Worcester Polytechnic Institute
Project Number: LDA-0902

Sustainable Design of Belmont Street/Route 9 Bridge

A Major Qualifying Project Report:
submitted to the Faculty of
the WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements
for the Degree of Bachelor of Science by

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Abstract

Based on inspection reports provided by MassHighway, the Belmont Street/Route 9 Bridge has three bridge components deemed deficient . The deck slab, girders, and columns were re-designed using AASHTO specifications and LRFD design. Additionally, sustainable bridge design aspects were examined including alternative building materials, maintenance protection, stormwater management, and transportation and urban planning. Lastly, a life-cycle cost analysis considering the re-designed bridge components and maintenance was conducted and a sustainable bridge guideline for future bridge design projects was created.

Capstone Design Statement

In fulfillment of the Major Qualifying Project, it is also necessary to complete a capstone design. According to the Accreditation Board of Engineering and Technology (ABET) under General Criterion 4, "students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political" (Criteria for Accrediting Engineering Programs, 2007). In compliance with this requirement, the project will consider economic, environmental, sustainability, constructability, ethical, and health and safety constraints.

Economic

Since the amount of funding for projects is limited, the design elements of a construction project should be both practical and affordable. In order to ensure that the project stays within budget, the types of materials that are going to be used and the cost of construction will be assessed. The project team will conduct a life-cycle cost analysis of building materials to examine typical costs associated with bridge construction.

Environmental

In recent years, environmental impacts have become an increasing concern, especially in the field of engineering and construction. It is becoming more of a necessity to protect the surrounding natural environmental to prepare for a sustainable future. In doing so, the project team will consider the use of recyclable materials that can be incorporated in bridge designs. Often materials such as concrete and steel can be salvaged from the demolition of existing structures and reused in a new design or rehabilitation operation. The project team will also provide appropriate stormwater management solutions based on the surrounding environment.

Sustainability

Sustainable design is an innovative practice which is necessary to promote economic growth while conducting practices that benefit the environment. When considering sustainability, the project team plans to analyze the expected life span of the bridge, as well as include innovative sustainable alternatives to reduce the carbon footprint. This will be accomplished by investigating beneficial stormwater management practices. Additional sustainable aspects that will be explored include the feasibility of various maintenance systems and the use of recycled adaptations of traditional building materials such as recycled steel and concrete.

Constructability

Constructability is a standard which defines the feasibility and ease of constructing a design. Such a standard is dependent upon the cost, labor, and availability of materials. It is also dependent upon the surrounding area and any constraints that may limit the actual construction of the project. Prior to making any final decisions, the project team will examine different materials and alternatives in order to produce the most practical design. The project team will also identify the impacts the surrounding traffic will have on the construction of the project in order to determine appropriate mitigation measures.

Ethical

According to the civil engineering code of ethics, civil engineers are obligated to "use their knowledge and skill for the enhancement of human welfare and the environment; be honest and impartial and serving with fidelity the public, their employers and clients; strive to increase the competence and prestige of the engineering profession; and support the professional and technical societies of their disciplines" (Code of Ethics, 2006). With this in mind, it is the goal of the project team to construct an innovative, modern solution that is economically and ecologically advantageous by applying the fundamental civil engineering principles studied at WPI.

Health & Safety

The most important parameter when re-designing the bridge will be safety. Although, cost and sustainability are negotiable based on the budget, health and safety are fixed variables and cannot be altered. All propositions and alternatives proposed will consider safety to be the guiding factor in the analysis. In the guidelines provided by the LFRD design specifications, factor of safety values will be incorporated in the calculations to ensure the structure is built to accommodate uncertainties in the design process. Prior to construction, the project team will propose a traffic control plan to provide a safe environment for workers and travelers.

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Authorship

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Chapter 6: Transportation and urban Planning Development – Justine Ziobron

Chapter 7: Sustainable Bridge Design – Sara Migdal

Chapter 8: Life-Cycle Cost Analysis – Nicole Maglione, Justine Ziobron

Chapter 9: Project Conclusions – Nicole Maglione

Table of Contents

1 Introduction 1

2 Bridge Design 5

2.1 Massachusetts Highway Department Bridge Projects 5

2.1.1 Bridge Inspection Unit 5

2.1.2 Bridge Project Development Team 7

2.1.3 In-House Bridge Design Unit 7

2.2 Case Study – Belmont Street/Route 9 Bridge 7

2.2.1 Recorded Bridge Accidents 8

2.2.2 Deficiency of Bridge Structure 9

2.2.3 Re-Design of Bridge 10

2.3 Sustainable Design 10

2.3.1 Alternative Building Materials & Maintenance 11

2.3.2 Stormwater Management 12

2.3.3 Transportation & Urban Planning Development 12

2.4 Bridge Design Conclusion 13

3 Structural Analysis & Design 14

3.1 Superstructure Design 14

3.1.1 Wearing Surface 15

3.1.2 Deck 15

3.1.3 Primary Members 15

3.1.4 Secondary Members 16

3.2 Substructure Design 16

3.2.1 Abutments 16

3.2.2 Piers 16

3.2.3 Bearings 17
3.2.4 Pedestals 17
3.2.5 Wingwall & Backwall 17
3.2.6 Foundation 18
3.3 Design Methodology 18
3.3.1 MassHighway Visit 18
3.3.2 Standards 19
3.3.3 RISA 2-D 19
3.3.4 Calculations 19
3.3.5 Spreadsheets 28
3.3.6 AutoCAD Cross Sectional Drawings 28
3.3.7 3D Model 28
3.4 Design Results 29
3.4.1 Superstructure Design 29
3.4.2 Substructure Design 38
3.5 Cross Sectional Drawings 40
3.6 Three Dimensional Model 41
3.7 Structural Analysis & Design Conclusions 43
4 Alternative Building Materials & Maintenance 44
4.1 Typical Building Materials 44
4.1.1 Reinforced Concrete Properties 44
4.1.2 Properties of Steel 46
4.2 Recyclable Building Materials 47
4.2.1 Recycled Steel 47
4.3 Maintenance of Highway Bridges 51

4.3.1 How Corrosion Occurs ... 51
4.3.2 Impact of Corrosion ... 53
4.3.3 Protective Sealants ... 54
4.4 Non-Chemical Alternative Corrosion Protectants ... 56
4.4.1 Increased Concrete Cover Thickness ... 56
4.4.2 Cathodic Protection ... 57
4.4.3 Composite Materials ... 57
4.5 Summary ... 58
4.6 Results: The Implications of Recycling ... 58
4.6.1 Steel Selection ... 58
4.6.2 Concrete Mix Design ... 59
4.6.3 Supplier Selection Based on Location ... 61
4.6.4 Economic Benefits of Recycling ... 63
4.6.5 Waste Management Plan ... 64
4.7 Recycling Conclusion ... 66
4.8 Approach to Determining Corrosion Protection Methods ... 66
4.8.1 Establishing Environmental Conditions for New England ... 67
4.8.2 Determination of Rehabilitation Methods ... 68
4.8.3 Maintenance Strategies ... 70
4.8.4 Creation of Corrosion Protection Method Matrix for Existing Bridges ... 71
4.9 Maintenance Results ... 74
4.9.1 Alternatives for Protection of New Bridge Construction ... 74
4.9.2 Protection of an Existing Bridge ... 78
4.10 Determination of Protection System on Belmont Street/Route 9 Bridge ... 80
4.11 Recommendation for Reducing Corrosion ... 84

5 Stormwater Management 86
5.1 Purpose of Stormwater Management 86
5.1.1 Challenges in Stormwater Management 87
5.1.2 Stormwater Management Planning Standards 87
5.1.3 Worcester Stormwater Management System 88
5.1.4 Sustainable Stormwater Techniques 90
5.2 Forming a Stormwater Management Plan 93
5.2.1 Weather & Climate 93
5.2.2 Rooftop Rainwater Harvesting 93
5.2.3 Runoff Rainwater Harvesting 94
5.2.4 Fountains 94
5.3 Stormwater Management Plan Proposal 95
5.3.1 Weather & Climate 95
5.3.2 Rooftop Rainwater Collection 96
5.3.3 Runoff Rainwater Collection 97
5.3.4 Fountains 97
5.4 Recommendations for Further Improvement 98
6 Transportation & Urban Planning Development 100
6.1 Traffic Impact Study 100
6.1.1 TIAS Methods & Procedures 101
6.2 Work Zones 103
6.2.1 Work Zone Classifications 103
6.2.2 Work Zone Safety 104
6.3 Traffic Control Plan 105
6.3.1 Creating a Traffic Control Plan 105
6.3.2 Procedures & Devices 106

6.3.3 Effectiveness of Traffic Control Plan 109
6.4 Key Concepts 109
6.5 Belmont Street/Route 9 Bridge Traffic Control Plan 109
6.5.1 Considerations 110
6.5.2 Approach 110
6.5.3 Analysis 112
6.5.4 Recommendations 116
6.6 Cost Analysis 121
6.7 Conclusion 123
7 Sustainable Bridge Design 124
7.1 LEED Building Standards 125
7.2 Existing Sustainable Bridge Designs 125
7.2.1 Wind Turbine Powered Bridge in Oregon 125
7.2.2 Recycled Road Sub-base on Bridge in Maine 127
7.2.3 Reinforced Poly-Fiber Grid System in Wisconsin Bridge Deck 127
7.2.4 Eco-Friendly Bridge in Chicago, Illinois 128
7.3 Creation of Sustainable Bridge Design Guidelines in Bridge Construction 129
7.4 Sustainable Bridge Design Guideline Recommendation 131
7.4.1 Materials & Resources 131
7.4.2 Design Durability & Maintenance 132
7.4.3 Sustainable Site 133
7.4.4 Alternative Utilities 133
7.4.5 Reduction of Traffic Pollution 133
7.5 Sustainable Bridge Designs of the Future 134
7.5.1 Feasibility of Implementing Sustainable Bridge Designs 134

7.5.2 Costs Associated with the Implementation of Sustainable Bridge Designs 137
8 Life-Cycle Cost Analysis 138
8.1 Background 138
8.1.1 Construction Costs 138
8.1.2 Maintenance 140
8.2 Methodology 144
8.2.1 Construction Cost Estimate 144
8.2.2 Bridge Management System 148
8.3 Results 149
8.3.1 Construction Cost Estimate 149
8.3.2 Bridge Management System 152
8.4 Summary 157
9 Project Conclusions 159
10 Bibliography 163
13 Appendices 169
Appendix A: Project Proposal 170
Appendix B: MassHighway 2008 Structures Field Report 184
Appendix C: Concrete Deck Hand Calculations 194
Appendix D: Rolled Steel Girder Hand Calculations 198
Appendix E: Concrete Column Hand Calculations 202
Appendix F: RISA 2-D Outputs 204
Appendix G: Microsoft Excel Deck Design Template 218
Appendix H: Microsoft Excel Non-Composite Girder Design Template 220
Appendix I: Microsoft Excel Composite Girder Design Template 221
Appendix J: Microsoft Excel Concrete Column Design Template 224
Appendix K: Consigli Construction Waste Management Plan Template 225

Appendix L: Construction Cost Estimate 226
Determine Quantity of Items 226
Girder Cost Estimate 228
Final Construction Cost Estimate 231

List of Figures

Figure 1: Conceptual model of the key components of the project 4
Figure 2: The existing Belmont Street/Route 9 overpass 8
Figure 3: Excerpt of MassHighway Structures: Inspection Field Report 2008 10
Figure 4: Structural components on typical bridge site 14
Figure 5: Components of superstructure 14
Figure 6: Wearing surface on the Belmont Street/Route 9 highway overpass 15
Figure 7: Components of the substructure 16
Figure 8: Concrete pier on the Belmont Street/Route 9 Bridge 17
Figure 9: Example of the wingwall and backwall on Belmont Street/Route 9 Bridge 18
Figure 10: Vehicle live loading case 19
Figure 11: Wearing surface on Belmont Street/Route 9 Bridge 30
Figure 12: Direction of reinforcement bars in bridge deck 33
Figure 13: Bent girder from impact of collision 34
Figure 14: Extensive column corrosion on Belmont Street/Route 9 Bridge 39
Figure 15: Longitudinal cross section of proposed Belmont Street/Route 9 Bridge Re-Design .. 40
Figure 16: Transverse cross section of proposed Belmont Street/Route 9 Bridge Re-Design 41
Figure 17: Proposed concrete deck for Belmont Street/Route 9 Bridge Re-Design 41
Figure 18: Proposed concrete columns and steel girders for Belmont Street/Route 9 Bridge Re-Design (View 1) 42
Figure 19: Proposed concrete columns and steel girders for Belmont Street/Route 9 Bridge Re-Design (View 2) 42
Figure 20: Overall proposed bridge Re-Resign 43
Figure 21: Exposed steel rebar in reinforced concrete column 46
Figure 22: Map of where recycled base concrete aggregate is used 49
Figure 23: Graph showing increased strength of concrete as a function of fly ash 50
Figure 24: Diagram showing how corrosion occurs 52
Figure 25: Example of corrosion on steel lateral bracing of bridge superstructure 52
Figure 26: Heavily corroded reinforced concrete support on the Belmont Street/Route 9 Bridge53
Figure 27: Recommendations for environmentally friendly mix design 60
Figure 28: Green concrete mix designs 60

Figure 29: Environmental and compressive strength characteristics of concrete mixes 61
Figure 30: Map of Aggregate Industries Recycling Divisions 62
Figure 31: Cost savings due to source separation and recycling 63
Figure 32: Average snowfall in Worcester, MA based on 2007 readings 67
Figure 33: Scales to determine category rating... 73
Figure 34: Typical strength vs. water to cement ratio curve... 75
Figure 35: Photomicrograph of a galvanized steel coating cross-section..................................... 77
Figure 36: Model of Fiber Reinforced Polymer Bridge... 78
Figure 37: Cycles for Pervious and Impervious Surfaces.. 87
Figure 38: Combined Sewer System.. 89
Figure 39: Rooftop Rainwater Collection System 91
Figure 40: Runoff Rainwater Collection System... 92
Figure 41: Map of Area of Interest 96
Figure 42: Rooftop Rainwater Harvesting For Flushing Toilets 97
Figure 43: Fountain.. 98
Figure 44: Flowchart showing steps to determining the type of traffic study to be used........... 102
Figure 45: Traffic control plan checklist 106
Figure 46: Long-term stationary work zone 108
Figure 47: Emergency access.. 111
Figure 48: MassHighway standard detail 117
Figure 49: Allowed movements.. 118
Figure 50: Restricted movements 118
Figure 51: Detour 1... 119
Figure 52: Detour 2... 119
Figure 53: Project site layout 120
Figure 54: Belmont Street/Route 9 traffic control plan – Stage 1 121
Figure 55: New Interstate 5 bridge crossing over the Columbia River shows vertical wind turbines in blue.. 126
Figure 56: Flat Interstate 5 bridge design with wind turbine mounted along the bridge, similar to a sculpture design.. 126
Figure 57: Polymer grid system being laid into bridge deck by a crane.................................... 128

Figure 58: Arial model of proposed "Eco-Friendly" bridge on Chicago harbor 129
Figure 59: Preliminary sustainable bridge design point rating guidelines................................. 130
Figure 60: Pie Chart of Average Breakdown of Costs for Bridge Projects. 140
Figure 61: Road pollutants.. 142
Figure 62: Inspection costs 143
Figure 63: Summary of Maintenance Scenarios 143
Figure 64: Cost of girders based on weight 146
Figure 65: Bridge management system... 153
Figure 66: Maintenance operations.. 155
Figure 67: Effects of maintenance 156

List of Tables

Table 1: Rating guide 6
Table 2: Categories of deficiency 6
Table 3: Bridge deck properties 31
Table 4: Design load factors 31
Table 5: Moment values for positive and negative regions 32
Table 6: Bar size and spacing for positive and negative flexure regions 32
Table 7: Steel girder properties 35
Table 8: Girder design load cases 36
Table 9: Girder Summarized Results 37
Table 10: Evaluation of degrees of deterioration of bridge deck based on ASTM Standards 69
Table 11: Amount of area to be painted based on ASTM Standards 70
Table 12: Matrix for determining corrosion protectants on an existing bridge 71
Table 13: Emergency access criteria 113
Table 14: Flow of traffic criteria 113
Table 15: Safety criteria 113
Table 16: Efficiency criteria 113
Table 17: Alternative 1 – Bridge Closed 114
Table 18: Alternative 2 – One way, one lane 114
Table 19: Alternative 3 – One lane, alternating traffic 115
Table 20: Alternative 4 – Two lanes, one each way 115
Table 21: Summary of results 116
Table 22: Point rating system for bridge design 135
Table 23: Summary table of sustainable point totals 136
Table 24: Bridge Component Quantity Calculations 145
Table 25: Summary of girder costs 150
Table 26: Cost Estimate 151
Table 27: Application of NYSDOT flowchart 154

1 Introduction

In a time when issues such as sustainability and cost efficiency take uncompromising precedence in our society, the next generation of structural engineers must consider the life-cycle of the bridges, stadiums, office buildings, and residential houses they design. Since much of our surrounding environment is overcrowded and densely inhabited, fewer and fewer engineers are asked to build new, extravagant skyscrapers or wide sprawling apartment complexes in the middle of the city. Instead, more and more civil engineers are presented with rehabilitation projects that deal with the reconstruction of an existing bridge or the construction of a fully functioning day care center. These reconstruction projects are often complicated and generally require careful consideration of intricate restrictions of the urban environment. Incorporating concerns of sustainability and cost poses an even greater challenge in finding appropriate solutions to these limitations.

For building construction, the Leadership in Energy and Environmental Design (LEED) has been developed to encourage and accelerate global adoption of sustainable green design and building practices. The Green Building Rating System has been created to establish criteria that rates building designs on their performance and efficiency based on the use of more sustainable materials and construction methods. According to the U.S. Green Building Council, LEED promotes an environmentally responsible building approach, recognizing performance in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality. There are both environmental and financial benefits to earning LEED certification. LEED-certified buildings aim to "lower operating costs and increase asset value, reduce waste sent to landfills, conserve energy and water, create an atmosphere that is healthier and safer for occupants, reduce harmful greenhouse gas emissions, and qualify for tax rebates, zoning allowances and other incentives in hundreds of cities, and demonstrate an owner's commitment to environmental stewardship and social responsibility" (LEED Project Certification, 2008).

Although great strides have been made to increase the number of LEED-certified buildings designed, there is yet to be a breakthrough to create similar building standards in bridge engineering. A guideline to building "green" bridges can be established by evaluating the use of recycled materials and bridge component protectants to reduce maintenance, and the implementation of systems that benefit the local community. Chicago, IL has received recognition in taking initiative in being one of the first cities to design an Eco-Bridge. The semi-circular bridge design creates a harbor-side green space for inhabitants and wildlife. The design will include an area to provide residents and visitors with space for recreational activities like sailing and rowing (Steffen, 2008). The enclosed area will provide an environmentally safe shelter for fish and other marine wildlife. The design also includes the addition of wind turbines to create natural energy for the city. Chicago has taken the first steps toward creating a standard for "green" design in bridge construction similar to the LEED certification in building construction.

