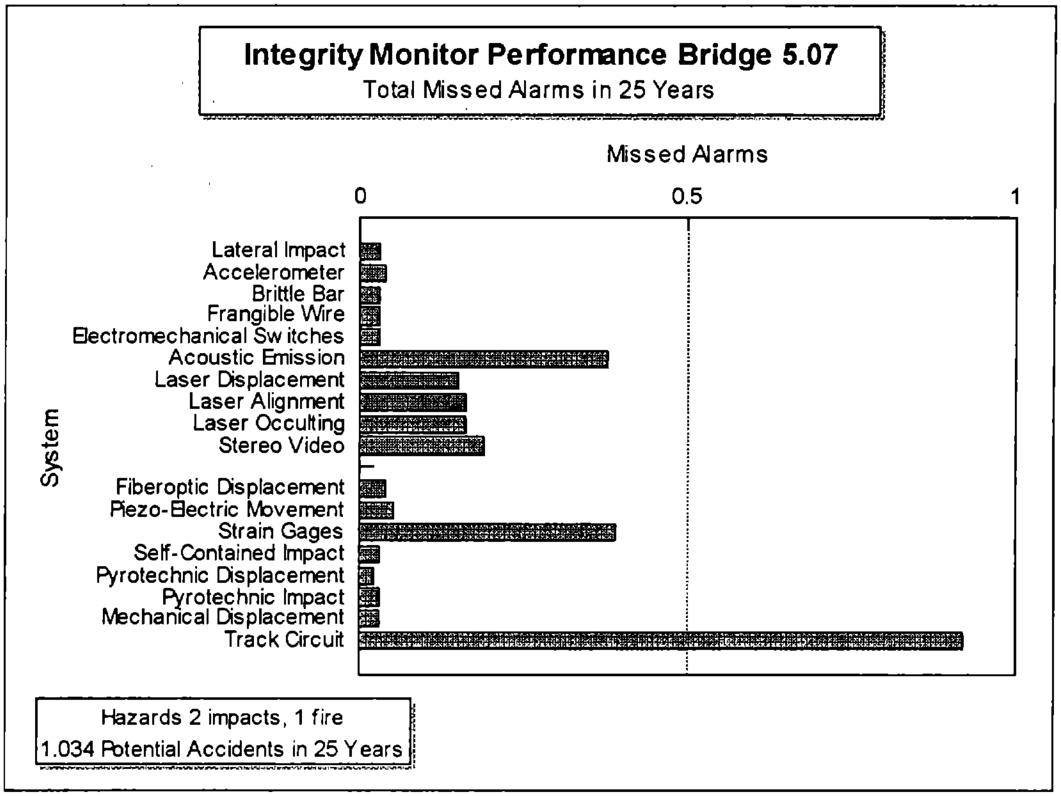


Figure 5.8 Missed Alarm Performance Bridge 5.07

All technologies performed well. On the average no system except the track circuit would have missed an alarm condition in the 25-year period. This is partially due to the severity of the impacts assumed so that almost any collision would lead to a true alarm condition.

5.3.4 Cost Comparison

The technologies were compared on the basis of installation cost and life cycle cost. Electrical power for operation of the bridge machinery was assumed to already be in place on the bridge so the $10,000 electrical interface cost was eliminated. Interlocking signal equipment and wiring is also in place on the bridge for the moveable span. Accordingly the $25,000 signal system interface cost was reduced to $20,000 for each system.

Figures 5.9-5.10 summarize the cost data for the multi-span truss bridge. The installation costs were higher on the large bridge than for the 40-foot girder bridge due to the increased number of sensors, and the fact that the systems were designed in three segments to monitor the two fixed spans on one side of the moveable span, the moveable span itself, and the remaining fixed span separately.

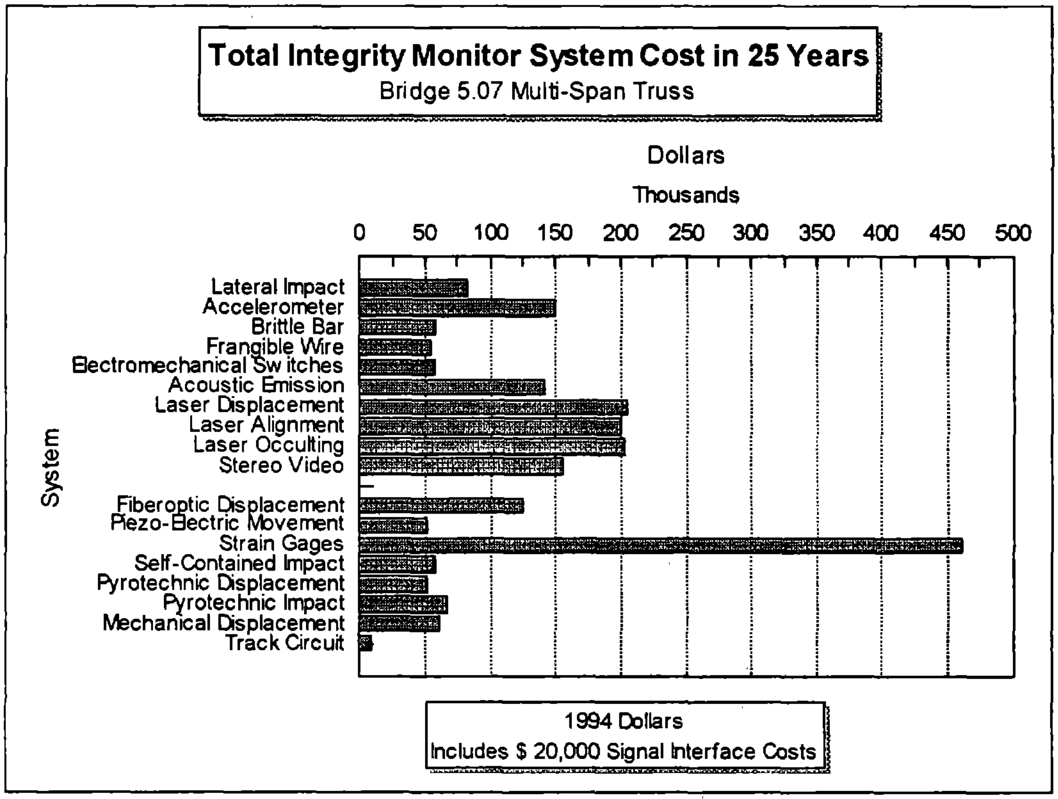


Figure 5.9 Installation Cost Comparison Bridge 5.07

As expected, the installation costs for this complicated bridge are considerably higher than on bridge 125.20. Technologies requiring a distributed network of sensors such as the accelerometer, acoustic emission, and strain gage systems had higher installation costs than those that can sense movement on each pier. The installation costs for the stereo video system was also high due to the number of cameras and the towers required for their mounting. Other than the stereo video, the non-contact sensor systems had approximately the same installation costs as the simple movement or impact systems.