Designing bridges based on sustainability guidelines can reduce the overall cost of a project and reduce the amount of future maintenance. Investigating the use of recycled materials, like pre-existing concrete waste from another project, or the use of materials considered "waste" can have a positive environmental impact as well as a financial impact. In Maine, a bridge was re-designed using old, shredded tires and geotextiles on the roadbed and reusing existing bridge railings and guardrails from highway bridge reconstruction projects rather than building with brand new material. The use of the recycled material reduced an estimated $10 million project to only $1.3 million and created a use for the otherwise considered waste products (Recycled Rubber Raises the Road: Maine Bridge Rehabilitation, 2003).

Maintenance of a bridge can be greatly reduced by taking proper measures to protect the bridge components. In the past, sealants such as epoxy coated rebar have been used to reduce the amount of corrosion in the reinforced concrete, prolonging the lifespan of the structure. With the advanced technology and testing capabilities available today, methods to mitigate the electric current that flows through the steel reinforcements have been developed. These methods do not wear off like epoxies and continuously protect the rebar from fluids and chemicals which can seep into the concrete and corrode the steel. Although this process is generally more costly than typical sealants, a life-cycle cost analysis may suggest that it is worth using to defer high maintenance costs in the future by repairing individual components on an as-needed basis.

As sustainable design becomes more popular in new construction, bridges can serve more than the traditional purpose of transportation of people and vehicles. Innovative systems like rainwater collection and storage systems or wind turbines as previously mentioned in the Chicago Eco-Bridge design, provide ways to use natural materials to benefit the local community. Rainwater collection systems can store rainwater then transport the reusable water to local buildings, businesses, and hospitals. The addition of wind turbines on a bridge uses wind power to create and store energy. This can then be transferred to form a natural alternative that produces electric power. These systems are usually more costly but the long term benefits to the people of the surrounding areas outweigh the high initial costs.

As LEED certification in building construction is becoming the optimal design, the need for sustainable design in all types of civil engineering projects is more evident. Various experiments testing the capabilities of recycled materials in construction are continuously being conducted to attain more sustainable alternatives. Life-cycle cost comparisons of the different methods of maintenance reduction allow engineers to determine the cost effectiveness of traditional protectant sealants versus the implementation of protective systems. The overall goal of sustainable design is to decrease the carbon footprint by creating a structure from materials that have been or can be reused. Using effective methods to preserve the structure also reduces high maintenance costs to keep the bridge structurally stable. Sustainable design also allows the possibility of investigating and offering environmentally friendlier benefits to the community.

The aim of this project is to investigate the process of designing a typical highway overpass with sustainable construction alternatives, including the design of key components of the superstructure and substructure. Figure 1 shows the specific sustainable alternatives that will be implemented in the design to create a more sustainable and long-lasting structure. A specific bridge of interest is the Belmont Street/Route 9 Bridge, located in Worcester, Massachusetts, which will be used as the case study for the project.

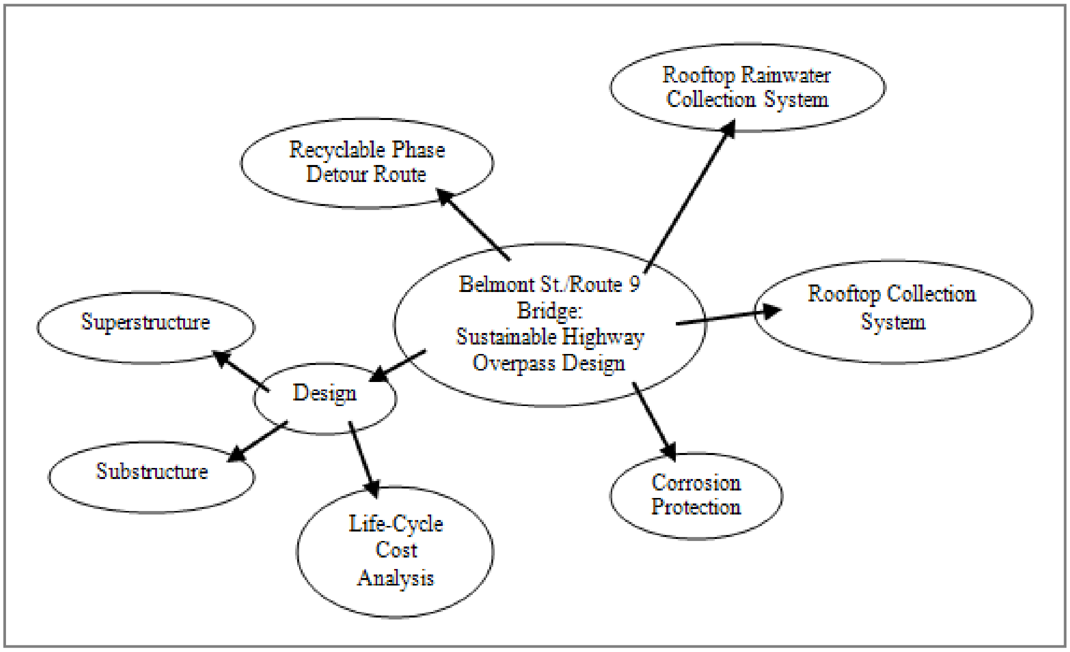


Figure 1: Conceptual model of the key components of the project

2 Bridge Design

This section provides background information on the topics relating to bridges in general, but more specifically to the Belmont Street/Route 9 Bridge. The chapter gives insight into what factors constitute a bridge as structurally deficient as well as discusses the role of the Massachusetts Highway Department in bridge projects. Combined, these topics provide all significant information necessary for the execution of project.

Furthermore, alternatives to create a more sustainable design will be researched to determine the feasibility of implementing them into the construction of a typical highway overpass. The use of recycled materials during construction, different methods of maintenance, the addition of a rainwater harvesting storage system, and alternative traffic routes during construction will be investigated. Arguments that determine the effects of each of these areas of interest on the overall goal of making the bridge more sustainable will conclude the report.

2.1 Massachusetts Highway Department Bridge Projects

The Massachusetts Highway Department is responsible for the design and maintenance of bridges throughout the Commonwealth. The spectrum of bridges includes 2,900 owned by MassHighway, and 1,500 municipally owned bridges. In order to ensure efficient operations, MassHighway has divided the state into five districts. Each district is responsible for projects which fall within the respective region. The main office is located in Boston, MA which is designated as district one (MassHighway, 2006).

2.1.1 Bridge Inspection Unit

MassHighway has an internal division known as the Bridge Inspection Unit which concentrates on safety inspections and load ratings of bridges. Bridge inspection is part of maintenance and has impact on repair, rehabilitation, and new bridge construction. This unit is presided over by a District Bridge Inspection Engineer who works directly with Boston Headquarters personnel to obtain information about bridges of interest. The unit assesses the condition of existing bridges and formulates Structure Inspection Field Reports for each bridge.

In this report, components of the deck, superstructure, and substructure are scored according to a Condition Rating Guide. Rating is based on scale of 0-9 with “0” meaning the component has failed and "9" meaning the component is in excellent condition. In addition to the condition ratings, levels of deficiency are evaluated for each component. The rating criteria can be referenced in Table 1 & Table 2.

Table 1: Rating guide (taken from MassHighway Structures Inspection Field Report 2008)

N	Not Applicable	
9	Excellent	Excellent condition.
8	Very Good	No problem noted.
7	Good	Some minor problems.
6	Satisfactory	Structural elements show some minor deterioration.
5	Fair	All primary structural elements show some minor deterioration.
4	Poor	Advance section loss, deterioration, spalling or scour.
3	Serious	Loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical	Advance deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"Imminent" Failure	Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put it back in light service.
0	Failed	Out of service- beyond corrective action.

Table 2: Categories of deficiency (taken from MassHighway Structures Inspection Field Report 2008)

Deficiency: A defect in a structure that requires corrective action.		
M	Minor Deficiency	Deficiencies which are minor in nature generally do not impact the structural integrity of the bridge and could easily be repaired.
S	Severe/Major Deficiency	Deficiencies which are more extensive in nature and need more planning and effort to repair.
C-S	Critical Structural Deficiency	A deficiency in a structural element of a bridge that poses an extreme unsafe condition due to the failure of the element which will affect the structural integrity of the bridge.
C-H	Critical Hazard Deficiency	A deficiency in a component or element of a bridge that poses an extreme hazard or unsafe condition to the public, but does not impair the structural integrity of the bridge.
Urgency of Repair		
I	Immediate	Inspectors immediately contact DBIE to report the deficiency and to receive further instruction from him/her
A	ASAP	Action/repair should be initiated by District Maintenance Engineer upon receipt of the inspection report.
P	Prioritize	Shall be prioritized by District Maintenance Engineer and repairs made when fund and/or manpower is available.

2.1.2 Bridge Project Development Team

Once the inspection report is complete, the Bridge Project Development team reviews the essential information. The Bridge Project Development team is mainly responsible "for providing a comprehensive and systematic review of the condition of MassHighway and municipally owned bridges, determining the type of work that is required for each, prioritizing the work and then preparing bridge project scopes of work" (MassHighway, 2006). As far as determining scope of work, the Bridge Project Development Unit first begins by classifying projects as necessitating full replacement, rehabilitation, or preservation. Priority is based on condition of bridges and proposed cost of project.

2.1.3 In-House Bridge Design Unit

The next action is to prepare a design for the specific project. MassHighway has an internal division known as the In-House Bridge Design Unit which is in charge of preparing load ratings, structural calculations, and bridge plans. This group works from the inspection report as input to the calculations for existing bridges. Engineers in this unit are also in charge of revising MassHighway's Bridge Manual and Standard Specifications for Highways and Bridges. They are currently in the process of converting from Allowable Stress Design (ASD) to the *American Association of State Highway and Transportation Officials* (AASHTO) Load and Resistance Factor (LRFD) Bridge Design Specification (MassHighway, 2006).

2.2 Case Study – Belmont Street/Route 9 Bridge

In the state of Massachusetts alone, there are currently 588 bridges considered to be structurally deficient. This factor represents approximately ten percent of the traveled bridges in the entire state (100 Busiest Structurally Deficient Bridges). Bridges deemed structurally deficient are of high priority for maintenance. A local overpass of specific concern, shown in Figure 2, is the Belmont Street/Route 9 Bridge (W-44-094) which spans over Interstate-290 located in Worcester, Massachusetts. MassHighway plans to reconstruct the bridge in the year 2011.

Figure 2: The existing Belmont Street/Route 9 overpass

The Belmont Street/Route 9 Bridge was constructed in 1958 and slightly modified in 1990. From the figure above, it can be viewed that the bridge is a simply-supported two-span structure with steel stringers and a concrete deck. The interior pier and abutments are also made of concrete and the wingwalls of the abutments are cantilever type. There are two spans extending 64'-0 ¼" and 66'-0 ¾". Each span is supported by 8 stringers spaced 8'-0" on center. The bridge is well-traveled since it is a connection to Interstate I-290 as well as the fact that UMass Medical Center is positioned on the easterly side of the bridge. It consists of four lanes of traffic along with 6' sidewalks for pedestrian travel. It is responsible for transmitting an average daily traffic count of 31,000 vehicles which makes it one of the busiest bridges in Massachusetts. The bridge also has minimal clearance over Interstate I-290 and is posted for load restrictions of 20, 25, and 40 ton vehicles (MassHighway, 2006).

2.2.1 Recorded Bridge Accidents

On December 8, 1987 an over height truck travelling on Route I-290 crashed into the Belmont Street/Route 9 Bridge. The vehicle struck the superstructure on the easterly span of the bridge. Then again on August 18, 1994, a truck exceeding height requirements crashed into the bridge stringers. After the second collision MassHighway conducted an Accident Inspection Report in 1994. It stated that the bridge superstructure was "generally in good condition with the exception of three stringers and related diaphragms that suffered collision damage." It recommended that "the girders be examined more closely to determine if straightening the flange displacements is possible. In addition the damaged diaphragms should be repaired/replaced" (MassHighway, 2006). All of the recommendations were taken into account, but since the bridge was still serviceable at the time, it was decided that the entire bridge would be reconstructed when there were signs that the conditions were worsening.

2.2.2 Deficiency of Bridge Structure

The Federal Highway Association mandates that bridges graded below 50% sufficiency need to be replaced. Ratings are determined by a formula which takes into account "structural adequacy and safety, serviceability, and how important the bridge is to a smooth flow of traffic" (100 Busiest Structurally Deficient Bridges). Regarding the Belmont Street/Route 9, the AASHTO rating of sufficiency is 35%. MassHighway has placed the bridge on a five year replacement program plan and the bridge is inspected routinely.

Factors such as the age of the bridge, high traffic volume, and the effects of the collisions, greatly contribute to the present deficient rating. As stated in the Bridge Inspections Unit Section, Engineers at MassHighway score components of the deck, superstructure, and substructure from 0-9, as well as note the levels of deficiency and urgency of repair. If one of the sections averages to a four or less, the bridge is considered as structurally deficient. The reason why the Belmont Street/Route 9 Bridge is categorized as structurally deficient is because the superstructure is rated as condition 4. Also, the deck and substructure of the bridge are rated 5 according to the most recent *Structures Inspection Field Report* conducted June 26, 2008. An excerpt of the 2008 *Structures Inspection Field Report* is located in Figure 3 (the complete report can be found in Appendix B).

ITEM 58 DECK	5	DEF
1. Wearing Surface	5	S-P
2. Deck Condition	5	S-P
3. Stay in place forms	N	-
4. Curbs	6	M-P
5. Median	N	-
6. Sidewalks	5	S-A
7. Parapets	6	M-P
8. Railing	6	S-P
9. Anti Missile Fence	7	-
10. Drainage System	N	-
11. Lighting Standards	N	-
12. Utilities	6	M-P
13. Deck Joints	4	S-A
14.	N	-
15.	N	-
16.	N	-

ITEM 59 SUPERSTRUCTURE		4	DEF
1. Stringers		4	S-P
2. Floorbeams		N	-
3. Floor System Bracing		N	-
4. Girders or Beams		N	-
5. Trusses - General		N	-
a. Upper Chords	N		-
b. Lower Chords	N		-
c. Web Members	N		-
d. Lateral Bracing	N		-
e. Sway Bracings	N		-
f. Portals	N		-
g. End Posts	N		-
6. Pin & Hangers		N	-
7. Conn Plt's, Gussets & Angles		4	S-P
8. Cover Plates		5	S-P
9. Bearing Devices		5	S-P
10. Diaphragms/Cross Frames		4	S-P
11. Rivets & Bolts		5	S-P
12. Welds		5	S-P
13. Member Alignment		4	S-P
14. Paint/Coating		4	S-P
15.		N	-

ITEM 60 SUBSTRUCTURE			5	DEF
1. Abutments	Dive	Cur	5	
a. Pedestals	N	N		-
b. Bridge Seats	N	5		M-P
c. Backwalls	N	4		S-P
d. Breastwalls	N	6		M-P
e. Wingwalls	N	6		M-P
f. Slope Paving/Rip-Rap	N	N		-
g. Pointing	N	N		-
h. Footings	N	H		-
i. Piles	N	N		-
j. Scour	N	N		-
k. Settlement	N	6		-
l.	N	N		-
m.	N	N		-
2. Piers or Bents			5	
a. Pedestals	N	N		-
b. Caps	N	5		S-P
c. Columns	N	5		S-P
d. Stems/Webs/Pierwalls	N	N		-
e. Pointing	N	N		-
f. Footing	N	H		-
g. Piles	N	N		-
h. Scour	N	N		-
i. Settlement	N	7		-
j.	N	N		-
k.	N	N		-
3. Pile Bents			N	
a. Pile Caps	N	N		-
b. Piles	N	N		-
c. Diagonal Bracing	N	N		-
d. Horizontal Bracing	N	N		-
e. Fasteners	N	N		-

Figure 3: Excerpt of MassHighway Structures: Inspection Field Report 2008

2.2.3 Re-Design of Bridge

The re-design of the bridge is supported by the Central Massachusetts Metropolitan Planning Organization (CMMPO) and funded through the 2010 Transportation Improvement Program. Since the bridge is designated as structurally deficient, federal funding constitutes 80% and state funding 20% of the project cost. The estimated cost of construction is $6,627,470.00. In respect to the general contractor of the project, MassHighway will compile a list of interested bidders and the project will be awarded to the lowest qualified bidder (MassHighway, 2006).

2.3 Sustainable Design

As the emphasis on sustainable design in building is becoming more prevalent, different approaches to building a more sustainable bridge are being investigated. Transitions have been made from using new building materials such as reinforced concrete and steel to using waste reinforced concrete and steel products from previous existing structures. Because of the importance of maintaining structures based on financial costs, engineers have begun to experiment with the use of protective systems rather than sealants or coatings. Part of a sustainable design includes implementing a system or process that can be beneficial to the surrounding environment and inhabitants. During the construction of a new design, detouring traffic routes can create problems in developed urban areas. Alternative traffic patterns can be determined to minimize the inconvenience to drivers but still ensure a safe traveling path through the community. Factors such as these can improve the conditions of the actual structure and the area that surrounds it.

2.3.1 Alternative Building Materials & Maintenance

The transition from utilizing traditional building materials to recycled materials is a major component of sustainable design. Recycling is a practice which is not only environmentally friendly, but cost effective. During demolition of old structures, materials generally constituted as waste can be salvaged to make brand new products. The most commonly recycled materials in bridge projects are steel and recycled concrete aggregates which are used to make steel girders and concrete decks or piers. Overall, the implementation of recycled products is very beneficial due to the fact recycling contributes to less waste transported to landfills, decreased pollution emissions, and reduced energy consumption.

Routine maintenance of a bridge prolongs the lifespan of the structure. When designing a bridge engineers take certain measures to create a design that will be durable and involve a minimal amount of maintenance. Epoxy coated rebar is often used because to protect steel reinforcement because it is very economical. The coating on the rebar protects the steel from fluids and chemicals that seep into the concrete and contribute to the corrosion of the steel. Engineers conduct continuous experiments with other methods of protection to find more effective processes. An example of a newly popular method is Cathodic protection. This involves a system that can be implemented in a bridge design to control and slow down the electric current that causes corrosion. Although this is a costly method, case studies in various locations around the world have been done to determine if the effectiveness of the system is worth the increased cost. In many cases, new innovative systems and techniques have proven to be more effective in increasing the service life of the structure. The goal of many scientists and engineers has been to create an economical system which will also minimize the rate of corrosion throughout the structure reinforcement. If a better system can be found, the time span of required will decrease which reduces the cost of continuous maintenance and repair.

2.3.2 Stormwater Management

Another key element in developing a sustainable bridge design is to assess the surrounding area and its impact. Contributing factors such as excess runoff from the surrounding area can cause severe corrosion problems and can accelerate the deterioration of a bridge. Simply controlling the runoff water and limiting the amount of moisture that causes corrosion can prolong the life-cycle of the bridge. Careful consideration of state standards and assessment of the current stormwater management system is necessary in order to determine the parameters and constraints of the region. Detailed research of innovative stormwater management practices is also important so that the most practicable, sustainable solution or alternative is selected for the area.

2.3.3 Transportation & Urban Planning Development

An important factor to the design and construction of any major project involves the evaluation of the surrounding area. Prominent regions of concern include the location of the project, who the project will affect, and the constraints of the project. In bridge design especially, one of the most important influences during construction is the surrounding traffic. For instance, in heavily populated areas, professionals need to consider re-routing traffic prior to construction so that the surrounding area can still function at a normal rate. Thus, the project team will identify the different services that are available along with any procedures or methods to conduct traffic studies and evaluate the traffic flows over major bridges. More specifically, the project team will develop a traffic control plan that could be implemented during the construction phase of the Belmont Street/Route 9 Bridge in Worcester, Massachusetts.

When evaluating the area of interest, the following will be considered to determine the most effective alternative construction route:

- Research similar detour projects
- Obtain traffic count based on area of interest
- Gain understanding of site surrounding area; major routes, residential areas, businesses, emergency access routes, and intersections
- Determine constraints and parameters
- Propose detour solution during construction with the aid of AutoCAD and GIS
- Compare solution with MassHighway’s suggestions

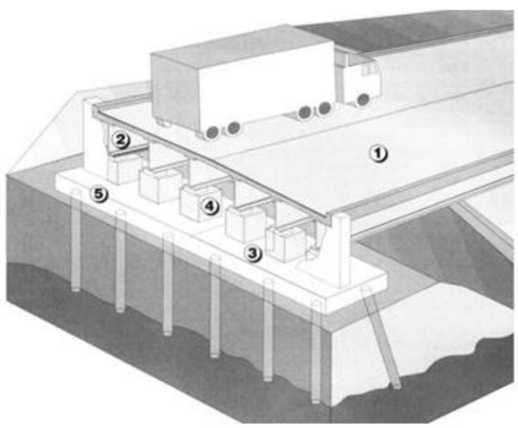
The proposed traffic route will consider both constructability and safety. One factor of the constructability of the project relies upon the location of interest and the traffic flowing through the construction site. Since the area surrounding the Belmont Street/Route 9 Bridge is heavily traveled, traffic routes must be altered to ease the constructability of the project. Also, providing awareness of the new traffic patterns during building is essential to ensure the safety and health of both the members of the community and the workers involved in the construction.

2.4 Bridge Design Conclusion

The contents of this project focus specifically on the Belmont Street/Route 9 Bridge. Since this bridge is located in the commonwealth of Massachusetts, MassHighway is responsible for both the re-design and maintenance. Part of their role is to perform routine safety inspections to rate the components of the structure. This is often completed by an internal division known as the Bridge Inspection Unit. A safety inspection report included in this project illustrates that the Belmont Street/Route 9 Bridge is deemed structurally deficient, meaning it is a high priority for maintenance. Thus, given the need for re-design, the main objective of this report is to achieve a sustainable design that addresses alternative building materials and maintenance; stormwater management; and transportation and urban planning development. These factors, along with the investigation of the design components, will be factored in to the design recommendations.

3 Structural Analysis & Design

When designing a bridge, engineers need to account for all aspects of the preliminary design phase so when they reach the construction stage, each element is considered. For a highway overpass the first step is to layout the site by surveying and mapping the land. Highway design, structural design, geotechnical engineering and hydraulic engineering should all be taken into consideration during the design process. Structural engineers, however, are only responsible for the design of highway overpass bridges. The bridges are broken up into two different sections: the superstructure and the substructure. Figure 4**Error! Reference source not found.** shows typical bridge site labeled with some of the key components of the bridge. The primary goal of the engineer when designing the bridge is to build the safest bridge. Engineers attempt to select the most economical building materials and effective component designs that suit the location of the bridge construction.



No.	Component
1	Wearing Surface & Deck
2	Girder
3	Bearing
4	Pedestal
5	Footing

Figure 4: Structural components on typical bridge site (taken from Bridge Engineering, 2007)

3.1 Superstructure Design

The superstructure consists of all bridge components located above the supports. From top to bottom, this includes the wearing surface, deck, primary members and secondary members as shown in Figure 5.

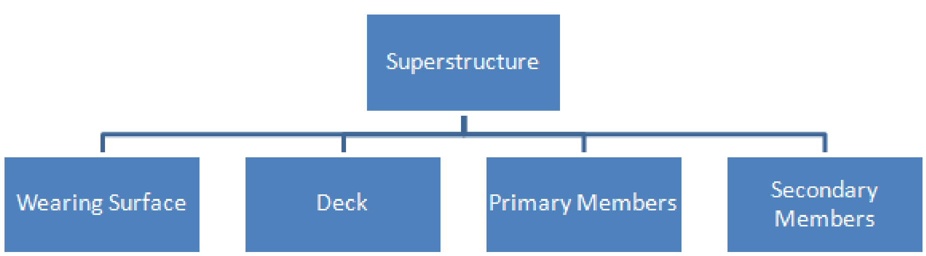


Figure 5: Components of superstructure

3.1.1 Wearing Surface

The wearing surface of the superstructure is the top layer of the road which usually consists of a pavement layer. This surface must be strong enough to withstand the load of traveling cars and trucks. As the life-cycle of a bridge increases, the roadway is reinforced to account for excessive wearing. This layer of the deck is typically 2 to 4 inches thick in the original design but increases as reinforcements are added. Figure 6 shows the wearing surface on the current Belmont Street/Route 9 Bridge.

Figure 6: Wearing surface on the Belmont Street/Route 9 highway overpass

3.1.2 Deck

The main function of the deck is to distribute the loads on the bridge from corner to corner. The deck can be described as an extension of the road across the bridged area. It can rest on or be integrated in the frame, which is designed to help distribute the loads in the longitudinal direction. Often the deck is made of a concrete slab.

3.1.3 Primary Members

Primary members are the girders or stringers that run along the longitudinal span of the bridge. They are the main reinforcement in preventing the structure from bending. In bridge design, girders are typically made from steel or prestressed concrete. For steel bridges, wide flanges like I-beam type girders are most commonly used. There are other possible shapes for girders including the rectangular or trapezoidal box girder design which are most effective on long span lengths.

3.1.4 Secondary Members

The last component of the superstructure is the secondary members. The secondary members provide the lateral bracing between the primary members. The secondary members are important in the superstructure design because they help resist the deformation of the cross section. They also help distribute the loads between the girders.

3.2 Substructure Design

Elements of the substructure include the abutments, piers, bearings, pedestals, backwall, wingwall, footing, and piles. The substructure consists of bridge components as shown in Figure 7 which act together to support the superstructure. The substructure acts as the foundation to the structure.

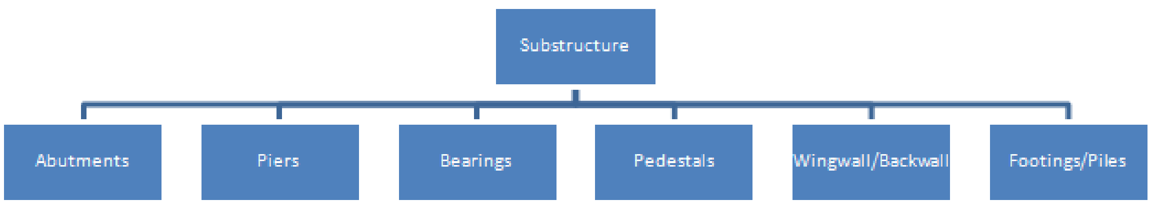


Figure 7: Components of the substructure

3.2.1 Abutments

Abutments are the walls on the sides of the bridge that support the overlaying roadway and bridge structure. The walls are critical because they resist the forces of the earth from caving in under the overpass. Depending on the function and location of the bridge, there are many different types of abutments that can be considered for bridge designs. Abutments are generally made of reinforced concrete.

3.2.2 Piers

Piers are the structures that hold the bridge up at intermediate points along the span between the abutments like the example shown in Figure 8. As the span of the bridge increases, so does the need to include more piers for support in the design. When the design is only one span, a pier is not needed for extra support. Similar to abutments, there are many different types of piers to choose from when designing a bridge. The typical building material used in piers design is reinforced concrete.

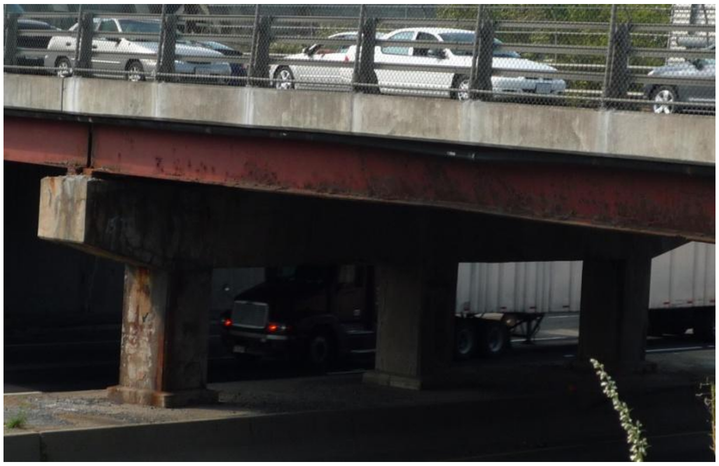


Figure 8: Concrete pier on the Belmont Street/Route 9 Bridge

3.2.3 Bearings

Bearings act as structural devices that are located between the superstructure and substructure. They function as the component of the bridge that transmits loads between the superstructure and substructure and accommodates any movements between the superstructure and substructure. When designing the bearings of the bridge, the engineer must consider all the loads applied from the weight of superstructure, the traffic that travels across the bridge, and any relevant wind or earthquake loads. A range of movement due to extreme thermal effects must also be considered during the design.

3.2.4 Pedestals

The pedestal is the short column located on the abutment of pier that directly supports a primary member of the superstructure. The bearing sits on top of the pedestal which is located on the footing of the bridge.

3.2.5 Wingwall & Backwall

The backwall is the stem of a cantilever retaining wall henceforth the alternative name, stem. It is the primary component in retaining abutments. The wingwall is the extension of the abutment backwall to the sides of the bridge. Its purpose is to retain and laterally support the earth located behind the abutment. An example of wingwall and backwall components is shown in Figure 9.

Figure 9: Example of the wingwall and backwall on Belmont Street/Route 9 Bridge

3.2.6 Foundation

The function of the footing of the bridge is to transfer the loads from the substructure to the subsoil. Piles are extensions from the footing into the ground. The existing soil at a construction site must be tested to ensure it is capable of providing enough support for the structure.

3.3 Design Methodology

After consulting the bridge inspection report provided by MassHighway for the Belmont Street/Route 9 Bridge, the concrete deck, steel girders, and concrete columns were deemed insufficient. The process for re-designing these components to meet capacity is addressed in the following section. The role of the structural design computer program RISA 2-D, as well as the use of spreadsheets proved to be an essential part of the process for determining axial loads, moment and critical design parameters for design. Flowcharts outlining the procedure to determine sizes and spacing for each of the three designed components are provided below. Lastly, the procedure for creating the cross sectional drawings and three dimensional model is presented.

3.3.1 MassHighway Visit

Initially, the project team planned a meeting at MassHighway District 3 with a representative from the Bridge Department. Besides researching the Belmont Street/Route 9 Bridge, the project team also established important contacts, in case interviews, questions, or requests for further information or assistance were necessary later on in the project. MassHighway provided inspection reports, specifications, and portions of the initial design process. The inspection reports from both 2007 and 2008 ranked the bridge components, showing the degree of sufficiency for all aspects of each component. Based on this report, the project team found the concrete deck, steel girders and concrete columns to be deficient. Therefore, it was determined the re-design would focus mainly on these three key components.

3.3.2 Standards

All calculations, assumptions, and tabulated values were taken from the *AISC Steel Manual*, *MassHighway Specifications*, and *ASSHTO Specifications* to meet Massachusetts design parameters. Throughout the design process, references to these specifications are noted as necessary. To explain the use of particular values, it may be necessary to consult the actual specifications to detailed information.

3.3.3 RISA 2-D

The first step to designing the bridge components was to learn and utilize the structural design computer program RISA. This program was used to evaluate the moment for the continuous concrete deck and single span steel girder designs. As necessary, the dead load on the girders differed from the dead load on the concrete deck and was altered accordingly. For the girder design several load cases were superimposed in RISA to reflect the worst case scenario, creating a moment appropriate for design. The following load case shown in Figure 10 provides the maximum moment subjected on the girder which includes a concentrated live load and uniform live load.

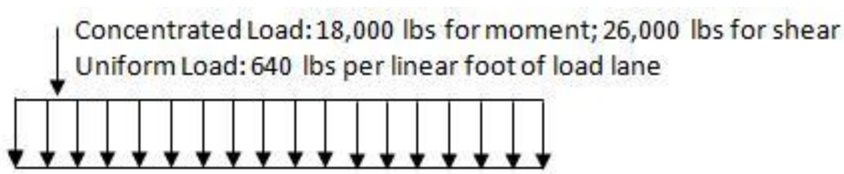


Figure 10: Vehicle live loading case

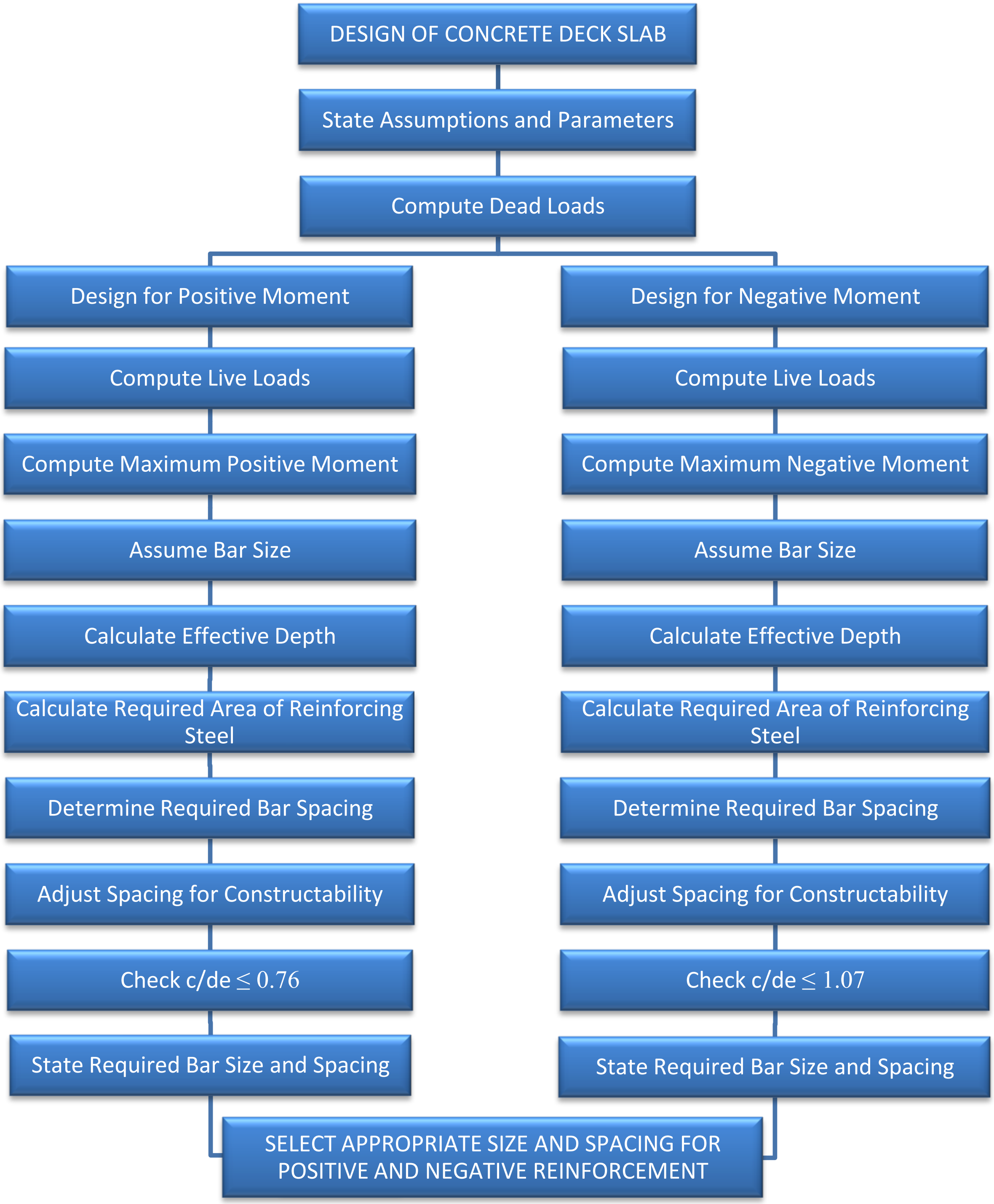
To view the shear and moment diagrams associated with the design of the concrete deck and the girders generated by RISA, refer to Appendix F.

3.3.4 Calculations

Continuing with the design process, flowcharts were developed outlining the overall process for calculating sizes, spacing, and reinforcement for all designed components. The calculations were conducted based on LRFD and all necessary procedures may be found in sample hand calculations for the deck design, girder design and column design are provided in Appendix C, Appendix D and Appendix E, respectively. However, in order to determine the most appropriate solutions, Microsoft Excel sheets were developed, such that varying parameters such as the spacing and rebar size could be varied and later investigated.