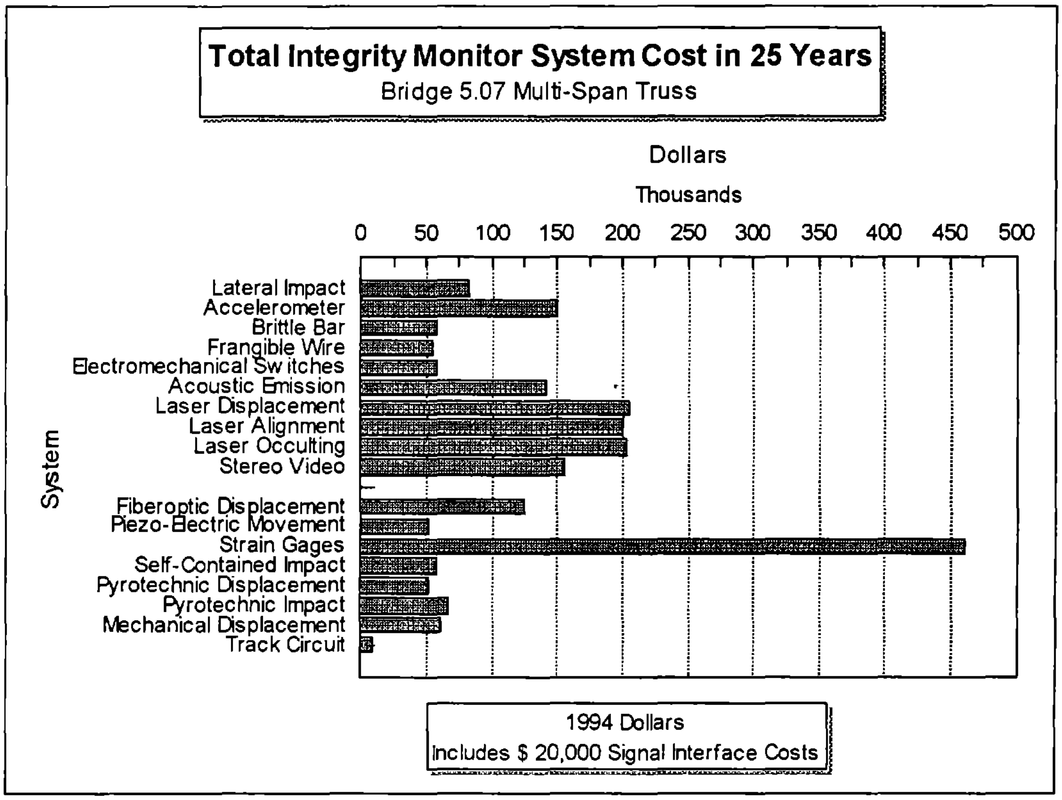


Figure 5.10 Total Costs During 25-Year Period Bridge 5.07

The total costs for the non-contact laser and video sensors were several times those of the simple systems. This was due to both the high installation cost, and the cost effect of false alarms and repairs to systems with many failures in 25 years. The self-contained impact, pyrotechnic impact, pyrotechnic displacement, and contact-type movement detection systems had the lowest overall cost. There was little difference in total cost between wired and radio linked systems.

5.4 Bridge 44.53 Sixteen-Panel 12-Ft Span Timber Trestle

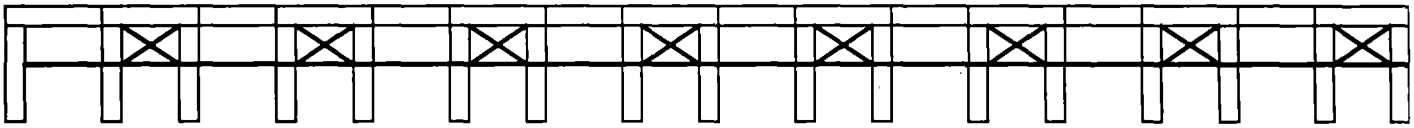


Figure 5.11 Timber Trestle Bridge 44.53

This bridge spans a portion of a waterway with a navigable channel at another location, both barge and small boat traffic. The bridge leads from the shoreline of a river to a midstream island. The shipping channel passes on the other side of the island under a moveable bridge. The timber trestle consists of 16 6-pile bents capped by 14x14 inch timbers. The bridge is in a climate not subject to ice or attack by marine borers. The railroad is a single track line operating with both freight and passenger service. Automatic block signals are in place on the track with signal circuits carried by cable.

5.4.1 Initiating Causes Bridge 44.53

The main hazards to the bridge are impact from loose barges and fire. Fire on the bridge decks from hot brake shoes or rail grinding is possible. Wildfire from vegetation on the shorelines is also possible. Barge tows normally do not enter the waterway that this bridge spans. However, occasionally moored barges upstream break free and can be carried toward this bridge by wind and current. The initiating causes assumed for bridge 44.53 are shown in table 5.11 below:

Table 5.47 Initiating Causes for Bridge 44.53 Timber Trestle

Initiating Cause	Comments	No in 25 Years *
Impact/Shock	Considered to be the most likely threat to this bridge. Possibility of occurrence of significant impacts from barges.	1
Fire	Considered at low frequency of occurrence 1 fire per 25 years.	1

* Note: Likelihood of events is exaggerated for study purposes

Tables 5.13 and 5.14 show the detailed effects resulting from the assumed distribution of initiating causes. Note that the barge impacts consider a barge drifting free at a random orientation rather than a barge tow under power and control of a towing vessel.

Table 5.48 Detailed Effects on Bridge 44.53 From Collision with Single Loose Barge

DETAILED EFFECTS	No of Occurrences per 100 Impacts	Number of Detailed Effect in 25 Years	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
ONE PILE ON THREE BENTS MOVED (LOW VELOCITY HEAD-ON)	20	0.2	0.7	0.14
THREE PILES ON ONE BENT MOVED (45 DEG IMPACT)	20	0.2	0.9	0.18
TWO PILES ON THREE BENTS MOVED (HEAD-ON IMPACT)	20	0.2	1.0	0.2
TWO PILES ON EIGHT BENTS MOVED (30 DEG ANGLE IMPACT)	20	0.2	1.0	0.2
TWO PILES ON 16 BENTS MOVED (90 DEG ANGLE IMPACT)	20	0.2	1.0	0.2