3.3.4.1 Concrete Deck Slab

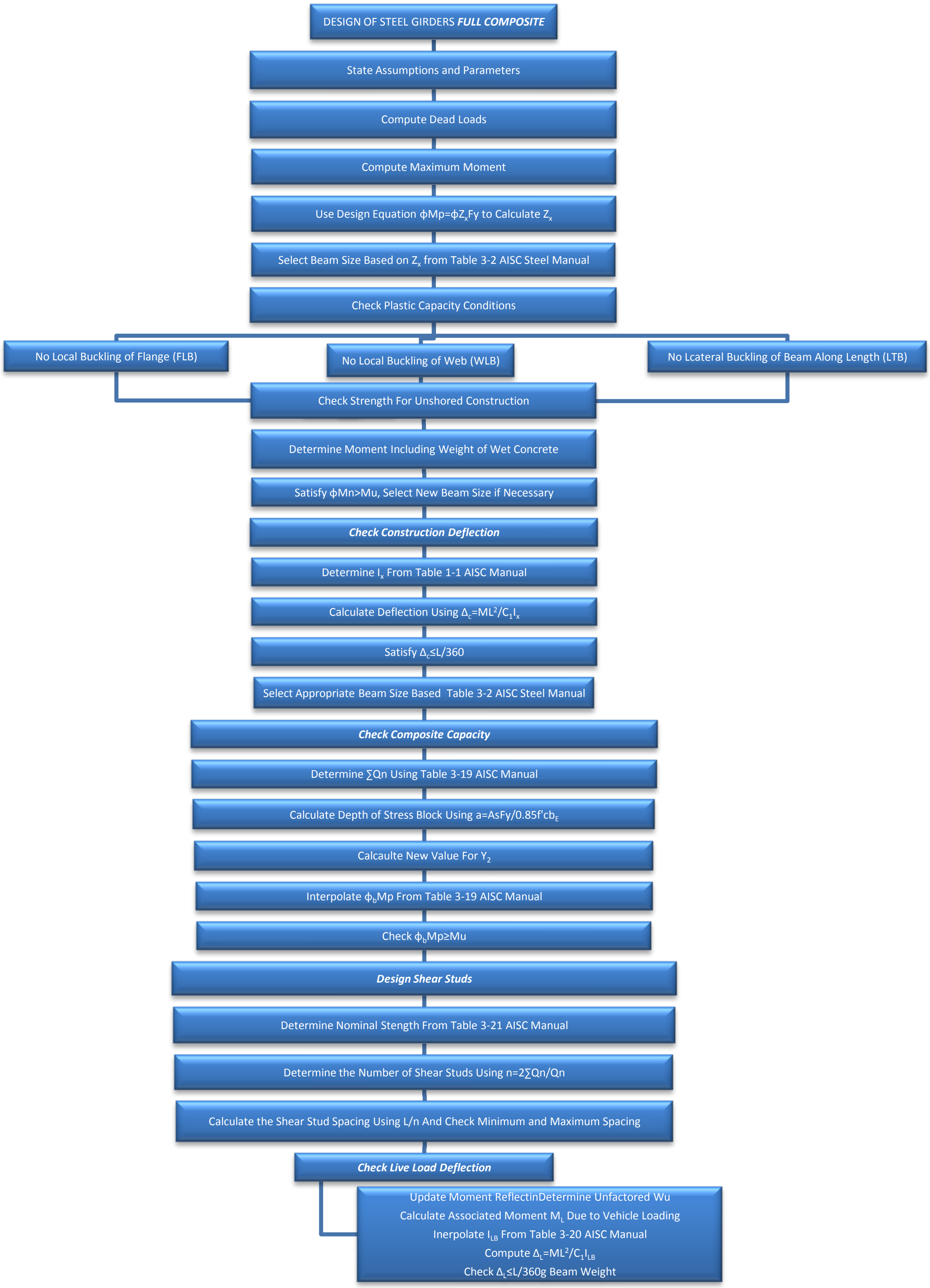
The following flowchart was used to design the concrete deck slab and sample step-by-step hand calculations are attached to the end of the report in Appendix C. The sample calculation design for an 8-inch continuous slab spans over two single span girders and considers the required moment capacities obtained from *AASHTO Specifications* STable A4.1-1 indicated in Appendix C. As mentioned, Excel sheets were created for the deck slab so that changes to the spacing and size of the rebar could be investigated to determine the most appropriate concrete deck slab design. Below, outlines the limit states and general procedure for designing the continuous concrete slab.

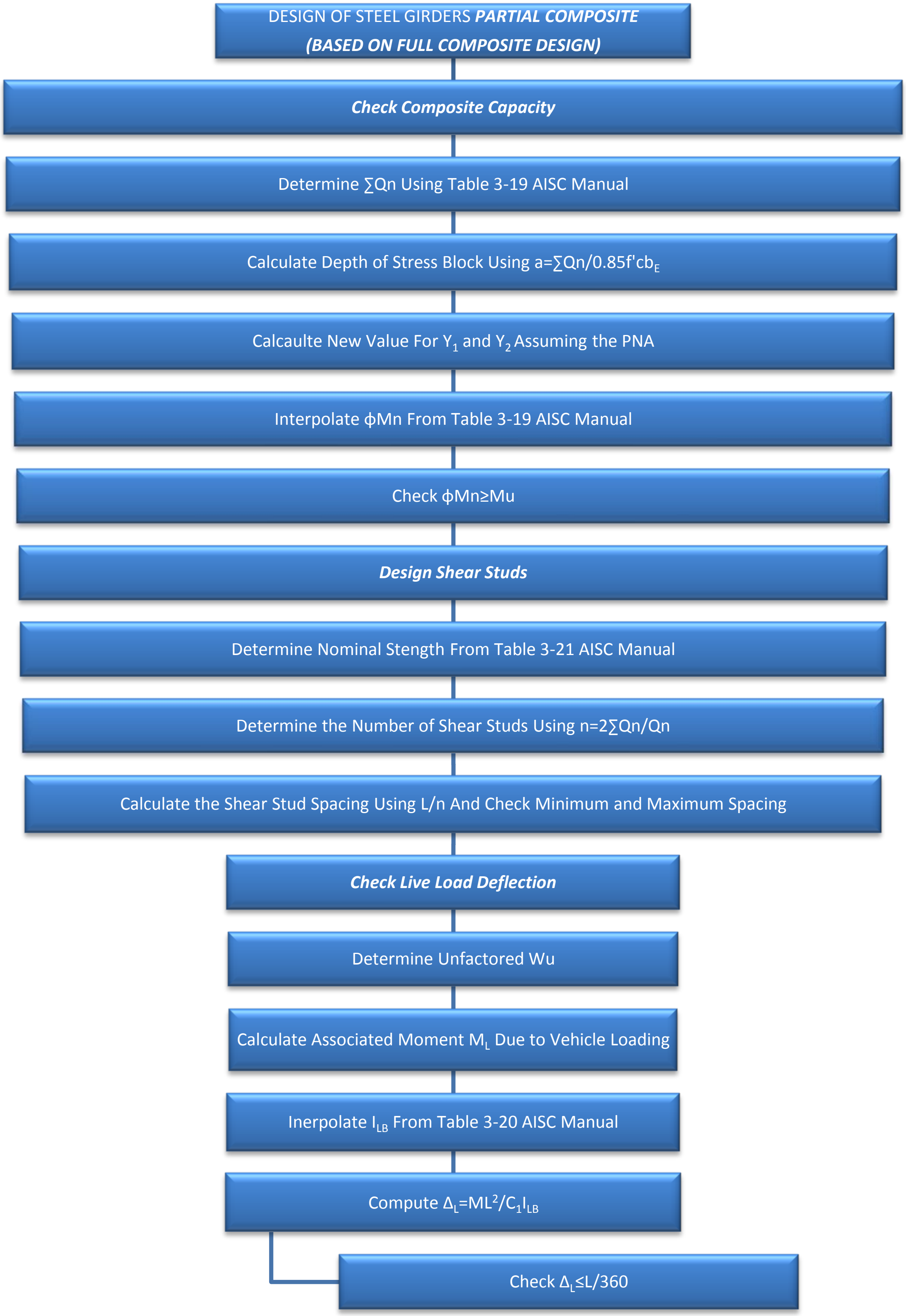

DESIGN OF CONCRETE DECK SLAB
State Assumptions and Parameters
Compute Dead Loads
Design for Positive Moment
Compute Live Loads
Compute Maximum Positive Moment
Assume Bar Size
Calculate Effective Depth
Calculate Required Area of Reinforcing Steel
Determine Required Bar Spacing
Adjust Spacing for Constructability
Check c/de ≤ 0.76
State Required Bar Size and Spacing
Design for Negative Moment
Compute Live Loads
Compute Maximum Negative Moment
Assume Bar Size
Calculate Effective Depth
Calculate Required Area of Reinforcing Steel
Determine Required Bar Spacing
Adjust Spacing for Constructability
Check c/de ≤ 1.07
State Required Bar Size and Spacing
SELECT APPROPRIATE SIZE AND SPACING FOR POSITIVE AND NEGATIVE REINFORCEMENT

3.3.4.2 Girders

The following flowcharts were used to calculate a series of two single span steel girder designs using non-composite, full composite, and partial composite design approaches. It is important to note that the flowcharts may be used only if the beam is compact without local buckling in the flange and web or lateral buckling along the beam's length. In the case that the beam is deemed non-compact, then further investigation of the governing criteria is necessary. Since all investigated sections were compact these flowcharts do not consider non-compact design. Complete sample hand calculations, assuming 8 girders spaced at 8 feet for non-composite, full composite and partial composite designs may be viewed in Appendix D. From completing previous projects, partial composite design was found to be the most cost effective approach for girder design, however, for verification, all designs were explored to ensure that partial composite was in fact the most adequate design. In order to investigate varying girder spacing, and therefore girder sizing, similar spreadsheets were developed using Microsoft Excel containing all the equations used in the hand calculations. From these spreadsheets, the most appropriate size girder was selected based on the smallest weight section.

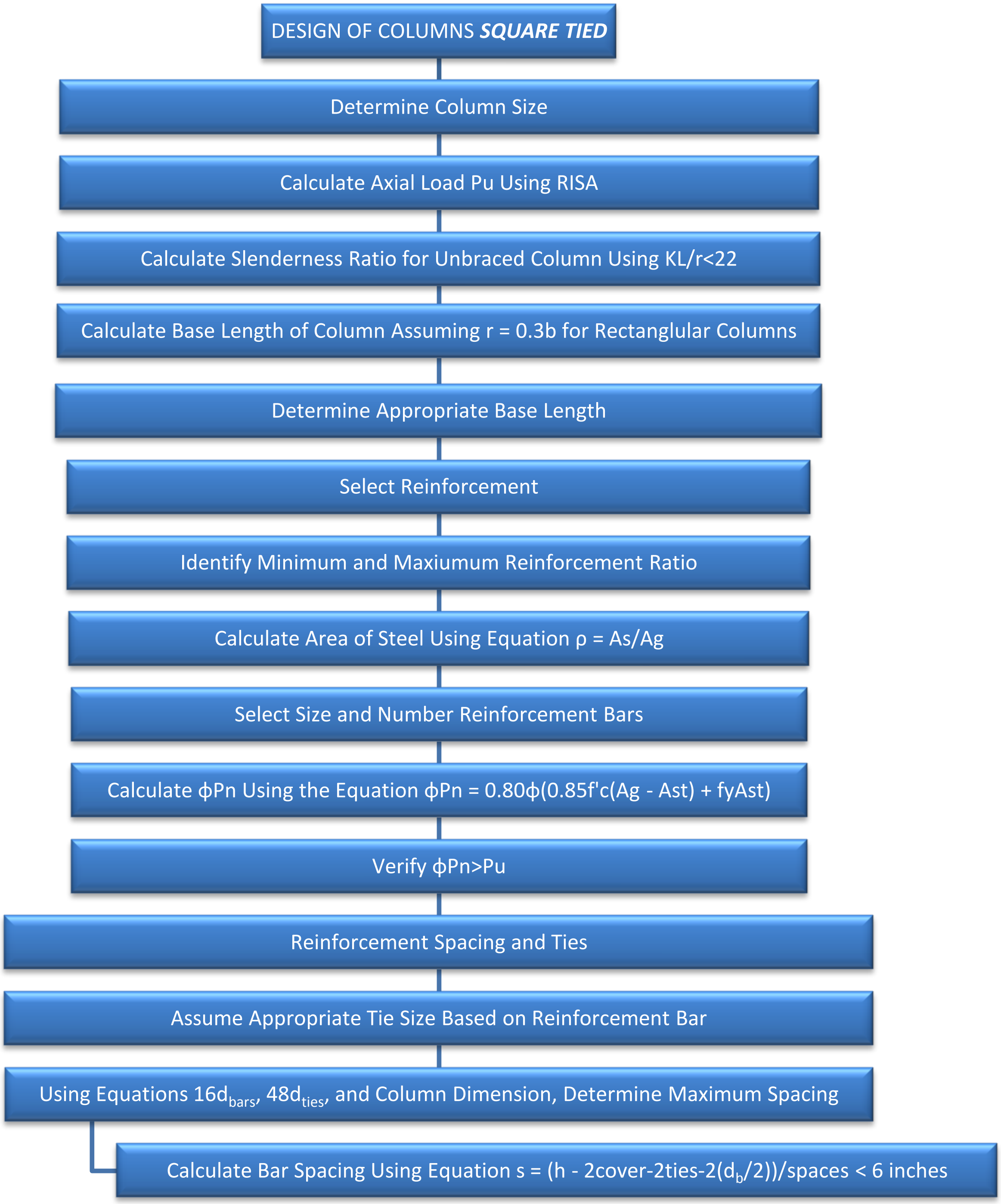

DESIGN OF STEEL GIRDERS ***NON-COMPOSITE***
State Assumptions and Parameters
Compute Dead Loads
Compute Maximum Moment
Use Design Equation $\phi Mp=\phi Z_x Fy$ to Calculate Z_x
Select Beam Size Based on Z_x from Table 3-2 AISC Steel Manual
Update Moment Reflecting Beam Weight
Satisfy $\phi Mp > Mu$
Check Plastic Capacity Conditions
No Local Buckling of Flange (FLB)
No Local Buckling of Web (WLB)
No Lcateral Buckling of Beam Along Length (LTB)


DESIGN OF STEEL GIRDERS ***FULL COMPOSITE***
State Assumptions and Parameters
Compute Dead Loads
Compute Maximum Moment
Use Design Equation ϕMp=ϕZ_xFy to Calculate Z_x
Select Beam Size Based on Z_x from Table 3-2 AISC Steel Manual
Check Plastic Capacity Conditions
No Local Buckling of Flange (FLB)
No Local Buckling of Web (WLB)
No Lcateral Buckling of Beam Along Length (LTB)
Check Strength For Unshored Construction
Determine Moment Including Weight of Wet Concrete
Satisfy ϕMn>Mu, Select New Beam Size if Necessary
Check Construction Deflection
Determine I_x From Table 1-1 AISC Manual
Calculate Deflection Using $\Delta_c=ML^2/C_1I_x$
Satisfy $\Delta_c \leq L/360$
Select Appropriate Beam Size Based Table 3-2 AISC Steel Manual
Check Composite Capacity
Determine ∑Qn Using Table 3-19 AISC Manual
Calculate Depth of Stress Block Using a=AsFy/0.85f'cb_E
Calcaulte New Value For Y_2
Interpolate ϕ_bMp From Table 3-19 AISC Manual
Check ϕ_bMp≥Mu
Design Shear Studs
Determine Nominal Stength From Table 3-21 AISC Manual
Determine the Number of Shear Studs Using n=2∑Qn/Qn
Calculate the Shear Stud Spacing Using L/n And Check Minimum and Maximum Spacing
Check Live Load Deflection
Update Moment ReflectinDetermine Unfactored Wu
Calculate Associated Moment M_L Due to Vehicle Loading
Inerpolate I_{LB} From Table 3-20 AISC Manual
Compute $\Delta_L=ML^2/C_1I_{LB}$
Check $\Delta_L \leq L/360$g Beam Weight


DESIGN OF STEEL GIRDERS PARTIAL COMPOSITE
(BASED ON FULL COMPOSITE DESIGN)
Check Composite Capacity
Determine ∑Qn Using Table 3-19 AISC Manual
Calculate Depth of Stress Block Using $a=\sum Qn/0.85f'cb_E$
Calcaulte New Value For Y_1 and Y_2 Assuming the PNA
Interpolate ϕMn From Table 3-19 AISC Manual
Check ϕMn≥Mu
Design Shear Studs
Determine Nominal Stength From Table 3-21 AISC Manual
Determine the Number of Shear Studs Using n=2∑Qn/Qn
Calculate the Shear Stud Spacing Using L/n And Check Minimum and Maximum Spacing
Check Live Load Deflection
Determine Unfactored Wu
Calculate Associated Moment M_L Due to Vehicle Loading
Inerpolate I_{LB} From Table 3-20 AISC Manual
Compute $\Delta_L=ML^2/C_1I_{LB}$
Check $\Delta_L \leq L/360$

3.3.4.3 Columns

The columns were designed based on the following flowchart, using the slenderness as the guiding limit state. It is important to note the following design may only be used for an unbraced column. The unbraced column length for the Belmont Street/Route 9 Bridge spans 15' 9 ½". Initially, when determining the axial load subjected on the column, an assumed number of two columns was selected to determine the tributary width for design. Since a hammerhead design is not included, the columns are placed below two girders and because the tributary width on each side of the columns is not precisely the same, the column design is slightly conservative. Additionally, the design accounts for gravity loads only and lateral force effects are not addressed in the design. It is assumed that the abutments will resist these loads and must be considered in the design of this component. Lastly, after determining an appropriate column size based on the slenderness ratio, the reinforcement bar size was examined and the spacing of the reinforcement was calculated, assuming #4 ties and a 2.5 inch cover.


DESIGN OF COLUMNS ***SQUARE TIED***
Determine Column Size
Calculate Axial Load Pu Using RISA
Calculate Slenderness Ratio for Unbraced Column Using KL/r<22
Calculate Base Length of Column Assuming r = 0.3b for Rectanglular Columns
Determine Appropriate Base Length
Select Reinforcement
Identify Minimum and Maxiumum Reinforcement Ratio
Calculate Area of Steel Using Equation $\rho = As/Ag$
Select Size and Number Reinforcement Bars
Calculate ϕPn Using the Equation $\phi Pn = 0.80\phi(0.85f'c(Ag - Ast) + fyAst)$
Verify $\phi Pn>Pu$
Reinforcement Spacing and Ties
Assume Appropriate Tie Size Based on Reinforcement Bar
Using Equations $16d_{bars}$, $48d_{ties}$, and Column Dimension, Determine Maximum Spacing
Calculate Bar Spacing Using Equation $s = (h - 2cover-2ties-2(d_b/2))/spaces < 6$ inches

3.3.5 Spreadsheets

Design spreadsheets were created in Microsoft Excel to examine multiple design alternatives after completing the flowcharts for each component. Theses spreadsheets helped determine the most effective sizes for each of the components while eliminating redundant hand calculations. For deck design, changes to the spacing and size of rebar were investigated. Adjustments such as the spacing of girders and alterations to the number of shear studs were examined using the spreadsheets to determine the most cost effective girder design. This was determined based on lightest weight section and fewest number of shear studs since the cost is calculated by the weight per foot and number of shear studs. The equations put into Excel followed the same procedure as the flowcharts above and process from the sample hand calculations. These completed Excel templates for concrete deck, non-composite girder, composite girder and column design may be found in Appendix G, Appendix H, Appendix I, and Appendix J, respectively.

3.3.6 AutoCAD Cross Sectional Drawings

The computer program AutoCAD was used to develop cross sectional views of the proposed bridge design. Dimensions and sizes for all re-designed components are highlighted and may be viewed in the results section of this chapter.

3.3.7 3D Model

Additionally, another deliverable created using the computer program Google SketchUp was used to model the proposed Belmont Street/Route 9 Bridge. The three re-designed components, as well as the remaining components that were deemed sufficient by MassHighway's inspection report were included in the model.

The methods and procedures for designing the three components of interest were discussed in this section. The role of RISA 2-D, Excel spreadsheets, AutoCAD, and Google SketchUp were also addressed above. The following section concludes the re-design of the bridge by discussing the selected number of members, sizes, and spacing and the reasons for selecting them. Challenges that arose during the design are also discussed in the next section.

3.4 Design Results

The following section presents the proposed sizes and number of members, as well as spacing for superstructure and substructure components. A re-design was investigated for the concrete bridge deck, steel girders and concrete columns and their results are discussed below. Design challenges are reviewed for each component as well. The impact of these challenges and their role in selecting member sizes is outlined below.

3.4.1 Superstructure Design

Based on MassHighway's 2008 Bridge Inspection Report provided in Appendix B, the most crucial elements of the superstructure were re-designed. This included principal superstructure elements such as the concrete deck and stringers. Other elements that received a lower rating but were not investigated as part of this project were the deck joints, connections, and diaphragms. With the exception of the deck joints, all other elements were categorized as having a severe deficiency meaning their repair should be based on priority. This means they are generally not considered until funds and manpower become available. The deck joints were in a condition that suggested repair immediately upon receipt of report to District Maintenance Engineer. Overall, the deck was given a rating of a 5 which is considered in "fair" condition and the superstructure received a rating of a 4 which is classified as "poor".

Although the deck received a total rating of a 5, a re-design was investigated. The new rating of a 5 was recently increased from a 4 because the deck has received various spot repairs and maintenance since the last inspection report. Based on the group's visual inspection and personal experience driving over the bridge, it was determined that the bridge could benefit from an improved deck. The bridge could also benefit from a new wearing surface layer. Figure 11 shows the severity of the cracks and exposed rusted rebar along various locations on the bridge deck. Even though the cracks and exposed rebar do not warrant immediate attention and repair, if they are not properly maintained, in time they can cause more severe issues. Cracks allow the rebar to be exposed to greater amounts of fluids and moisture on the bridge. Once the initial cracks occur, it is easier for water to seep into the concrete deck to the rebar and enhance the rate of corrosion. This reduces the section of reinforcing steel which in turn, lowers the tensile capacity the reinforcement.

Figure 11: Wearing surface on Belmont Street/Route 9 Bridge

Changes were made to the initial design based on the group's attempt to create a design that would require less maintenance in the future and last longer than the typical bridge deck. In order to ensure a longer service life of the new deck design, more sustainable building alternatives could also be explored, as discussed in further detail in the later chapters of this report.

3.4.1.1 Concrete Deck Design

The deck was constructed of reinforced concrete material and included an 8-inch thick slab as required for minimum slab thickness by *AASHTO Specifications*. Other properties of the bridge such as the thickness of the surface layers, weight of the materials, and general dimensions are included in Table 3. Based on the typical values for material weights and the decided values for layer thicknesses, the unfactored weight of the slab and wearing surface were determined to be 0.64 k-ft/ft and 0.19 k-ft/ft, respectively.

Table 3: Bridge deck properties

Bridge Superstructure Element	Established Value
Slab thickness	8”
Bituminous concrete thickness	2.5”
Tributary area	8’
Weight of concrete	150 pcf
Weight of wearing surface	145 pcf
Span of bridge	151 ft
Width of bridge	60 ft
Compressive strength of concrete (f’c)	4 ksi
Steel yield strength	60 ksi

In order to determine the size and amount of reinforcement needed in the concrete deck, the positive and negative moment values were determined for each region using the different loads that affect the bridge deck. The loads were then factored based on *AASHTO Specifications* to ensure safety in the design. The factors assigned to dead and live loads used for the Belmont Street/Route 9 Bridge are included in Table 4 along with the reference from the *AASHTO Specification Manual*.

Table 4: Design load factors

Design Factor	Design Factor Value	Reference
Maximum slab dead load factor	1.25	STable 3.4.1-2
Maximum wearing surface dead load factor	1.5	STable 3.4.1-2
Live load factor	1.75	STable 3.4.1-1
Multiple presence factor (> 3 lanes)	0.65	S3.6.1.1.2-1
Dynamic load allowance (IM)	0.33	STable 3.6.2.1-1

Table 5 indicates the total factored loads in the positive and negative moment region. For the Belmont Street/Route 9 Bridge, the total factored negative load of 12.61 k-ft/ft governed the design as shown in Table 5, therefore the bar size and spacing for that region was used throughout the deck in both the positive and negative regions. Using the deck design template that was created in Microsoft Excel, different size bars and spacing were investigated to determine the most desirable bar size and spacing option.

Table 5: Moment values for positive and negative regions

Positive moments		Negative moments	
Unfactored LL	5.69 k-ft/ft	Unfactored LL	6.58 k-ft/ft
Factored LL	9.96 k-ft/ft	Factored LL	11.52 k-ft/ft
Unfactored slab DL	0.64 k-ft/ft	Unfactored slab DL	0.64 k-ft/ft
Factored slab DL	0.80 k-ft/ft	Factored slab DL	0.80 k-ft/ft
Unfactored wearing surface DL	0.19 k-ft/ft	Unfactored wearing surface DL	0.19 k-ft/ft
Factored wearing surface DL	0.29 k-ft/ft	Factored wearing surface DL	0.29 k-ft/ft
Total Factored Positive Load	11.05 k-ft/ft	**Total Factored Negative Load**	12.61 k-ft/ft

Although different bar sizes and spacing can be determined for each flexure region, based on productability and economical reasons, the same bar size spacing was chosen for both regions.

Table 5 shows that the difference between the total factored positive and negative load is minimal. Using the governing value from the negative region, it results in a more conservative design for the positive reinforcement region. Table 6 shows the bar size, calculated spacing and spacing when considering constructability. When the same bars are used throughout the design, the cost associated with fabrication of the material is lowered. Using the same size bars and spacing also reduces the risk of confusion or misinterpretation during installation. The spacing in the positive and negative regions is the same for #5 and #8 bar sizes. For reinforcement, #5 bars were chosen based on their typical use in concrete bridge decks. In both the positive and negative regions, the calculated spacing was determined to be less than 6 inches. To simplify the layout and installation of the bars, 6-inch spacing between bars was used in both the positive and negative flexure zones.

Table 6: Bar size and spacing for positive and negative flexure regions

Positive Flexure			Negative Flexure		
Bar Size	**Calc. Spacing**	**Con. Spacing**	**Bar Size**	**Calc. Spacing**	**Con. Spacing**
#5	6.39 in	6 in	#5	6.25 in	6 in
#6	9.06 in	9 in	#6	8.87 in	8 in
#7	12.12 in	12 in	#7	11.89 in	11 in
#8	15.57 in	15 in	#8	15.3 in	15 in

Primary steel reinforcement bars in bridge decks are laid out along the longitudinal direction, perpendicular to the direction of the traffic to resist deflection as shown in Figure 12. Based on a 131 ft bridge span, 262 total #5 bars at 6-inch spacing are required for the bridge deck reinforcement. Calculations used to determine sufficient concrete deck design and reinforcement are included in Appendix C.

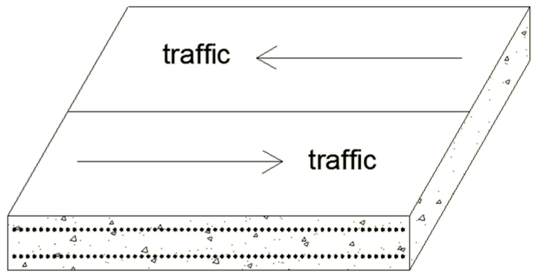


Figure 12: Direction of reinforcement bars in bridge deck (not drawn to scale)

Although the deck currently has a rating of 5 which means it is functional and isn't in danger of any immediate failure issues, investigating a more effective design can be beneficial. The bridge deck has had patch work done to various exposed areas to fill some of the cracks and limit the amount of moisture that seeps into the bridge deck. A "temporary" fix on the deck is to increase the thickness of the wearing surface, or simply re-cover the top layer of concrete. This protects the bridge deck because it fills all the holes on the previous wearing surface. One issue with re-surfacing the top layer of the bridge is that new layers increase the weight of the wearing surface which affects the maximum moment reaction of the bridge. If an allowance for future wearing surfaces is not accounted for in the original design, the additional weight may exceed the capacity the bridge was originally designed to withstand.

When maintenance is only performed on an as-needed basis, it tends to create a repair cycle. Engineers believe they are saving money by only fixing the components that pose immediate danger to the structural integrity of the bridge, but that is not often the case. As-needed repairs are required more often which means more money is spent on labor and equipment each additional time maintenance is performed. By creating a new deck design with higher strength materials, the bridge will be able to better withstand the recurring wear and tear of the everyday traffic and surrounding environmental conditions and will not require repairs as often. For example, in the original 1958 Belmont Street/Route 9 Bridge, a 3000 psi concrete compressive strength was used based on the reasonable standards of the time. For the new bridge design, a higher 4000 psi strength concrete was used to compensate for the increased traffic loads traveling across the bridge. Also, in the initial design, the type of rebar used was unknown so it is difficult to know if the reinforcement is protected by any type of coating. MassHighway now requires that all bridge deck reinforcement be epoxy-coated or galvanized.

Later chapters will discuss additional alternatives that can optimize the performance of a bridge. The goal in incorporating some of the more sustainable alternatives is to extend the typical 40 to 50 year service life of a bridge and reduce the cost of maintenance needed during its lifespan.

3.4.1.2 Girder Design

According to the 2008 MassHighway bridge inspection, the girders received a rating of 4. This is largely due to multiple collisions with trucks exceeding the 14’11” vertical clearance limit. The impact of the trucks has resulted in a number of bent girders that are rotated out of plane like the one shown in Figure 13. This has a significant effect on the capability of the girders to support the bridge deck; therefore, a re-design of the girders was investigated.

Figure 13: Bent girder from impact of collision

The girders were designed based on ASSHTO specifications and the material properties of the concrete deck. A detailed description and complete procedure for evaluating the girder sizes and weights may be found in the methods section of this chapter. This section focuses on the results based on the assumed values for the girder dimensions and properties listed below in Table 7.

Table 7: Steel girder properties

Weight of Concrete	0.15	k/ft^3
Weight of Steel (W36x150)	0.15	k/ft^3
Flange Width	1.00	ft
Flange Thickness	0.08	ft
Web Height	3.00	ft
Web Thickness	0.05	ft
Span (L)	131.00	ft
Width of Bridge	60.00	ft
Thickness of Concrete Slab	0.67	ft (8 in)
Thickness of Pavement	0.21	ft (2.5 in)
Height of Girder	3.00	ft (36 in)
Number of Girders	8	
Dead Load Factor	1.25	
Live Load Factor	1.75	

It is important to note that the dead load accounts for the weight of the deck and all other associated dead loads with the deck design, such as barriers, pavement, utilities, railings, curbs, chain link fence, end posts and assumed girder weight. From the tabulated distributed load, the maximum calculated moment subjected on each girder was found to be 2076 ft-k. The load cases examined and there resulting maximum moments are included in Table 8.

Table 8: Girder design load cases

Girder Design - Longitudinal Direction						
Case	**Description**	**Max. Pos. Shear (k)**	**Max. Neg. Shear (k)**	**Max. Pos. Moment(ft-k)**	**Max. Neg. Moment (ft-k)**
1	Uniform Dead Load	81.04	-83.83	1093.52	-620.59
2	Uniform Live Load 2 Spans	45.8	-44.27	597.44	-339.06
3	Uniform Live Load 1 Span	32.12	-41.24	298.72	-460.56
4	Con. Load (Center of 1st Span)	12.81	-18.69	192.4	-419.61
5	Con. Loads (Center both Spans)	21.63	-21.63	384.8	-323.41
6	Con. Load at Center Support	45.38	-0.12	7.53	-7.48
7	Combined Cases 1 & 2	125.31	-129.63	1690.96	-959.65
8	Combined Cases 1 & 3	85.6	-125.07	1392.24	-1075.13
9	Combined Cases 3 & 4	35.76	-48.15	405.77	-741.95
10	Combined Cases 3 & 6	48.64	-28.41	220.9	-325.68
11	Combined Cases 1, 2, & 4	128.25	-148.32	1883.36	-1300.81
12	Combined Cases 1, 2, & 5	**151.26**	**-146.93**	**2075.76**	-1217.73
13	Combined Cases 1, 3, & 4	95.37	-143.76	1584.64	**-1434.74**
14	Combined Cases 1, 3, & 5	107.22	-146.7	1777.04	-1347.33
Maximum Factored Values		**151.26**	**-146.93**	**2075.76**	**-1434.74**

3.4.1.2.1 Governing Check

When designing the girders, construction capacity and deflection checks, a service live load check and plastic capacity limitations were investigated for composite construction. For this design, unshored construction is assumed and is the limiting state that governs in all designs. In general, unshored construction is more a cost effective method so for the design of the girders unshored construction was assumed. Since temporary braces are not necessary for unshored construction, the amount of time and labor involved for construction is reduced. Also, because Interstate 290 runs below the bridge, shoring would cause traffic issues during construction. Since the capacity and deflection for unshored construction typically dictate the sizing for girders, it was examined first. The minimum required moments based on unshored construction and the design capacity allowances for each girder size are shown below in Table 9. The PNA locations found displayed in the table refer to the distance from the top of the flange to the location of the PNA in inches.

Table 9: Girder Summarized Results

GIRDER SIZE	PNA	Mu	ΦM_p	NO. STUDS	NO. GIRDERS	NO. SPANS
W40x199	0	4184	5120	224	8	2
	2	4184	5097	193	8	2
	3	4184	5034	161	8	2
	4	4184	4917	128	8	2
W40x211	0	4201	5457	238	8	2
	2	4201	5450	206	8	2
	3	4201	5394	174	8	2
	4	4201	5290	142	8	2
W40x215	0	4207	5504	243	8	2
	2	4207	5497	207	8	2
	3	4207	5440	170	8	2
	4	4207	5317	133	8	2
W40x235	0	4235	5989	265	8	2
	2	4235	6007	229	8	2
	3	4235	5966	193	8	2
	4	4235	5871	157	8	2
W36x247	0	4252	5816	279	8	2
	2	4252	5860	236	8	2
	3	4252	5825	193	8	2
	4	4252	5708	150	8	2
W36x231	0	4229	5519	261	8	2
	2	4229	5534	222	8	2
	3	4229	5479	182	8	2
	4	4229	5370	142	8	2
W36x232	0	4231	5596	262	8	2
	2	4231	5610	225	8	2
	3	4231	5570	188	8	2
	4	4231	5463	152	8	2

3.4.1.2.2 Composite Design

Another important concept examined is composite and non-composite design. As displayed in Table 9, calculations were performed assuming different locations for the plastic neutral axis for composite design. From previous experience and sample calculations provided in Appendix D, non-composite design was eliminated as an effective solution. Using this design, the girder must support a significantly larger capacity than with composite design. Table 9 shows full composite and partial composite design results with an adequate number of shear studs listed. For composite design, the plastic neutral axis drops down from the top of the flange and from Table 9 it is clear that the plastic neutral axis depends on the number of studs. As the studs decrease, the plastic neutral axis occurs lower in the cross section. Since the cost depends on the number of shear studs, the most cost effective design utilizes a W40x199 with a plastic neutral axis of 4 inches from the top of the flange.

In order to effectively determine the most efficient girder design, several different girder sizes with varying weights were analyzed. After comparing these results, a W40x199 section was selected for the girders. With this section size, 128 shear studs were found to provide adequate girder support. As shown in Table 9, a W40x199 girder is the lightest section analyzed. Since construction material costs vary by the weight and the number of shear studs, this section costs the least. It can be noted that a W40x199 is larger than the original W50x132. This is because increased traffic loadings are more common today than they were in 1958 and *AASHTO Specifications* have been adjusted to meet the new requirements.

3.4.2 Substructure Design

According to MassHighway's 2008 Bridge Inspection Report for the Belmont Street/Route 9 Bridge, the substructure received a rating of 5. Both the piers and the abutments were given an individual rating of 5. The columns on the piers were looked at for re-design based on the team's visual inspection of the bridge and their individual rating of 4. An example of the severity of the corrosion of the columns is shown in Figure 14. Large areas of the reinforced concrete columns (up to 4 ft high by 3 ft wide by 2 ft deep) suffer from severe corrosion. Based on the visual inspection of the abutments, the team agreed with their "good" rating and that the elements were not in immediate need of repair.

Similar to the reinforced concrete deck, if the columns are not maintained properly, the corrosion will eventually cause major issues with the capacity limits of the members. Being that columns are the main members that hold up the weight of the superstructure, it is important that they have adequate capacity.

Figure 14: Extensive column corrosion on Belmont Street/Route 9 Bridge

The design of a simple square-tied column was investigated for the bridge pier. Unlike the current bridge, the design does not include a hammerhead pier. Hammerhead piers require an increased area of concrete based on their design, where single square tied columns require less but are generally larger to substitute for the increased capacity they must support.

3.4.2.1 Column Design

When re-designing the columns for the Belmont Street/Route 9 Bridge, the computer program RISA 2-D was used to determine the applied axial load on the ends of the columns. From here, the columns were designed based only on the axial force subjected on the column. No lateral analysis was evaluated and it was assumed that the abutment design would consider these effects. Unlike the design of the concrete deck slab and the steel girders, the columns were investigated using hand calculations that may be viewed in Appendix E. Although a spreadsheet was not used to determine the selected column size for this project, a spreadsheet was still created to analyze different column sizes and spacing and may be used for other design projects. This spreadsheet may be viewed in Appendix J.

3.4.2.1.1 Slenderness Check

For the design of unbraced, axially loaded columns, the slenderness ratio dictated the selected column size. Since the columns were not designed for combined bending and axial forces, the slenderness ratio is the only necessary limit state that was considered. Based on the hand calculations in Appendix E, a 36"x36" column was selected. Although reinforcement bars and ties were selected for the design, they only made the capacity of the member greater.