Table 5.49 Detailed Effects on Bridge 44.53 From Fire on Bridge Deck

DETAILED EFFECTS	No of Occurrences per 100 Fires	Number of Detailed Effect in 25 Years	Criticality of Effect	Number of Bridge Failures Due to Effect in 25 Years
<= 1 TIE BURNS	70	0.7	0	0
2 TIES BURN	20	0.2	0.1	0.02
3 TIES BURN	5	0.05	0.7	0.035
4 TIES BURN	3	0.03	0.9	0.027
25% OF TIES BURN	0.5	0.005	1	0.005
50% OF TIES BURN	0.5	0.005	1	0.005
100% OF TIES BURN	0	0	1	0

5.4.2 Integrity Monitor Systems and Detection Probabilities Bridge 44.53

The same integrity monitor technologies used for bridge 125.20 were considered for this bridge also. The systems were redesigned to accommodate the increased number of spans to monitor. The increased amount of movement expected on the timber trestle as compared to the stiff steel girder bridge caused design changes in some technologies to bent-mounted sensors. The estimates of fire detection ability was also changed due to the timber structure. Only the changes to each system from the design for the simple bridge 125.20 will be noted below:

Lateral Impact Sensors

One sensor was placed on each of the 16 bents monitoring for impacts on that bent. Impacts on stringers between bents would probably also be detected. Any impact against the stringers or bents from marine traffic above a specified magnitude will cause the switches to lose electrical continuity momentarily and cause a latching relay to cause a restrictive aspect on the local railroad signal system. The system is electrical and requires a latching relay but no logic circuits or processor. The sensor output is transient unless impact results in enough tilting of the girder to keep the switch open. The lateral impact G switch sensor was assumed to be set at a magnitude of acceleration above that normally found during train passage. Due to its simplicity, this sensor was considered to always trip if accelerations at its mounting location exceeded the limit. Fire detection capability was considered as the probability that a connecting wire would burn in two at some point on the bridge during the fire. This probability was assumed to increase with the number of ties involved in a deck fire.

Table 5.50 Lateral Impact System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.80	Probable detection of impact.
Three piles on one bent moved (45 deg impact)	0.90	Probable detection of impact.
Two piles on 3 bents moved (head-on impact)	1.00	Impact exceeds detection threshold.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Impact exceeds detection threshold.
Two piles on 16 bents moved (90 deg impact)	1.00	Impact exceeds detection threshold.
One tie burns or partially burns	0.02	Basic assumption for wired systems.
Two ties burn	0.05	Basic assumption for wired systems.
Three ties burn	0.10	Basic assumption for wired systems.
Four ties burn	0.20	Basic assumption for wired systems.
50% of ties on bridge burn	1.00	Wire burn through on timber structure.
75% of ties on bridge burn	1.00	Wire burn through on timber structure.
100% of ties on bridge burn	1.00	Wire burn through on timber structure.

Accelerometers

One sensor was placed on each of the 16 bents monitoring for impacts on that bent. Accelerations due to impacts on stringers between bents would probably also be detected by one of the accelerometers on the bents at either end of the stringer span. The output of each accelerometer is monitored continuously and a processor decides if alarm thresholds are exceeded. The system must not alarm during normal train passage. The sensors are also able to detect major twisting or distortion in the outer main girders. The accelerometer system was assumed to operate with the same detection probability as the impact sensors. The added complexity of the computer system needed to analyze the accelerometer signals was accounted for in the failure rate calculations for false alarms. No degradation in detection probability was assumed due to software since the simple software needed to declare alarms was IF-THEN type logic. Due to the simplicity of the sensor and software, this system was considered to always trip if accelerations at its mounting location exceeded the limit.

Table 5.51 Accelerometer System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.80	Probable detection of impact
Three piles on one bent moved (45 deg impact)	0.90	Probable detection of impact
Two piles on 3 bents moved (head-on impact)	1.00	Impact exceeds detection threshold
Two piles on 8 bents moved (30 deg angle impact)	1.00	Impact exceeds detection threshold
Two piles on 16 bents moved (90 deg impact)	1.00	Impact exceeds detection threshold
Fire Detection		Basic assumption for wired systems

Brittle Bar Sensors

Brittle bars were placed on each bent and connected to the stringer beams. Excessive relative motion between the stringers and the bent would break the bar and open an electrical circuit that controls a relay in the track signal system. Rigging of the system must permit normal vibration under train passage and thermal expansion of the sensor components without fracturing the brittle bars. The brittle bars provided a degree of redundancy due to their location on either end of the stringer timbers. The detection probability of this simple system was therefore very high.

Table 5.52 Brittle Bar System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.90	Detection of movement between bent and stringer likely
Three piles on one bent moved (45 deg impact)	0.95	Detection of movement between bent and stringer likely
Two piles on 3 bents moved (head-on impact)	1.00	Large relative movement between bent and stringers
Two piles on 8 bents moved (30 deg angle impact)	1.00	Large relative movement between bent and stringers
Two piles on 16 bents moved (90 deg impact)	1.00	Large relative movement between bent and stringers
Fire Detection		Basic assumption for wired systems

Frangible Wire

One frangible wire loop were used. This wire loop was routed along the stringers and attached to each bent so that impact on the stringers between bents or excessive relative movement between a bent and either stringer would break the loop. The wire loop was connected to a power supply and latching relay. If there is any excessive relative movement between the bridge girders and the abutments, or between the bottom flanges of the outer girders, the wire will part and the relay in the signal system will cause a restrictive signal. Rigging of the system permits normal vibration under train passage. The frangible wire provided a degree of redundancy due to the possibility of more than one break in the wire loop. The detection probability of this simple system, therefore was very high.

Table 5.53 Frangible Wire System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	1.00	Breaking of continuous loop assured.
Three piles on one bent moved (45 deg impact)	1.00	Breaking of continuous loop assured.
Two piles on 3 bents moved (head-on impact)	1.00	Breaking of continuous loop assured.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Breaking of continuous loop assured.
Two piles on 16 bents moved (90 deg impact)	1.00	Breaking of continuous loop assured.
One tie burns or partially burns	0.02	Basic assumption for wired systems.
Two ties burn	0.05	Basic assumption for wired systems.
Three ties burn	0.10	Basic assumption for wired systems.
Four ties burn	0.40	Continuous loop increases probability of detection.
50% of ties on bridge burn	1.00	Wire burn through on timber structure.
75% of ties on bridge burn	1.00	Wire burn through on timber structure.
100% of ties on bridge burn	1.00	Wire burn through on timber structure.

Electromechanical Switches

Displacement switches were placed on each bent and connected to the outer stringers. Excessive relative movement between bents and stringers would open the switch. A total of 32 switches were used. Relative lateral movement of the stringers relative to the bent causes the switch on that bent to open the electrical circuit and a latching relay in the signal system to cause a restrictive signal. Rigging of the system must permit routine vibration under train passage. The switches provided a degree of redundancy due to the possibility of sensing stringer movement at two bent locations. The detection probability of this simple system was therefore very high.