3.4.2.1.2 Reinforcement

An important consideration is the amount of reinforcement required for large columns. Although the column size may be sufficient based on slenderness, an ACI requirement states that reinforcement bars must be spaced no less than 6 inches apart. For the 36"x36" square tied column, there is a significant amount of extra reinforcement bars that aren't necessary for capacity checks regarding reinforcement. However, when the reinforcement bar size is decreased, the reinforcement ratio is no longer satisfied. Based on this, for the 36"x36" square tied column, size No. 7 reinforcement bars were selected spaced every 5.5 inches. The ties are No. 4 and the cover is 2.5 inches.

3.5 Cross Sectional Drawings

Using AutoCAD, drawings were created to show the both the longitudinal and transverse directions based on the proposed steel girders and concrete deck slab. The resulting cross sections may be found in Figure 15 and Figure 16. The proposed girders were designed as single span beams and the resulting section size was a W40x199. The proposed concrete deck slab was treated as a continuous span with an 8 inch slab. The reinforcement needed to provide sufficient capacity was determined to be No. 5 reinforcement bars spaced every 6 inches in both the top and bottom of the slab.

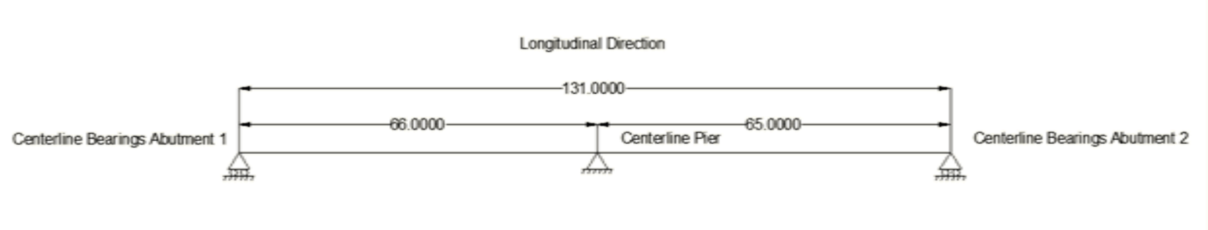


Figure 15: Longitudinal cross section of proposed Belmont Street/Route 9 Bridge re-design

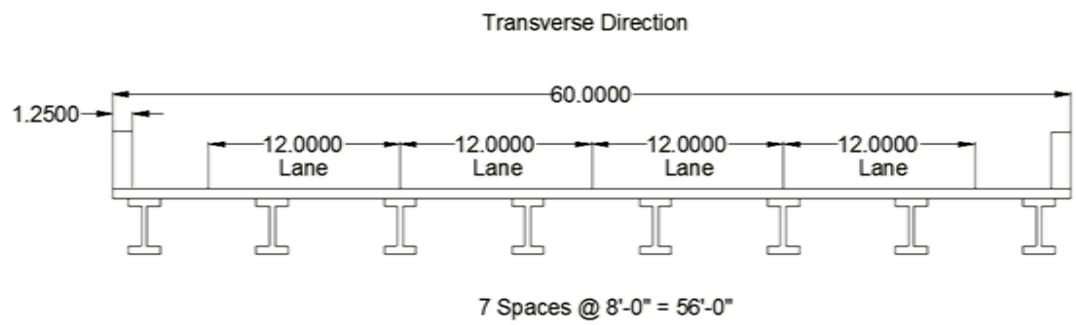


Figure 16: Transverse cross section of proposed Belmont Street/Route 9 Bridge re-design

3.6 Three Dimensional Model

Using the computer program RISA 2-D, a three dimensional model was created to accurately depict the proposed re-design for the Belmont Street/Route 9 Bridge. The proposed deck slab with sidewalks, fencing, end posts, and railings is shown in Figure 17 while the proposed girders and columns may be found in Figure 18 and Figure 19. Lastly, an overall layout of the bridge re-design is shown in Figure 20, showing both re-designed components and current components.

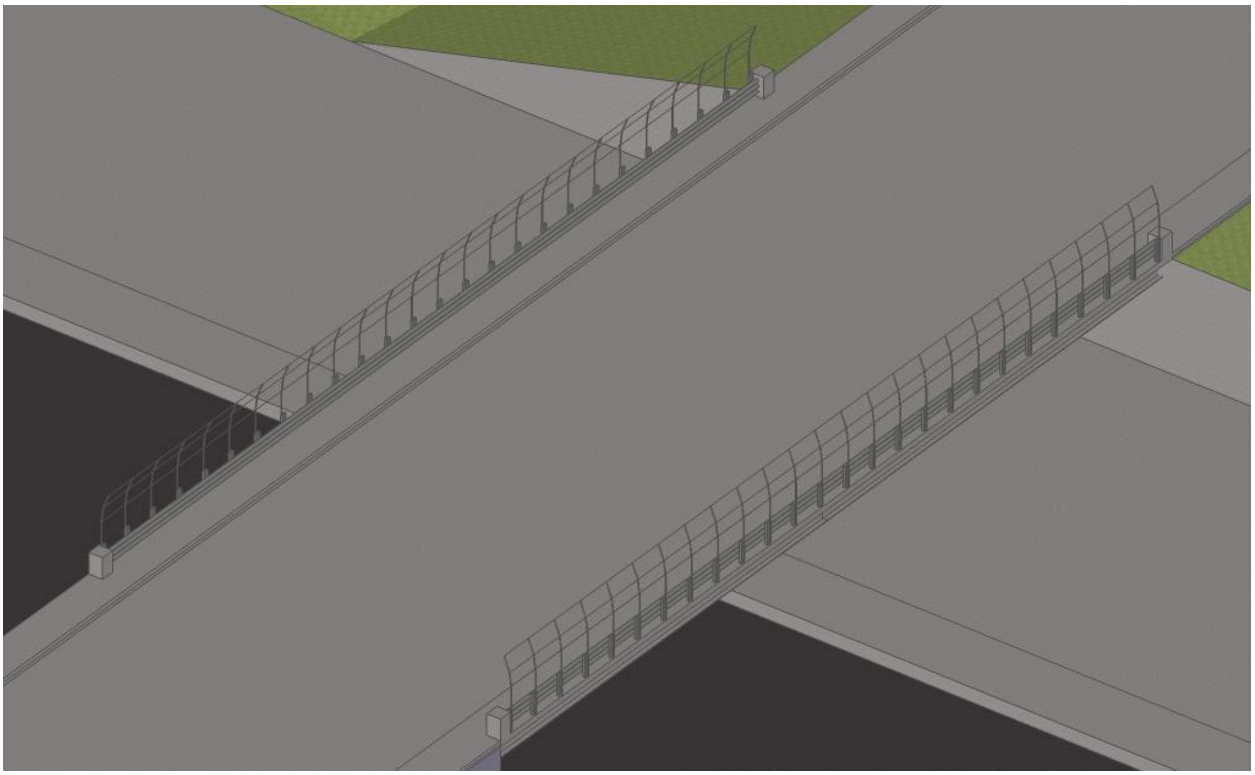


Figure 17: Proposed concrete deck for Belmont Street/Route 9 Bridge re-design

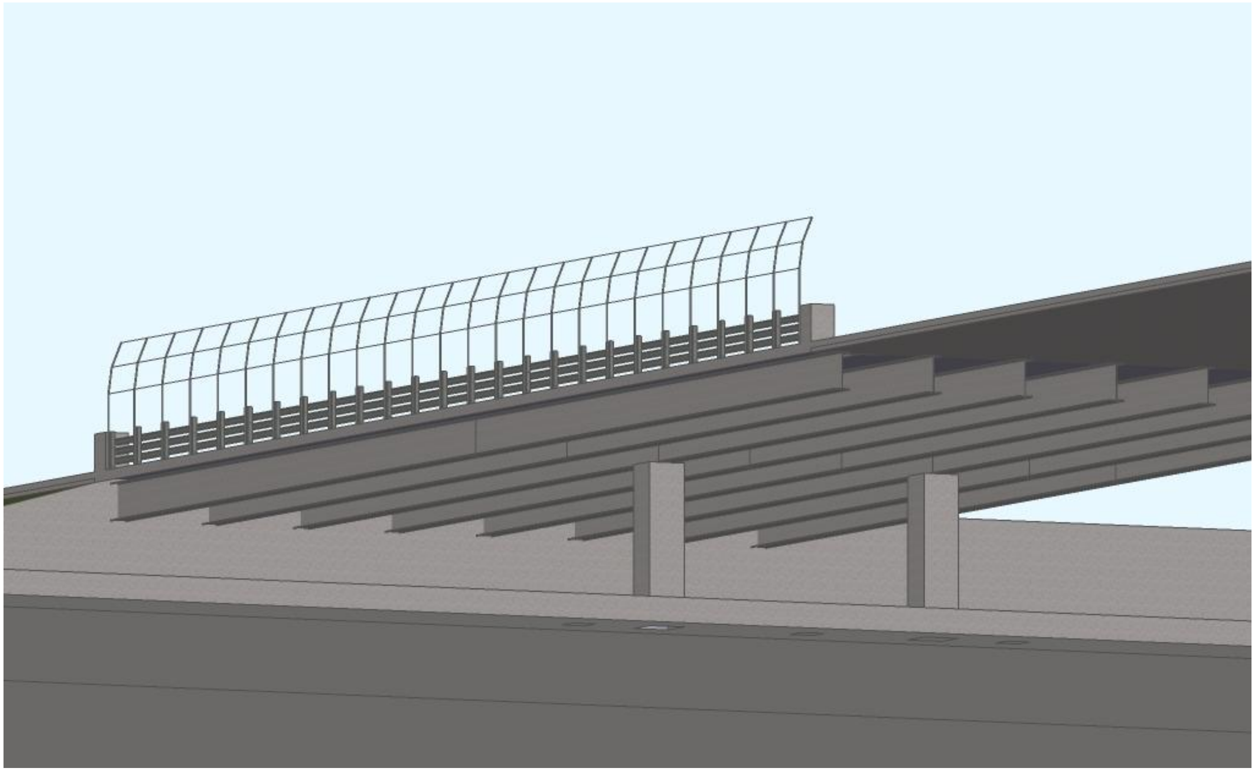


Figure 18: Proposed concrete columns and steel girders for Belmont Street/Route 9 Bridge re-design (View 1)

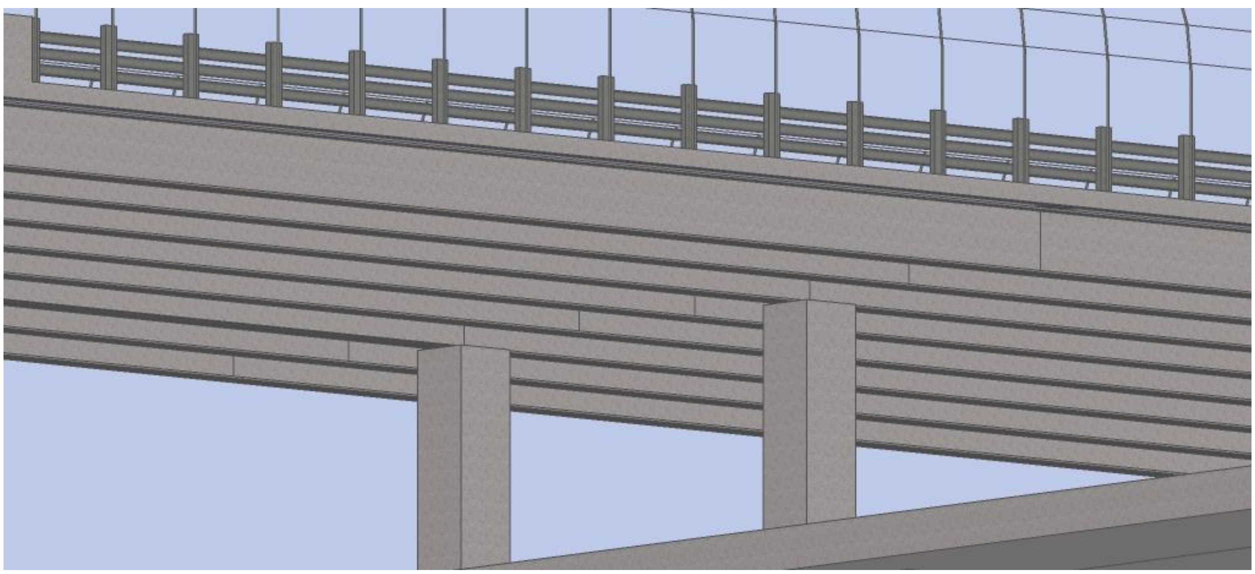


Figure 19: Proposed concrete columns and steel girders for Belmont Street/Route 9 Bridge re-design (View 2)

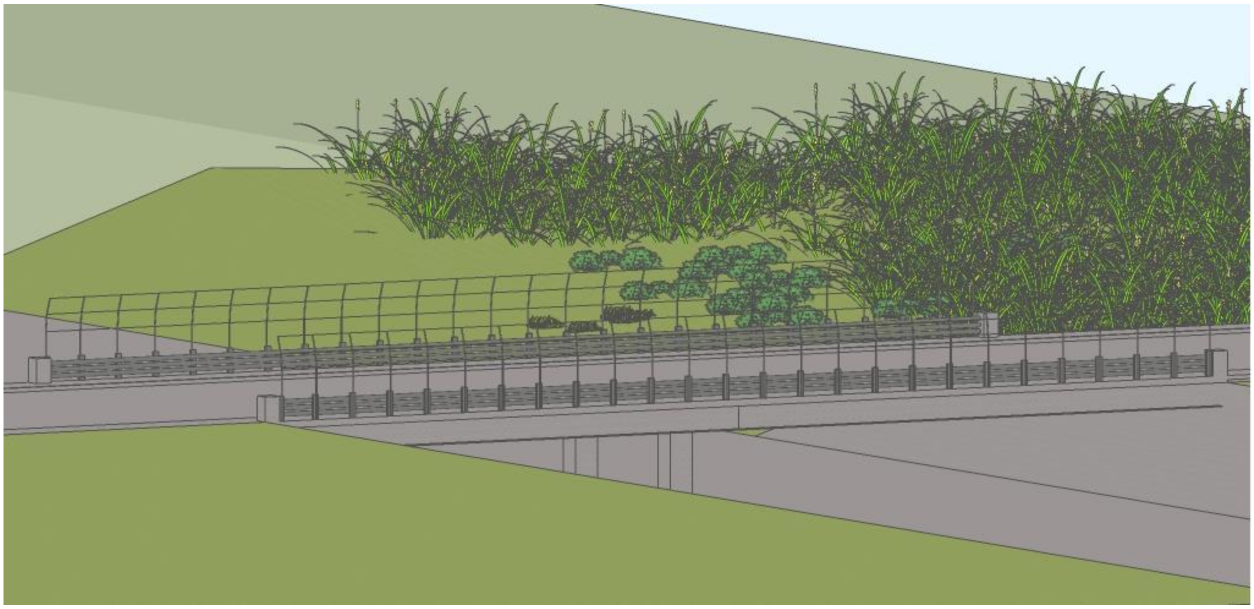


Figure 20: Overall proposed bridge re-design

3.7 Structural Analysis & Design Conclusions

The focus of this section was primarily on the design elements of the Belmont Street/Route 9 Bridge project. The elements analyzed were selected based on structural ratings of the safety inspection report. According to this report, the deck, girders, and columns are in severe condition and require replacement. These elements were re-designed according to *AASHTO LRFD Specifications*. The computer applications RISA-2D and Microsoft Excel were utilized to simplify the design process. It is important to note that the design of the bridge is only one part of achieving a sustainable design. The following chapters investigate several sustainable alternatives that may be implemented to ensure the most feasible design.

4 Alternative Building Materials & Maintenance

Included in the idea of sustainable design is the option to build with recycled materials. These materials generally include "waste" steel and concrete from previous structures rather than consuming more resources to produce brand new products that were fabricated especially for the project. The use of recycled materials not only significantly cuts down on the project cost but it reduces the carbon footprint of the construction project.

Once a bridge is built, care in maintaining it should become a top priority. When bridge maintenance is neglected, the lifespan of bridges tend to decrease. Bridge maintenance can be reduced with the application of different corrosion protectants and sealants. Other maintenance strategies such as patching areas of the bridge in need of repair are used. As technology and the ability to test new procedures increases, new protection systems can be implemented into the bridge site to control the rate of component deterioration.

4.1 Typical Building Materials

In bridge design there are two main types of material used in construction, reinforced concrete and steel. Separately, reinforced concrete and steel have desirable properties for bridges. Concrete is very strong in compression and when used in conjunction with steel its tensile weakness is compensated for. When used together their properties combine to create a stronger, more durable structure.

4.1.1 Reinforced Concrete Properties

Concrete is made from a mixture of cement, coarse and fine aggregates such as gravel and sand respectively, water and admixtures. The water in the mix reacts with the cement powder-like substance to form an adhesive that bonds the other materials together. Different proportions of the ingredients in the mixture can produce a range of desired results for durability, strength, consistency, workability, and density of the material. Before concrete reaches its required compressive strength the mixture must harden and cure for 28 days.

Plain concrete is fifteen times stronger in compression than in tension. Concrete's weakness in tension can lead to cracking which can be dangerous when used for construction. When tensile stresses exceed their limits in concrete members, the structure will fail very abruptly giving almost no warning. Premature deterioration, which can be precipitated by cracking, of the members that stabilize structures like buildings or bridges can cause the entire structure to collapse, making plain concrete a less than desirable material to use.

Modifications in the way concrete is made have created a more effective building material. The addition of steel bars molded into concrete, called reinforced concrete is one of the most dominant building materials used in engineering construction today. The steel bars are generally ridged to increase the bond between the concrete and steel and are called rebar. The inclusion of steel bars in concrete members increases the tensile strength of the component, making the entire structure stronger and safer. Another advantage of the added rebar is that if the concrete begins to crack, the steel reinforcements can withstand the tensile forces for an extended period of time before the entire structure abruptly collapses (MacGregor & Wight, 2005). The steel gives bridge inspectors and engineers time to determine the maintenance required to fix the bridge without having to entirely close the bridge.

In bridge design reinforced concrete can be used to build components because of its durability, if properly mixed, placed, and cured, and relatively inexpensive cost. Components include: wearing surfaces, decks, girders, bracing, abutments, piers, bearings, pedestals, walls, footings and piles. When reinforced concrete was first used in bridge construction it seemed to function fairly well until inspectors found that it began to require maintenance in less than five years after being built (US Department of Transportation, 1998). In areas of extreme weather conditions or extensive traffic wear, cracking of the concrete made the steel rebar more susceptible to fluids and chemicals which accelerate the corrosion process. Figure 21 shows an example of exposed rebar in a concrete bridge member when a reinforced concrete component is not maintained properly (US Department of Transportation, 1998). The concrete mix design and structural detailing of the components can play a role in the effectiveness of the design. When building with reinforced concrete, it is not only important to understand the properties that make it an ideal construction material but also how to protect and maintain it to increase the lifespan of the structure.