Table 5.54 Electromechanical Switch System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.80	Detection of movement between bents and stringers likely.
Three piles on one bent moved (45 deg impact)	0.90	Detection of movement between bent and stringer likely.
Two piles on 3 bents moved (head-on impact)	1.00	Large relative movement between bent and stringers.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Large relative movement between bent and stringers.
Two piles on 16 bents moved (90 deg impact)	1.00	Large relative movement between bent and stringers.
One tie burns or partially burns	0.02	Basic assumption for wired systems.
Two ties burn	0.05	Basic assumption for wired systems.
Three ties burn	0.10	Basic assumption for wired systems.
Four ties burn	0.40	Basic assumption for wired systems.
50% of ties on bridge burn	1.00	Wire burn through on timber structure.
75% of ties on bridge burn	1.00	Wire burn through on timber structure.
100% of ties on bridge burn	1.00	Wire burn through on timber structure.

Acoustic Emission

Not used since this technology can monitor only metallic structures.

Laser Displacement

Not used due to excessive life cycle costs on other theoretical bridges.

Laser Alignment Mid Span Detector

Not used due to excessive life cycle costs on other theoretical bridges.

Laser Alignment Occulting Detectors

Two lasers were used, one on each side of the bridge mounted on a foundation on the shore. A photo diode detector is mounted on the opposite shore. A series of targets are mounted on the bents and outer stringers.. Each target has a small hole or slot and the targets are mounted and aligned so that the laser beam passes through the slots in each target from the laser to the photo diode detector. Movement of the bridge stringers or bents beyond normal limits established by the hole and slot dimensions cause one or more of the targets to interrupt the laser beam. A processor sets an alarm state if the laser beam does not reach the detector. The system's sensitivity is reduced by heavy rain, fog, or snow. A sustained interruption of the laser beam by animals, birds, insects, etc., can cause a false alarm.

Table 5.55 Laser Occulting Target System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.80	Detection of sag in bents.
Three piles on one bent moved (45 deg impact)	0.90	Detection of bent or stringer motion.
Two piles on 3 bents moved (head-on impact)	1.00	Detection of bent or stringer motion.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Detection of bent or stringer motion.
Two piles on 16 bents moved (90 deg impact)	1.00	Detection of bent or stringer motion.
One tie burns or partially burns	0.02	Beam interrupted by smoke.
Two ties burn	0.05	Beam interrupted by smoke.
Three ties burn	0.10	Beam interrupted by smoke, or movement of stringer.
Four ties burn	0.20	Beam interrupted by smoke, or movement of stringer.
50% of ties on bridge burn	1.00	Beam interrupted by smoke, or movement of stringer.
75% of ties on bridge burn	1.00	Beam interrupted by smoke, or movement of stringer.
100% of ties on bridge burn	1.00	Beam interrupted by smoke, or movement of stringer.

Stereo Video

Two cameras were used. They were located on a tower on the bank viewing the entire bridge length. The images produced by the cameras are processed and compared to previously stored images to determine if the bridge has moved or changed. The processor would have to account for the different appearance of the bridge during train passage and not cause alarms due to trains sitting on or moving across the bridge. An alarm state would occur if the bridge moved laterally or vertically beyond preset limits or if obstructions were found on the bridge itself. This system's sensitivity would be decreased by rain, snow, and fog. Animals or people crossing the bridge might also trigger the alarm unless the system's alarm threshold was lowered.

Table 5.56 Stereo Video System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.95	Detection of movement or of barge in contact with bridge.
Three piles on one bent moved (45 deg impact)	0.95	Detection of movement or of barge in contact with bridge.
Two piles on 3 bents moved (head-on impact)	0.95	Detection of movement or of barge in contact with bridge.
Two piles on 8 bents moved (30 deg angle impact)	0.95	Detection of movement or of barge in contact with bridge.
Two piles on 16 bents moved (90 deg impact)	0.95	Detection of movement or of barge in contact with bridge.
One tie burns or partially burns	0.20	Detection of smoke or flame.
Two ties burn	0.30	Detection of smoke or flame.
Three ties burn	0.40	Detection of smoke or flame.
Four ties burn	0.65	Detection of smoke, flame and movement.
50% of ties on bridge burn	0.80	Detection of smoke, flame and movement.
75% of ties on bridge burn	0.95	Detection of smoke, flame and movement.
100% of ties on bridge burn	0.95	Detection of smoke, flame and movement.

Fiber Optic Displacement Sensor

One fiber-optic loop was used. This loop was routed along the stringers and attached to the bents so that distortion of stringers or excessive relative movement between the stringers and bents would be detected. A light signal is pulsed down the cable and the reflected and transmitted signals are processed to determine if there is any change from the previous pulse. Movement of the structure sufficient to damage or bend the cable will change the characteristics of the returning signals. Alarms can be set to predetermined levels of movement. The processor must recognize and ignore signal changes from normal bridge movement under trains.

Table 5.57 Fiber Optic Displacement System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.95	Detection of movement between bents and stringers likely.
Three piles on one bent moved (45 deg impact)	0.95	Detection of movement between bents and stringers likely.
Two piles on 3 bents moved (head-on impact)	0.95	Detection of movement between bents and stringers likely.
Two piles on 8 bents moved (30 deg angle impact)	0.95	Detection of movement between bents and stringers likely.
Two piles on 16 bents moved (90 deg impact)	0.95	Detection of movement between bents and stringers likely.
One tie burns or partially burns	0.02	Basic assumption for wired systems.
Two ties burn	0.05	Basic assumption for wired systems.
Three ties burn	0.10	Basic assumption for wired systems.
Four ties burn	0.20	Basic assumption for wired systems.
50% of ties on bridge burn	0.90	Basic assumption for wired systems.
75% of ties on bridge burn	0.90	Cable burn through likely.
100% of ties on bridge burn	1.00	Cable burn through assured.

Piezo-electric Movement Sensor

One loop of piezo-electric material was used. This loop was routed along the stringers and attached to the bents so that distortion of stringers or excessive relative movement between the stringers and bents would be detected. Any movement of the piezo-electric material causes a signal to be generated while the motion is taking place. A processor monitors the output of the material and sets an alarm if a predetermined level is exceeded. The processor must recognize and ignore signal changes from normal bridge movement under trains.

Table 5.58 Piezo-electric Movement System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	1.00	Movement detected during impact.
Three piles on one bent moved (45 deg impact)	1.00	Movement detected during impact.
Two piles on 3 bents moved (head-on impact)	1.00	Movement detected during impact.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Movement detected during impact.
Two piles on 16 bents moved (90 deg impact)	1.00	Movement detected during impact.
One tie burns or partially burns	0.01	Basic assumption for wired systems.
Two ties burn	0.02	Basic assumption for wired systems.
Three ties burn	0.10	Basic assumption for wired systems.
Four ties burn	0.20	Basic assumption for wired systems.
50% of ties on bridge burn	0.90	Cable burn through likely.
75% of ties on bridge burn	0.90	Cable burn through likely.
100% of ties on bridge burn	1.00	Cable burn through assured.