Figure 21: Exposed steel rebar in reinforced concrete column (taken from http://www.corrosion-club.com)

4.1.2 Properties of Steel

Structural steel is classified based on chemical composition and strength. The four main types of structural steel include carbon steel, heat-treated carbon steel, heat-treated alloy steel, and high-strength low-alloy steel. All types consist of a combination of iron and carbon. Structural steel is manufactured in a variety of sizes, shapes, and ASTM strengths for use in virtually any construction project. Typical member shapes include W, MS, S, HP, C, and MC. A few major advantages of using structural steel as a construction material include high strength, strength to weight ratio, ductility, elasticity, toughness and uniformity (Brockenbrough & Merritt, 1999).

For bridge construction, Grade 50 and Grade 70 are typical yield strengths for structural members such as girders, flanges and splicing elements while Grade 36 can be used for stiffeners, girder connector plates, and diaphragms. Specifications provided by state codes and regulations can determine the type of steel to be used in specific bridge design depending on location.

Like concrete, steel is affected moisture from the environment around it. Typically steel bridge components such as girders are painted to protect the steel from rusting. It is common for the painted girders to chip and begin to rust therefore it is difficult to keep the structural steel protected from corrosion inhibitors. Rusting causes the section of steel to be reduced which can affect the expected durability of the girder. The same problem occurs with reinforcing steel.

Once the concrete bridge deck which protects the steel bars is penetrated, the rebar is exposed to the same moisture that causes corrosion of the steel section. Although steel is considered a very durable material, its durability is greatly affected by corrosion.

4.2 Recyclable Building Materials

Renovation projects generally include a demolition and construction phase where a massive amount of waste accumulates. In the past, the waste was simply transported off-site and disposed of in landfills. This process resulted in significant expenses. The new reality of using recycled materials has considerably reduced the amount of waste produced. Materials such as concrete and steel can be salvaged from decommissioned infrastructure and used to make new and improved products.

4.2.1 Recycled Steel

Steel is an intrinsically sustainable material. According to the Steel Recycling Institute, in North America, "to buy steel is to buy recycled" (Steel Takes LEED with Recycled Content, 2005). The comprehensive system of steel production is based on the continuous process of recycling and reclaiming steel products. The process involves using recycled steel to produce new products; then at the time when the new products exceed their lifetime, they are recovered and recycled again. This ongoing process optimizes the life-cycle of steel, and ranks it as the most recycled material in the world. Approximately 95% of steel is salvaged and used to make new steel. The reclaimed steel comes from sources such as automobiles, household appliances, and structural components.

Typically there are two methods to produce steel based on the intended application. The two techniques are the basic oxygen furnace (BOF) and the electric arc furnace (EAF). BOF is responsible for producing steel for input to manufacturing of items such as cans, household appliances, and parts for automobiles. This process uses about 25-35 percent recycled steel to produce new products. On the other hand, the EAF produces steel of exceptional strength and employs a greater quantity of recycled material. The electric arc furnace method generates structural products such as steel decks, beams, plates, and reinforcing bars. These products are produced with almost 95-100% reclaimed steel (Steel Takes LEED with Recycled Content, 2005).

The statistics allude to the fact that steel is economically and environmentally efficient. According to the American Steel Recycling Institute, 2500 pounds of iron, 1400 pounds of coal, and 120 pounds of limestone are conserved when one ton of steel is recycled. Therefore the recycling process conserves energy as well as preserves natural ores and additional materials which would be needed for production. Since steel is a very durable and lasting material, it is necessary to continue extracting natural ore to satisfy overall demand, but not at the same rate which would be needed if steel could not be recycled (The Inherent Recycled Content of Today's Steel, 2007).

4.2.1.1 Types of Recycled Aggregates for Concrete

Concrete has proven to be a durable and versatile material. Varied types and proportions of ingredients can be supplemented into the mix design for different purposes. Recycled concrete aggregate is generally used for a base material and fly ash can be substituted in part for cement.

4.2.1.1.1 Recycled Concrete Aggregate

The Massachusetts Department of Environmental Protection promotes the practice of recycling construction waste. The most common solid waste materials caused by demolition of existing infrastructure are asphalt pavement, brick, and concrete, commonly known as "ABC rubble." All of these materials can be utilized as aggregates in concrete mix, but recycled concrete aggregate is generally used as the base material (Waste and Recycling, 2008). Recycled concrete aggregate can be used for applications such as pavement, highway dividers, and bridge foundations.

According to the Federal Highway Association (FHWA) of the United States, thirty-eight of the fifty states employ recycled concrete as an aggregate base in highway pavement projects. A layout of the states is depicted in Figure 22, which is an excerpt from a study conducted by the FHWA. The states in green do use recycled concrete as a base aggregate, and the states in red (ME, NH, VT, MD, AL, TN, MO, HI, AK, MT, ID) do not. It is apparent from this study that Massachusetts is familiar with the recycling process of concrete.

Figure 22: Map of where recycled base concrete aggregate is used (taken from Recycled Concrete Aggregate, 2007)

The concept of converting demolition waste to aggregates presents environmental and economical benefits. In the first respect, recycling helps to preserve natural resources, and reduces the amount of waste which would usually be transported to landfills. Regarding renovation projects, concrete from deficient structures can be salvaged and used to make new products. This process is beneficial because it reduces cost and smaller quantities of waste require disposal (Rakshvir, 2006).

4.2.1.1.2 Fly Ash Concrete

Fly ash is a product which can be added to concrete mix to produce high strength performance concrete. Fly Ash is a fossil fuel residue which poses potential negative effects to the environment. It is a by-product formed from electricity generation, specifically from the combustion of coal. Since coal combustion is responsible for about half of the energy generated in the United States, the increasing rate of fly ash production and disposal is a widespread matter of concern (Fly Ash and the Environment, 2005). Dating back to 1999, 55 million tons of fly ash was produced in the U.S., with a total recycled amount of only 9 million tons. The remaining waste, accounting for two-thirds of the total produced, was transported to landfills for disposal (Fly Ash Concrete, 2008).

Recent implementation of fly ash as an alternative lightweight aggregate in concrete has converted the by-product to a sustainable source. The use of fly ash has reduced the amount of disposed waste, as well as reduced the amount of concrete needed to be produced. It can also be added in proportion to concrete mix in order to lessen the amount of cement in the mix design without compromising the strength of the final product. From an environmental standpoint, reducing cement production is a significant step towards cutting down greenhouse gas emissions. The Portland Cement industry alone is responsible for producing 7% of human produced carbon dioxide emissions (Meyer, 2002). Carbon dioxide is harmful to the atmosphere and there are implications that it may contribute to growing trend of global warming (Meyer, 2002).

Regarding the function of fly ash, it is constituted as a cementitious material, or more formally as a "pozzolan." A pozzolan is defined as "a substance comprised of aluminous and silicious material that forms cement with the introduction of water" (Fly Ash Concrete, 2008). It should be noted that fly ash is not a direct substitute for cement, and the two materials actually work in conjunction. When water is added to cement, it works as an adhesive paste and also produces a substance termed "free lime." Without fly ash, the lime may combine with harmful substances such as sulfate and negatively affect the integrity of the concrete. However, when fly ash is added to the mix, it chemically reacts with the lime enhancing the adhesiveness and compressive strength of concrete (Fly Ash and the Environment, 2005).

Figure 23 illustrates the comparison of compressive strengths of conventional cement concrete versus concrete containing fly ash. Notice that the trend is relatively similar until day 56 when the fly ash concrete gains a significant amount of strength. Furthermore, in a year the fly ash concrete exhibits an increased strength of 1000 psi compared to the typical cement concrete.

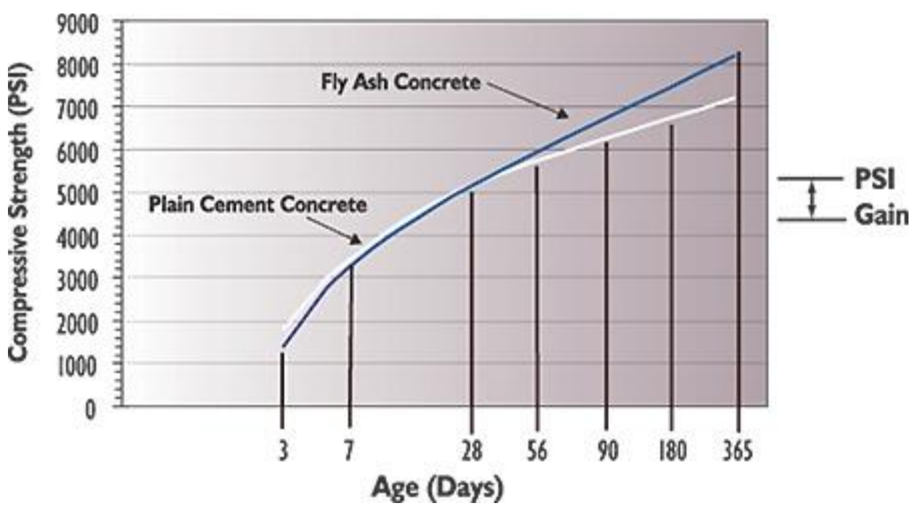


Figure 23: Graph showing increased strength of concrete as a function of fly ash (taken from Fly Ash and the Environment, 2005)

Fly Ash also has benefits due to its physical properties. It is made of tiny particles that resemble glass-like spherical beads. Fly ash is described as having a "ball bearing effect." Due to the convenient spherical shape, the amount of friction is reduced which provides for better workability and eased flow. Therefore it is possible to pump wet concrete over longer distances with less energy (Fly Ash Concrete, 2008). The miniscule nature of the beads works well to fill in the voids of the concrete. Also, the water content of concrete made with fly ash can be reduced up to 10% because of this "ball bearing effect." (Fly Ash and the Environment, 2005). Reduced water enhances the quality of the concrete. A low water to cement ratio concrete is more durable than a high water to cement ratio concrete. Therefore the overall strength, durability, and reliability of concrete improves with the correct proportions of fly ash.

4.3 Maintenance of Highway Bridges

Concrete is one of the most widely used materials in construction because of its low cost and the ability to reuse discarded materials from demolished structures, which reduces the impact of the material on the environment. Reinforced concrete is concrete with steel rebar supports. Keeping up with the service and maintenance of concrete bridge components can reduce the effects of deterioration and increase the overall life-cycle of the bridge. One of the biggest issues in maintaining a bridge is the attempt to reduce and control the rate of corrosion of the steel rebar embedded in concrete.

4.3.1 How Corrosion Occurs

Corrosion in reinforced concrete has become an area of extensive concern for bridge engineers as an increased number of bridges across the world are being deemed structurally deficient. Corrosion occurs when steel reinforcements inside the concrete members begin to rust or deteriorate. The corroding steel expands, causing the concrete surrounding them to crack due to the tensile stresses that develop in the concrete like shown in Figure 24. Corrosion can also happen on steel components on the bridge like the lateral bracing as shown in Figure 25.

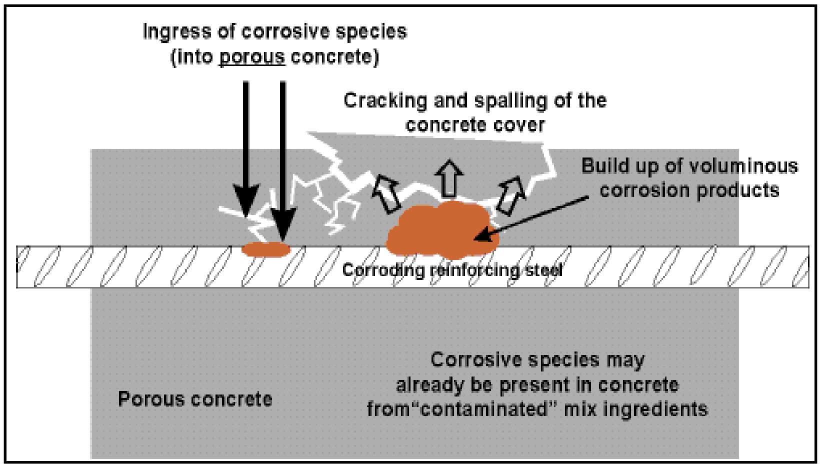


Figure 24: Diagram showing how corrosion occurs (taken from http://www.corrosion-club.com/concretecorrosion.htm)

Corrosion in steel is a loss of electrons that react with water and oxygen. It is caused by factors which induce stress directly on the component such as general wear from everyday traffic. Because concrete is a porous material, extreme temperature fluctuations which cause freezing and thawing and interactions with chemicals can also accelerate the corrosion rate through a process called spalling. Spalling is the deterioration of concrete when chunks of concrete chip off and separate from the structure. Corrosion tends to occur more commonly in places that receive high amounts of snowfall annually. Salt, which is used as a de-icing technique on the road surface, is a common corrosion catalyst when it seeps into worn areas of the bridge deck.

Figure 25: Example of corrosion on steel lateral bracing of bridge superstructure (taken from http://minnesota.publicradio.org/collections /special/columns/news_cut)

On a reinforced concrete bridge corrosion problems stem from the joints. In areas that receive high amounts of snow and rainfall, the salts used to de-ice the roads, debris and car fluids like gas and oil can leak into the abutments then down to the backwall. Because there is nowhere for the fluids to go and no way to dry these areas out, sodium and calcium chlorides from the deicing salts seep into the concrete and begin to gradually penetrate the protective coating on the steel until it is destroyed and the steel becomes exposed. Once the protective coating is removed environmental conditions such as high temperatures and intermediate levels of humidity and moisture can lead to increased rates of corrosion. Steel stringers and bearing plates are also affected by this process which leads to intensified corroding.

4.3.2 Impact of Corrosion

When corrosion is not prevented, it can lead to cracking of the concrete as shown in Figure 26. Once cracking occurs, the concrete component loses strength and will eventually begin to fail due to the excessive forces being applied to it. Once the rebar is initially exposed, the rate of corrosion which causes more of the surrounding concrete to crack. As the steel begins to rust, its strength properties are weakened. After a concrete component is subjected to cracking, the cost of maintenance and repair becomes extremely high. An alarming 17% (101,518 of 581,862) of the recorded bridges in the United States are deemed structurally deficient (US Department of Transportation, 1998). Although they are not in immediate risk of collapsing, they are, however creating an increasingly high financial burden on states and local transportation agencies. Estimated costs to repair the damage caused by the corrosion of reinforcements in concrete exceed $8.3 billion in the United States annually (Virmani, 2002). Because it is necessary to use de-icing salts on roads to make winter driving conditions safer for travelers, the corrosion problem on concrete bridges is going to continue to increase.

Figure 26: Heavily corroded reinforced concrete support on the Belmont Street/Route 9 Bridge

In an attempt to reduce the economic effects induced by these high maintenance costs, corrosion control methods, including the use of waterproof protective sealants and alternative non-chemical based protectants is becoming increasingly essential to United States infrastructure. Standard sealants and spray coatings can release harmful chemicals into the air. Also, certain chemicals in some sealants can wash away and affect the drainage system on the bridge. On site accidents including improper storage or handling of the products could also have a negative environmental impact. In an attempt to design using "green" standards, engineers have been experimenting with organic materials and alternative systems that don't have a negative impact on the environment. The one time implementation of corrosion diversion systems can reduce the waste generated from the storage and application of sealants and protective coatings.

4.3.3 Protective Sealants

Part of the maintenance of concrete elements includes the application of protective sealers. Waterproof sealants help to extend the life span of bridge components, especially the decks. Generally, sealants are applied to new concrete elements because they are not as effective on components which have already been subjected to deterioration. If a member has already started to deteriorate, the coating will not be applied to a smooth surface and will not be absorbed by the entire area of the member. If the member has begun to rust or flake, the protective coat will be applied to a surface that will continue to chip off. This process can result in a huge waste of money because the coating will not be effective.

4.3.3.1 Linseed Oil

Linseed oil mixtures are an organic alternative to protective sealers. Protection with the use of linseed oil is an economical method used by many state's Department of Transportation agencies because of their limited budgets and resources. Linseed oil is generally applied to a surface using a type of spray equipment. It is recommended that two coats of the protectant be applied to ensure the entire surface is covered (Morris, 1961). There are many disadvantages of using linseed oil that make it a less than optimal protectant for reinforced concrete bridge components. Compared to other alternatives, structures protected with linseed oil have lower flexure strengths, increased curing rates, and generally do not last as long. Linseed oil is sensitive to UV rays from direct sunlight which is a problem when used on bridges that are constantly exposed to extreme environmental conditions such as sunlight (Bushell, 2003).

4.3.3.2 Resin-Based Mortars

Most sealers react with the concrete by coating the exterior surface of the component. Silicon resins are different in that they penetrate into the element to create a sealed exterior (Tonias, 1995). A few resin-based mortars that have ideal bond characteristics include epoxies, polyesters, and polyurethanes. Resin-based mortars must be used with adequate concrete strengths because if used with a poor quality concrete, the resin will be very costly and not effective (Perkins, 1997).

4.3.3.2.1 Epoxies

When applied correctly, epoxy resins can be an effective protection product. Epoxies are two-component self-bonding adhesives that are injected directly into a cracked area. When the components are mixed and compared to sections of concrete not affected by corrosion, sections protected with epoxy coatings typically have higher strength values (Ropke, 1982). Fusion bonded epoxy coated rebars (ECR) are the preferred types of corrosion protectants used in most states. This method has been implemented on over 20,000 reinforced concrete bridge decks across the United States. Although epoxy coated rebar does not completely eliminate corrosion, it has succeeded in delaying the rate at which the steel rebar corrodes. It is estimated that in the last 25 years, the use of epoxy coated rebar in bridge design has saved taxpayers billions of dollars (US Department of Transportation, 1998).

Developments in the types of alloys and cladding of steel rebar have been applied in an effort to increase the service life of concrete decks. Although they ensue higher costs, solid stainless steel 316 rebar and stainless steel clad black bars are alternatives that have performed exceedingly well during corrosion testing. Studies on other alternatives such as a combination of epoxy coated rebar and corrosion inhibiting admixtures including calcium nitrate have been tested. Researchers continue to test the use of other inhibitors that could be more effective than calcium nitrate.

4.3.3.2.2 Polyesters

Polyester resins react similarly to epoxy based resins but have a few key differences, some being advantages over other types of resins while others are disadvantages. One observation is that polyester resins tend to shrink at a higher rate than epoxies during the curing process. The coefficient of thermal expansion of polyester resins exceeds that of epoxies by approximately 1.5 times (Perkins, 1997). Because polyester resins experience a high rate of shrinking, they do not fill a sufficient amount of the crack gap. If the resin does not adequately fill the gap, moisture can seep through the space between the resin and member. Since this is not an effective protective measure, its application can result in a waste of money.