Strain Gages

Not used for timber construction.

Self-Contained Impact

Impact type sensors were distributed one per bent. These would sense impacts on each bent and possibly impacts on stringers between bents. Impact sensors are contained in a sealed container. If impact to these girders exceeds a preset value the sensor activates a small radio transmitter and deploys an antenna. A nearby receiver detects the signal and opens a relay in the railroad signal system. No wiring on the bridge is required.

Table 5.59 Self-Contained Impact System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.80	Impact detected.
Three piles on one bent moved (45 deg impact)	0.90	Impact detected.
Two piles on 3 bents moved (head-on impact)	1.00	Impact detected.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Impact detected.
Two piles on 16 bents moved (90 deg impact)	1.00	Impact detected.
One tie burns or partially burns	0	No impact to detect.
Two ties burn	0	No impact to detect.
Three ties burn	0	No impact to detect.
Four ties burn	0.05	Slight possibility of falling structure creating impact.
50% of ties on bridge burn	0.10	Possibility of falling structure creating impact.
75% of ties on bridge burn	0.20	Possibility of falling structure creating impact.
100% of ties on bridge burn	0.40	Possibility of falling structure creating impact.

Pyrotechnic Displacement

Displacement sensors were also used on each bent to monitor the relative positions of stringers and bents. A total of 16 displacement sensors were used. The sensors are connected to a sodium azide supply in a sealed container, similar to the "air bags" used to protect occupants in automobiles. Movement of the structure activates the system causing the sodium azide to ignite and provide a high-energy supply of hot gas. This energy is used to transmit a signal to a nearby receiver which then opens a relay in the railroad signal system. No wiring on the bridge is required.

Table 5.60 Pyrotechnic Displacement System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.80	Movement detected during impact.
Three piles on one bent moved (45 deg impact)	0.90	Movement detected during impact.
Two piles on 3 bents moved (head-on impact)	1.00	Movement detected during impact.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Movement detected during impact.
Two piles on 16 bents moved (90 deg impact)	1.00	Movement detected during impact.
One tie burns or partially burns	0	Displacement below activation range.
Two ties burn	0	Displacement below activation range.
Three ties burn	0	Displacement below activation range.
Four ties burn	0.05	Slight change of displacement.
50% of ties on bridge burn	0.50	Detection of displacement of stringers.
75% of ties on bridge burn	0.90	Detection of displacement of stringers.
100% of ties on bridge burn	1.00	Detection of displacement of stringers and/or bents.

Pyrotechnic Impact

Impact sensors were used on each bent to monitor for impacts against bents or stringers. A total of 16 impact sensors were used. The sensors are connected to a sodium azide supply in a sealed container, similar to the "air bags" used to protect occupants in automobiles. Impact above limits activates the system causing the sodium azide to ignite and provide a high-energy supply of hot gas. This energy is used to transmit a signal to a nearby receiver which then opens a relay in the railroad signal system. No wiring on the bridge is required.

Table 5.61 Pyrotechnic Impact System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.80	Impact detected.
Three piles on one bent moved (45 deg impact)	0.90	Impact detected.
Two piles on 3 bents moved (head-on impact)	1.00	Impact detected.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Impact detected.
Two piles on 16 bents moved (90 deg impact)	1.00	Impact detected.
One tie burns or partially burns	0	No impact to detect.
Two ties burn	0	No impact to detect.
Three ties burn	0	No impact to detect.
Four ties burn	0.10	Slight possibility of falling structure creating impact.
50% of ties on bridge burn	0.20	Possibility of falling structure creating impact.
75% of ties on bridge burn	0.30	Possibility of falling structure creating impact.
100% of ties on bridge burn	0.40	Possibility of falling structure creating impact.

Mechanical Displacement

A circuit controller and mechanical links were used on each bent to monitor the relative position of the stringers and the bent. Lateral movement of the stringers relative to the bent causes the switch circuit controller to open the electrical circuit and a relay in the signal system to display a restrictive signal. Rigging of the system must allow normal vibration under train passage.

Table 5.62 Mechanical Displacement System

Detailed Effect	Detection Probability	Comments
One pile on 3 bents moved (low velocity head on)	0.90	Movement detected during impact.
Three piles on one bent moved (45 deg impact)	0.90	Movement detected during impact.
Two piles on 3 bents moved (head-on impact)	1.00	Movement detected during impact.
Two piles on 8 bents moved (30 deg angle impact)	1.00	Movement detected during impact.
Two piles on 16 bents moved (90 deg impact)	1.00	Movement detected during impact.
One tie burns or partially burns	0.02	Basic assumption for wired systems.
Two ties burn	0.05	Basic assumption for wired systems.
Three ties burn	0.10	Basic assumption for wired systems.
Four ties burn	0.20	Basic assumption for wired systems.
50% of ties on bridge burn	0.50	Basic assumption for wired systems.
75% of ties on bridge burn	0.90	Wire burn through likely.
100% of ties on bridge burn	1.00	Wire burn through assured.

Track Circuit

The standard railroad track signal circuit will cause a restrictive signal indication any time either rail continuity is broken or if an electrical short circuit exists between the two rails. The track circuit only will cause a restrictive signal to be displayed if the two rails are either shorted together or if either rail is broken to form an open circuit. The only conditions assumed likely to cause either of these conditions on this bridge other than total collapse were during the deck fire. None of the other specific effects were given a non-zero detection probability.

Table 5.63 Track Circuit System

Detailed Effect	Detection Probability	Comments
50% of ties on bridge burn	0.1	Slight probability of short to rails from deck damage.
75% of ties on bridge burn	0.2	Slight probability of short to rails from deck damage or open circuit on one rail.
100% of ties on bridge burn	0.3	Possibility of short to rails from deck damage or open circuit on one or both rails.

5.4.3 Performance Comparison

Due to the timber construction of this bridge, the acoustic emission and strain gage systems were not applied. The laser alignment and laser displacement sensors were not used since these laser systems had experienced excessive false alarm rates on the other hypothetical bridges. The laser occulting system was used to provide data on a laser-based system. The remaining integrity monitor systems were compared on the basis of number of true alarms (mission success), number of missed alarms (mission failure), and number of false alarms (system reliability). The expected number of bridge failures or train accidents in the 25-year life cycle period was 1.02 resulting from the extremely adverse distribution of initial causes assumed for the purposes of this analysis. Fractions of a failure were retained solely for the purposes of compare the different systems over the short 25-year period. Therefore, integrity monitor systems with fewer than one alarm indicated a tendency to miss failures, while systems with greater than one alarm indicated a tendency to ward false alarms whether from the technology, or from internal failures. Except for the track circuit, all of the sensor systems produced alarms during the 25-year time period. All of the systems indicated a tendency toward false alarms with at least twice the desired number of alarms. The laser system had the largest number of alarms. Figures 5.12-5.13 compare the alarm performance of the systems.

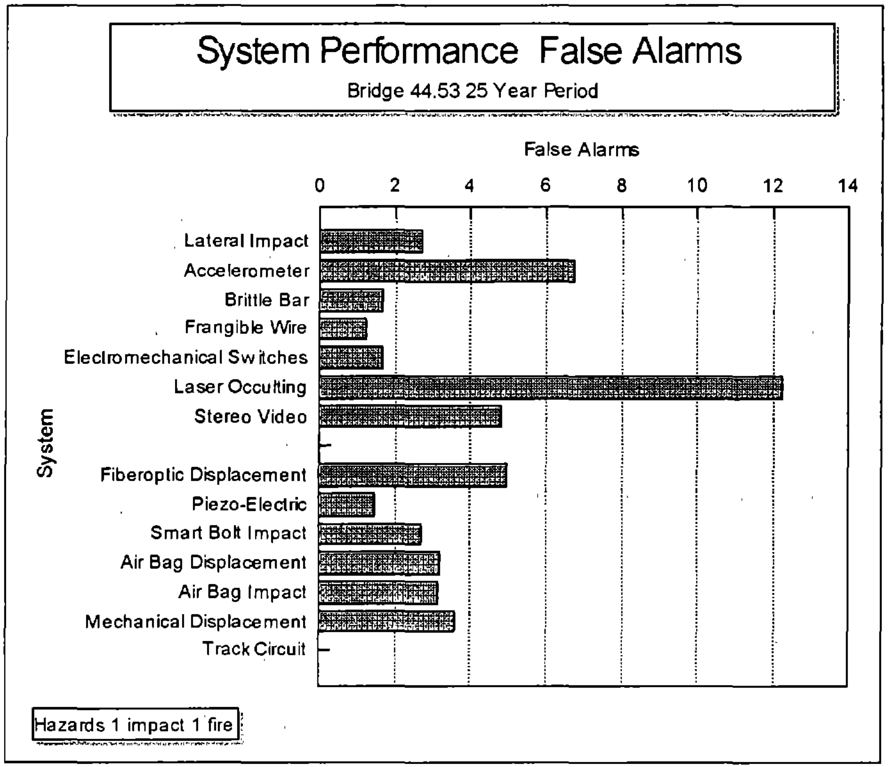


Figure 5.12 False Alarm Performance Bridge 44.53

The best performance in terms of fewest false alarms was from the frangible wire, piezo-electric movement, brittle bar, and electromechanical switch displacement systems. The impact sensing systems were next best, followed by the stereo video and fiberoptic displacement systems. The laser system had the highest false alarm rate due to component failures.

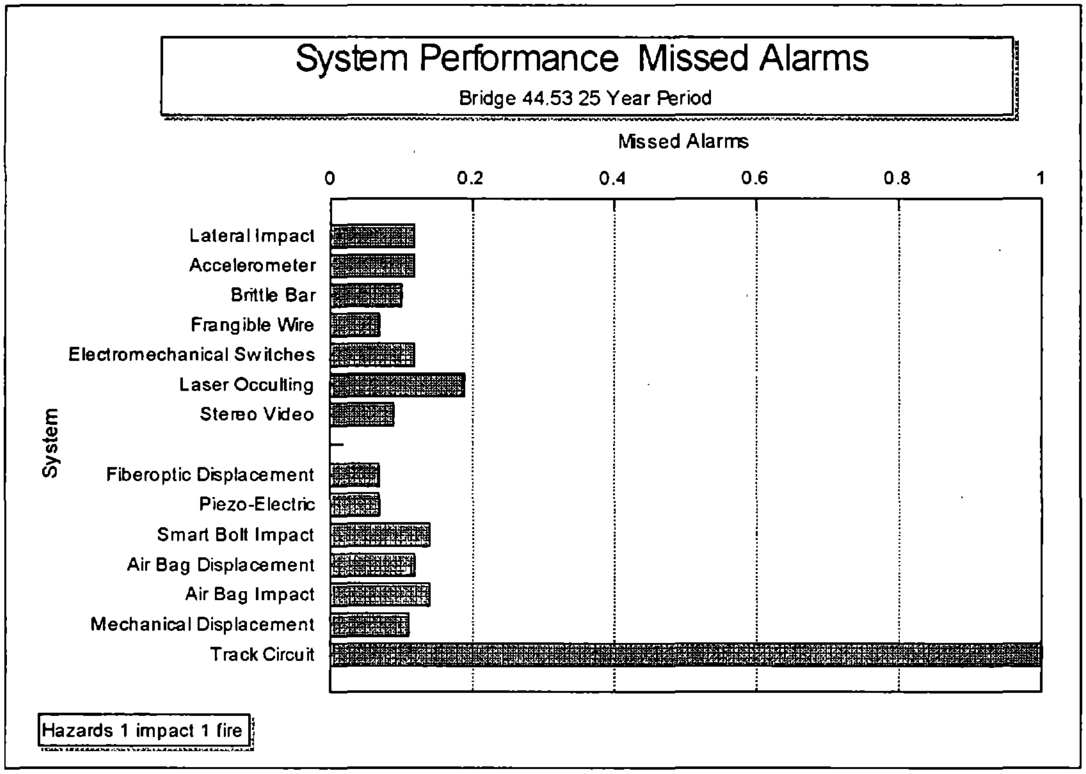


Figure 5.13 Missed Alarm Performance Bridge 44.53

The track circuit missed all of the possible alarms. The other sensors were very consistent and probably would not miss any of the impacts or fires postulated for this bridge.

5.4.4 Cost Comparison

The technologies used on this bridge were compared on the basis of installation cost and life cycle cost. Installation costs assumed that electric power was already available to operate the nearby turn span. Also due to the turn span, signal equipment was assumed to be located on the bridge so that interface costs would only include $20,000 for the signal system interfaces for each system. Figures 5.14-5.15 summarize the cost data for the timber trestle bridge.

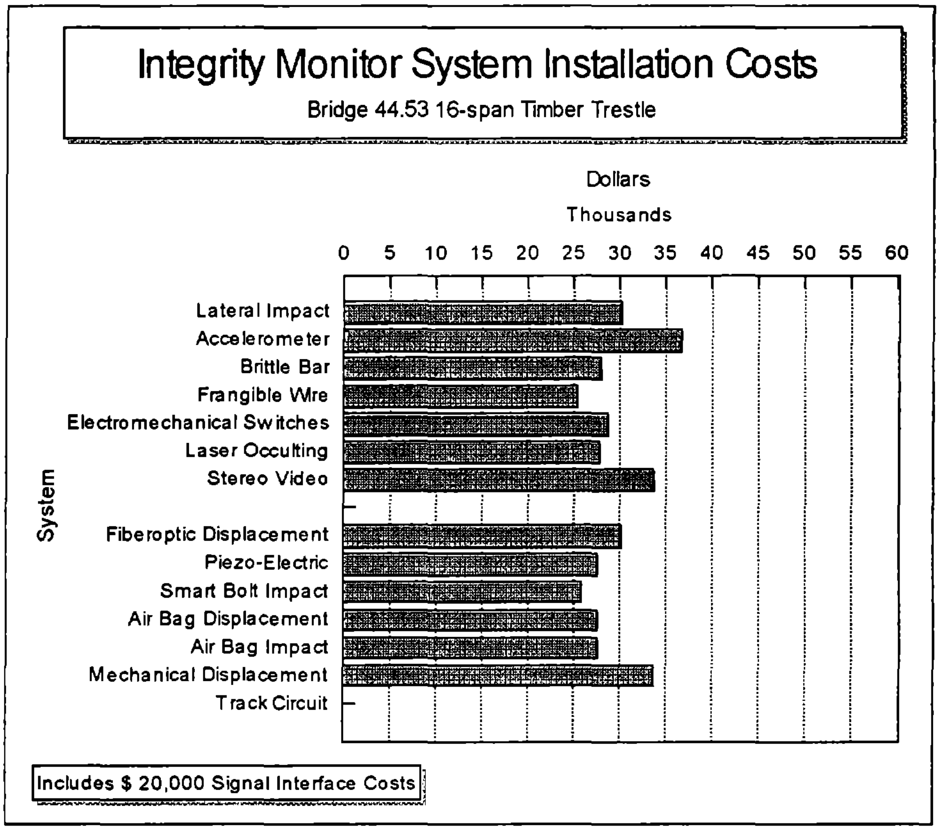


Figure 5.14 Installation Costs Bridge 44.53

The installation costs, as expected, were higher on this multi-span bridge than for the 40-foot girder bridge due to the increased number of sensors. The installation costs for this trestle were highest for the systems with sensors on each bent. The non-contact systems had lower installation costs than some of the simpler technology. This would be more apparent on bridges with more than 16 bents. The radio link systems had approximately the same installation cost as the wired systems.

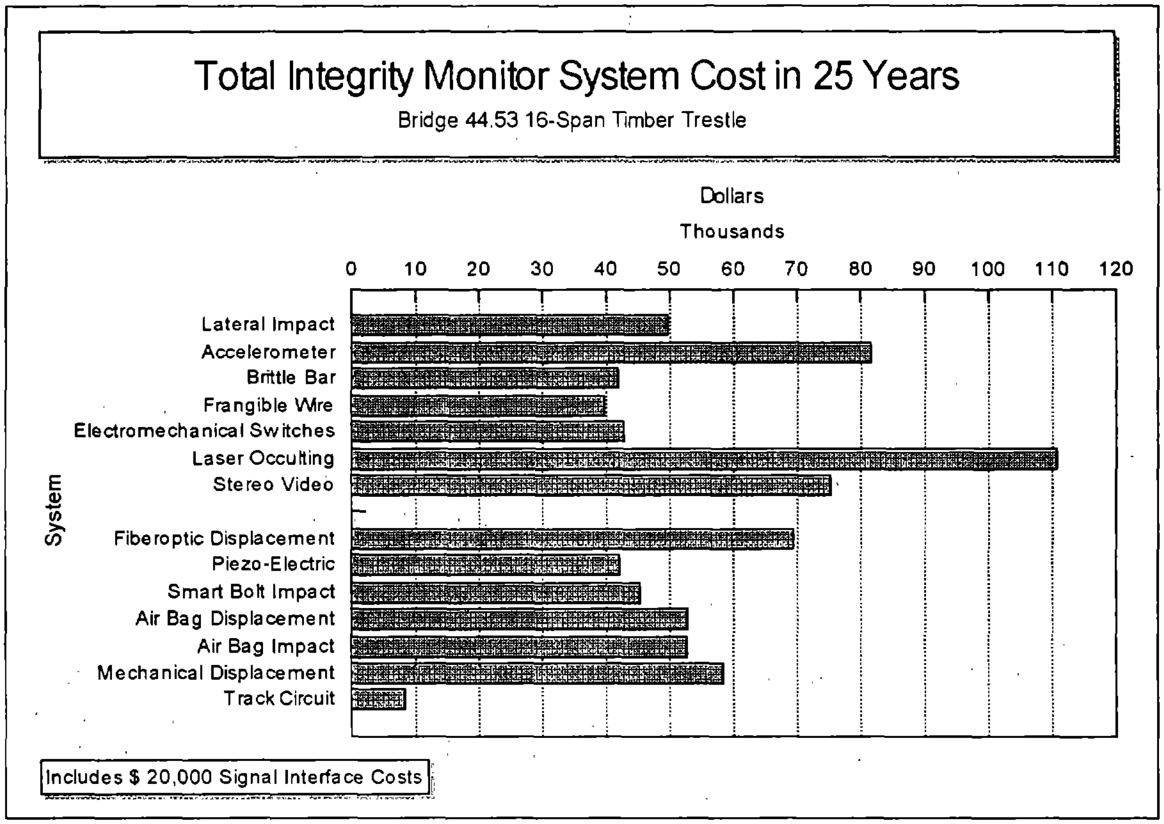


Figure 5.15 Life Cycle Costs Bridge 44.53

The total life cycle cost for the majority of the sensor systems was in the range of $40,000 to $55,000. The laser system had considerably higher life cycle costs due to the effect of false alarms. Systems using processors such as the accelerometer, stereo video, and fiber-optic displacement systems had higher life cycle costs than the simpler systems.

6.0 RESULTS

The results of the analysis of the hypothetical bridges in Section 5.0 can be discussed in terms of individual bridges or on the basis of the entire population of U.S. railroad bridges.

6.1 Individual Bridges

The performance estimates in Section 5 indicated that integrity monitors can detect and warn of hazardous bridge conditions. The cost estimates indicated that the hypothetical bridges could have integrity monitors installed and operated for 25 years at cost of between $45,000 to $70,000. This compares favorably with the estimated cost of one railroad train bridge-related accident of $252,000.

Certainly if the probability of a train accident on a given bridge could be determined with a high degree of confidence and was found to be high, then addition of integrity monitoring to that bridge could be cost-effective. However, for the purpose of the analysis of the hypothetical bridges, the hazards assumed were magnified to the extent that the three bridges constituting 0.003% of the U.S. railroad bridge population experienced approximately six failures or 12% of the total railroad bridge accidents expected nationwide in a 25-year period. Also the performance analysis showed that railroad bridge accidents might still occur on monitored bridges due to "missed" alarms.

6.2 System-wide Implications

The results of the hypothetical bridge analysis indicated that both installation costs and life cycle costs increase with the length of bridge monitored, as expected. To quantify this trend, and to provide a basis for an order of magnitude estimate for the entire railroad system, four integrity monitoring technologies were chosen that provided good performance on all three of the hypothetical bridges. These technologies were:

1. Frangible wire.
2. Piezo-electric Movement.
3. Pyrotechnic Impact.
4. Self-contained Impact.

The installation and life cycle costs of these technologies were then plotted against the total bridge length as shown in Figure 6.1.

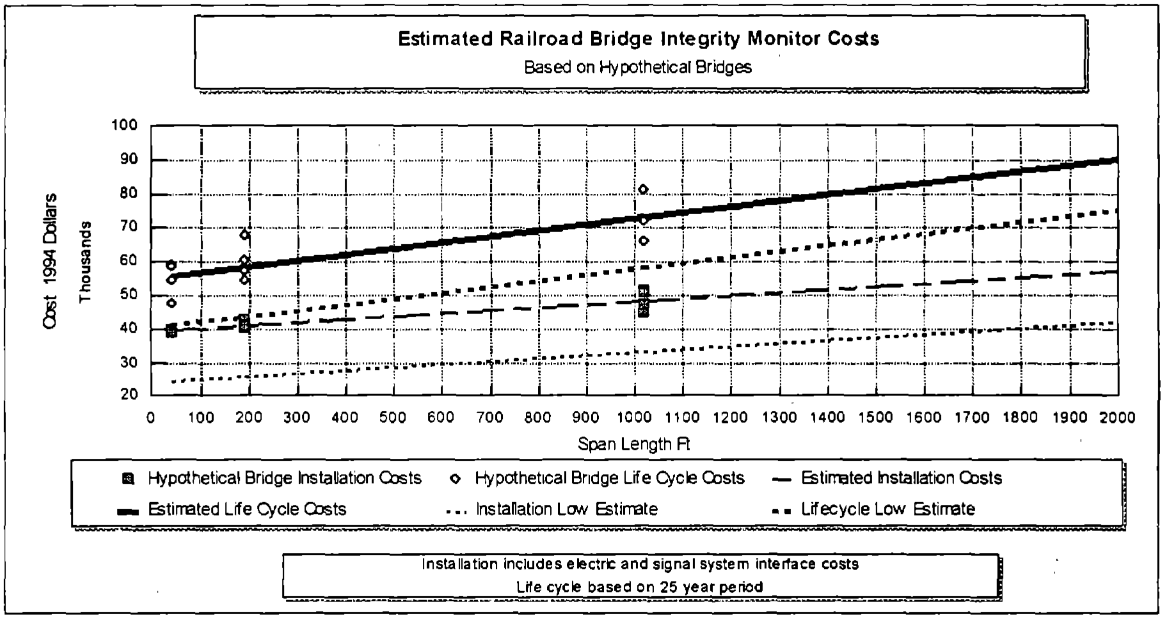


Figure 6.1 Railroad Bridge Integrity Monitor Costs

Figure 6.1 indicates that the minimum cost to install an integrity monitor system on even a very simple bridge ranges from $24,400 to approximately $44,400 depending upon whether electric power is already in place on the bridge and the availability of nearby interfaces to the wayside signal system. The installation cost increases at approximately $9.00 per foot of bridge length since longer bridges require more sensors and additional cabling.

The corresponding life cycle costs have a minimum of $40,400 to $55,400 on a simple bridge, and increase at a rate of approximately $17.50 per foot of bridge length.

Using these figures and the national average length of 120-feet per bridge, a rough estimate was made for the range of costs to install and operate integrity monitors on every railroad bridge in the U.S. The minimum cost was estimated assuming that electricity and signal interfaces were located on every bridge. The maximum cost was estimated assuming that new electric and signal interfaces would be needed on every bridge. The actual cost to monitor all U.S. railroad bridges could then be bounded.

Installation cost:

Min	100,900 bridges * ($24,400 + 120 feet * $9.00 per foot)	= $2.57 billion
Max	100,900 bridges * ($40,400 + 120 feet * $9.00 per foot)	= $4.18 billion

Total 25-year life cycle costs

Min 100,900 bridges * ($44,400 + 120 feet * $17.50 per foot) = $4.69 billion
Max 100,900 bridges * ($55,400 + 120 feet * $17.50 per foot) = $5.80 billion

These overall costs can be compared to the cost savings expected from elimination of railroad bridge accidents over the same 25-year period. Using the average of two railroad bridge-related train accidents per year, the estimated accident cost of $252,000 per accident, and the inflation and discount factors from Section 4, results in a total accident cost of $14.7 million.

Clearly on a national basis, the cost of installing and operating railroad bridge integrity monitors is not offset by the savings estimated from total railroad bridge accident prevention over the same period of time. If a vulnerability analysis could be completed that reduced the number of candidate bridges for integrity monitoring, the system-wide costs would be reduced. However, if such a study designated only 10% of the railroad bridges as candidates for integrity monitoring, the associated life cycle costs would still be between $469-$580 million which is still greater than the estimated accident cost over the same period of time.

7.0 CONCLUSIONS

1. There are approximately 100,900 railroad bridges in the United States.
2. Nearly all railroad bridges are subject to periodic inspection using defined standards.
3. An average of two bridge-related train accidents occur each year.
4. Existing track circuits provide almost no bridge integrity monitoring capability except in the case of complete collapse.
5. Some railroad bridges have had automatic monitoring systems in place since the 1930's.
6. Addition of integrity monitors will cause traffic disruption due to false alarms.
7. Some new technology systems do not provide a significant performance improvement or cost saving compared to simpler systems over a 25-year life cycle.
8. High technology integrity monitor systems would require very reliable computer systems and power supplies to compete with simple technology. To achieve these requirements would add to the initial cost of those systems.
9. Addition of any integrity monitor system including interfaces to electric power and wayside signals will cost a minimum of $24,000-$40,000 even on a simple bridge.
10. The total life cycle cost for a railroad to add an integrity monitor to a simple bridge and to operate it over a 25-year period was estimated to be a minimum of $40,000-$55,000.
11. Bridge integrity monitor costs increase from the minimum values by approximately $9.00 per foot of bridge for installation and by approximately $17.50 per foot of bridge for life cycle costs.
12. The cost to install bridge integrity monitors on every railroad bridge in the U.S. would be between $2.6- $4.2 billion.
13. The overall cost to install integrity monitors and operate them for 25 years on all U.S. railroad bridges would be between $4.7-$5.8 billion.

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