Unlike epoxies, the shelf life of polyesters is limited, although the amount of catalyst used in polyesters does not require as high of a percentage of measurement accuracy as epoxies. To ensure the most effective use of polyester resins, a primer should always be used since the curing of polyester is dependent on the amount of moisture present (Perkins, 1997).

4.3.3.2.3 Polyurethanes

Like most sealants, there are a variety of types of polyurethane sealants that are used for different purposes. Polyurethanes are commonly used to seal joints on bridges. A few of the most notable characteristics of polyurethane sealants are their resistance to abrasion, impact and chemical attack, flexibility, and their ability to bond well to concrete and mortar with dry surfaces.

4.4 Non-Chemical Alternative Corrosion Protectants

In an effort to become more environmentally friendly and sustainable, methods for reducing corrosion without the use of chemical based substances have been created. Many of these methods include exploring the effectiveness of using completely organic corrosion sealants. These methods range from increased wearing surface covers to the use of non-corrosive materials such as fiber-reinforced polymer.

4.4.1 Increased Concrete Cover Thickness

One idea to prevent corrosion of a concrete wearing surface of a bridge is to increase the thickness of the cover. This involves simply placing another concrete slab over the pre-existing corroded slab. This technique has many disadvantages including high costs and safety factors involved in raising the height of the road. Unless engineers can calculate the rate at which the concrete wearing surface is going to corrode, it is hard to predict an offset for the initial slab thickness. This creates an issue in accounting for increased thickness of the cover as a part of routine maintenance. By adding a layer of cover, the weight of the wearing surface will increase. This will affect the moment of the slab and can have significance in the maximum capacities of the original bridge components, especially if some of the other original bridge components are experiencing different levels of failure.

4.4.2 Cathodic Protection

The use of Cathodic protection systems on bridge decks have become a fairly routine rehabilitation technique in bridge maintenance due to improved applications based on extensive research and development of durable anodes, monitoring devices, and installation techniques. Corrosion occurs at anodes through electrochemical reactions triggered by chlorides, oxygen and moisture. A low-level electrical current is generated at the steel surface. The area where the current leaves the steel and enters the concrete is called an anode. The spot where the current leaves the concrete and returns back to the steel is called the cathode. Corrosion occurs once the rust occupies more volume than the original protected steel rebar which causes tension forces in the concrete. Being that concrete is weak in tension, cracks develop in the concrete; the cracks expose the steel, which further accelerates the corrosion process.

The process of Cathodic protection offers a way to shift the electric currents provided to an external current source to counteract the corrosion current. This process is meant to stop, or at least slow down and control the electrical current that causes concrete corrosion. There are two main types of Cathodic protection, energy demand versus material consumption systems. Impressed current Cathodic protection involves inserting a low voltage direct current into the reinforcing steel through the concrete from a motionless anode material. The galvanic systems process uses metal like zinc to function as a sacrificial anode that protects the steel rebar (Scannell & Sohanghpurwala, 1993).

4.4.3 Composite Materials

As advances in uses of composite materials in building have become more popular, opportunities to design with non-corrosive materials have become an admired possibility. Designing with composite materials have many advantages over traditional building materials including, a higher strength to weight ratio, a more effective stiffness to weight ratio, ability to resist chemical attacks, and more flexible custom design features (Constructability, Maintainability, and Operability of Fiber-Reinforced Polymer Bridge Deck Panals, 2004).

One example that has been researched and implemented on an actual bridge design is a fiber-reinforced polymer bridge. This bridge uses a prefabricated plastic grid in the concrete deck in place of the steel rebar. The plastic material is resistant to corrosion and more durable in the winter months.

4.5 Summary

The in depth background research will aid in the analysis of choosing appropriate materials and protectants for the design of the bridge. Choices will be based on cost, availability, efficiency, and value to sustainability. The results section illustrates the many factors that are incorporated in the decision making process.

4.6 Results: The Implications of Recycling

This section focuses on the implications of sustainability through recycling. Regarding construction projects, recycling can occur during demolition and construction phases. Therefore, the analysis will be split into plans for implementing recycled materials into the design for construction and recycling the existing components of the withstanding bridge.

The sections discussing recycled materials are:

- *Steel Selection*
- *Concrete Mix Design*
- *Supplier Selection based on Location*

The actual procedure of recycling the bridge components will be addressed in:

- *Economic Benefits of Recycling*
- *Waste Management Plan*

4.6.1 Steel Selection

After conducting background research about *recycled steel*, it is concluded that steel is inherently recycled. Therefore, *steel* and *recycled steel* are essentially synonymous. As discussed previously, the Electric Arc Furnace (EAF) reconstitutes steel scraps to comprise new structural products. This technology also makes it possible to achieve higher strength steel and approximately 95% of the steel used for this process is reclaimed. Since new products are generally fashioned from steel products at the end of their lifetime, the steel girders from this project could be provided by any one of MassHighway's approved steel distributors.

4.6.2 Concrete Mix Design

The process of creating a concrete mix is a science and an art. Concrete mix can be comprised of different ingredients and varying proportions of the ingredients to achieve desired properties. Innovative mix designs incorporate recycled materials to enhance the overall life-cycle efficiency of the concrete, and to reduce the impacts on the environment.

In 1998, the Danish Centre for Green Concrete was established in Denmark based on the fact that concrete is a very popular building material, but traditional concrete production has negative effects on the environment. The Danish Centre for Green Concrete is a united effort of many prominent businesses and universities to remediate the negative effects of concrete and formulate ways to make concrete a "green" product. Recommendations for an environmentally friendly mix design are shown in Figure 27.

The following criterion for "green" mix design was established by the Danish Centre for Green Concrete:

• CO_2 emissions shall be reduced by at least 30 %.
• At least 20 % of the concrete shall be residual products used as aggregate.
• Use of concrete industry's own residual products.
• Use of new types of residual products, previously landfilled or disposed of in other ways.
• CO_2-neutral, waste-derived fuels shall substitute for fossil fuels in the cement production by at least 10%

(Dundee, 2002).

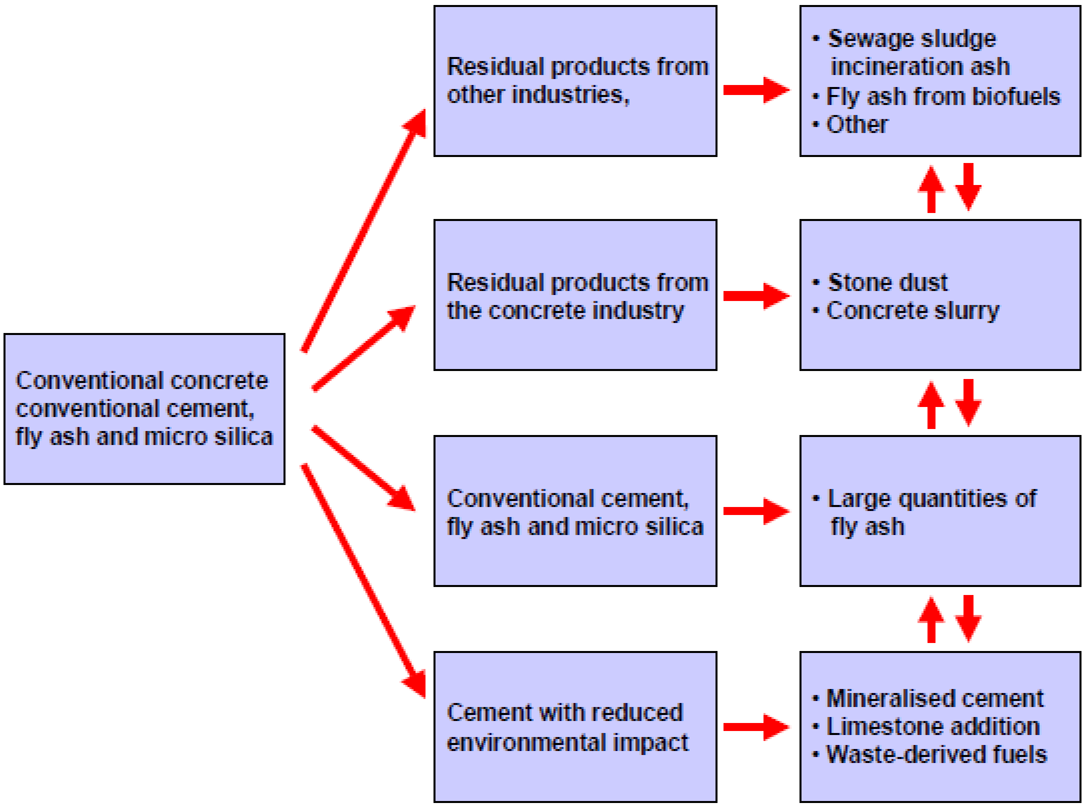


Figure 27: Recommendations for environmentally friendly mix design (taken from Dundee, 2002)

The Danish Centre for Green Concrete incorporated byproducts like fly ash into various mix designs and conducted a pilot study to determine the results. Some of the ingredients included in the designs included fly ash (FA), sewage sludge incineration ash (SSIA), Silica fume (SM), superplasticizer (SPT), and cement with reduced environmental impact (CREP). The mix design proportions are shown in the Figure 28.

	AR Reference	A0 CREP	A1 40 % FA + CREP	A3 10 % SSIA + CREP	A5 Concrete slurry	A6 50 % stone dust
Cement, kg/m^3	288	287	189	277	398	397
FA, kg/ m^3	34	32	137	-	-	-
SF, kg/m^3	17	17	18	17	-	-
SPT, kg/m^3	-	-	3.4	3.2	4.0	6.8
Equiv. w/c	0.45	0.47	0.46	0.45	0.38	0.37

Figure 28: Green concrete mix designs (taken from Dundee, 2002)

Each mix was tested and compared to the reference concrete which is a typical concrete mix design. The concrete mixes were examined for workability, compressive strength, air-content, elastic modulus, density, and setting time. The results concluded that "the mechanical properties of a green concrete show that these do not differ significantly from the mechanical properties of the reference concretes" (Dundee, 2002). Figure 29 depicts the assessed environmental and compressive strength goals.

	Aggressive environmental class				
Name	A0 CREP	A1 40 % FA + CREP	A3 10 % SSIA + CREP	A5 Concrete slurry	A6 50 % stone dust
• Own residual product	-	-	-	√	√
• New type of residual product	-	-	√	-	√
• Waste-derived fuels	√	√	√	√	√
Environmental intentions	√	√	Wastewater quality? (Zn, Pb, Cu, P_2O_5)	√	√
Compressive strength					
28-day, MPa	51 √	58 √	58 √	64 √	62 √
56-day MPa, (% of reference concrete)	58 √ (112)	61 √ (117)	68 √ (130)	68 √ (130)	63 √ (121)

Figure 29: Environmental and compressive strength characteristics of concrete mixes (taken from Dundee, 2002)

Results from the table show that the concrete mixes met the goals for environmental benefits, and 28-day and 56-day compressive strengths. The green design concretes have significantly higher 56-day compressive strength than the reference concrete. All of the mixes exceeded the compressive strengths of a typical concrete mix. The analysis proves that concrete can be made with recycled materials without compromising the strength and durability of the concrete. This study can be used as a framework when proportioning recycled concrete aggregate mixes.

4.6.3 Supplier Selection Based on Location

In order to determine whether it is feasible or not to use recycled base materials, it is necessary to investigate if local concrete producers offer such products. Since MassHighway has jurisdiction over the reconstruction of the Belmont Street/Route 9 Bridge contractors need to be qualified, and it is an advantage to have experience with MassHighway projects in the area. For example, Aggregate Industries is the closest approved subcontractor offering concrete with recycled aggregates. They were responsible for supplying the concrete for local MassHighway projects such as the Worcester Via-Duct and the Reconstruction of the I-290 Bridge over Brosnihan

Square/ MA 146 (MassHighway, 2006). Aggregate Industries has two plants in Worcester, as well as plants in North Grafton, Millbury, Berlin, Charlton, Littleton, and Lunenburg. In addition to concrete plants they "accept and recycle over 200,000 tons of concrete each year" (Aggregate Industries, 2009). Aggregate Industries has 12 recycling divisions located in Massachusetts. Figure 30 pinpoints the locations of the recycling plants is presented below.

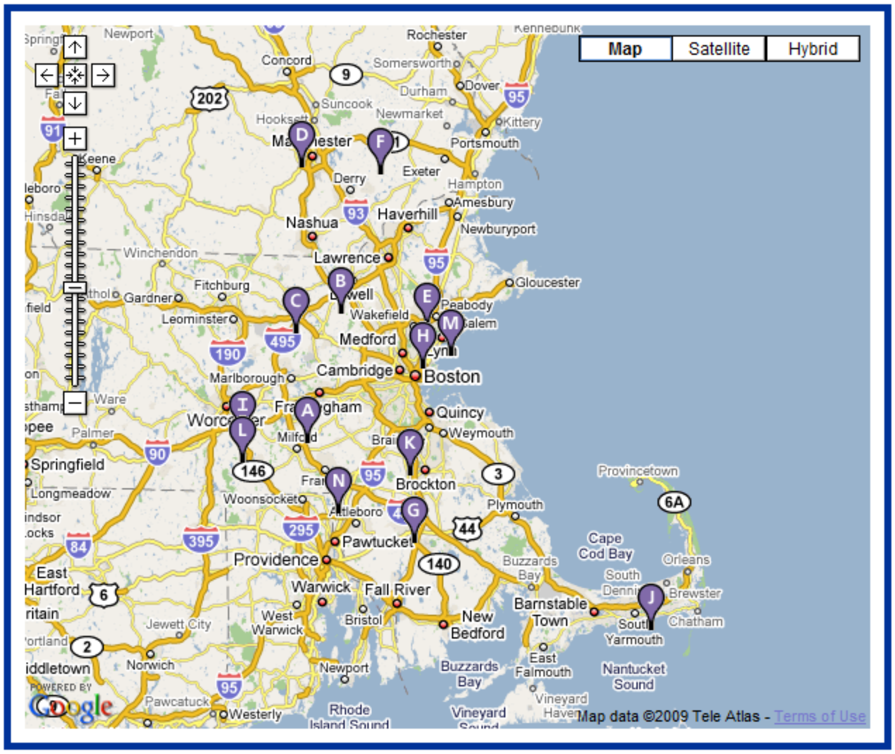


Figure 30: Map of Aggregate Industries Recycling Divisions (taken from Aggregate Industries, 2009)

Furthermore, Aggregate Industries recycled based products are approved by MassHighway. They have the ability to make recycled base concrete for structural purposes and can incorporate the recycled fly ash byproduct into ready-mix concrete. Utilizing recycled products from Aggregate Industries "can contribute valuable LEED certification credits for Recycled Content (MR 4.1 & 4.2) and Local / Regional Materials (MR 5.1 & MR 5.2)" (Aggregate Industries, 2009).

For the purpose of this project Aggregate Industries seems to be the best option for producing the recycled based concrete. They are a company who is striving for innovative design and have experience with sustainable products. Also, supplies are readily available at local plant locations which will cut down on emissions created by transportation.

4.6.4 Economic Benefits of Recycling

The Massachusetts Department of Environmental Protection (MassDEP) conducted a Case Study in 2003 in order to determine the economic and environmental benefits associated with recycling construction debris. The Case Study concentrated on the demolition and reconstruction of the Douglas School, located in Douglas, Massachusetts. This project is of special interest because it is located approximately 20 miles from Worcester, MA. Since the Douglas school is located within close proximity to the Belmont Street/Route 9 Bridge then the recycling cost and the recycling methods should be comparable (Bureau of Waste Prevention, 2003).

Consigli Construction Inc., located in Milford, MA, was the primary contractor for the project. Employees of Consigli worked in conjunction with MassDEP personnel to create a cost benefit analysis of recycling. The primary materials recycled were concrete, metal, wallboard, cardboard, and wood. Figure 31 depicts the amount saved by recycling each material is depicted below. The recycling costs presented from the table come are due to equipment and separation charges. Disposal rates may have changed since 2003, but the case study is still a valuable reference (Bureau of Waste Prevention, 2003).

Material	Tons	Recycling Cost	Avoided Disposal Cost*	Savings
Concrete	285	$8,265	$31,065	**$22,800**
Metal	69	$1,380	$7,521	**$6,141**
Wallboard	49	$2,559	$5,450	**$2,891**
Cardboard	0.67	$67	$70	**$3**
Wood	40	$4,381	$4,358	**(-$23)**
TOTALS	**443.67**	**$16,652**	**$48,464**	**$31,812**

**Cost that would have been paid if material was disposed.*
Disposal costs based on local rates in 2003.

Figure 31: Cost savings due to source separation and recycling (taken from Bureau of Waste Prevention, 2003)

It is apparent from the table that recycling construction materials is a better alternative than disposing the debris into landfills. According to the Case Study, waste was reduced 57% by weight and $31,812 was salvaged by recycling alone. Since recycling 285 tons of concrete results in a savings of $22,800.00 then recycling one ton of concrete approximately saves $80.00.

Respectively, $89.00 is saved by recycling one ton of metal. These savings can be used to estimate how much money could be saved by recycling the materials of the Belmont Street/Route 9 Bridge (shown below).

Material	Tons	Savings Per Ton	Savings
Concrete	x	$80.00	X*$80.00
Metal	Y	$89.00	Y*$89.00

Total Savings=X*$80.00 + Y*$89.00

Only concrete and metal scraps need to be assessed for the bridge project. Once the tons of materials to be demolished and recycled are known then total savings can be calculated. Recycling would generously reduce the cost for the reconstruction of the Belmont Street/Route 9 Bridge as well as offer an environmentally friendly solution to discarding materials.

4.6.5 Waste Management Plan

It cannot solely be suggested that materials on site should be recycled; a waste management plan must be devised and incorporated into the contract to put this idea into action (Bureau of Waste Prevention, 2003). The waste management plan should be composed in the planning stages of a project to ensure all of the requirements are met. A comprehensive plan provides a framework of expectations for the project. By assimilating the waste management plan into the contract, the contractor is aware of the recycling specifications and procedures for the project. In the case study mentioned previously, Consigli Construction Inc. outlined what they found to be *"Keys to Success: Oversight of Recycling."* The objectives are listed below: (Bureau of Waste Prevention, 2003)

- Tie the subcontract language to a waste management plan that requires recycling, specifies recycling techniques, and provides incentives for recycling.
- Negotiate disposal fees by type of material to reduce costs based on the market value of the material rather than paying a flat fee for all materials.
- Verify that recyclable materials are brought to a recycler by requiring that the contractor provide "weight slips" from a recycling facility.

These points should be implemented into the waste management plan to ensure the contractor will comply with the specifications. Once the plan is completed, copies should be dispensed to all personnel involved in the construction project, and discussed for greater clarity.

The waste management plan proved to be beneficial for Consigli Construction. They maintained the waste reduction planning process "made for a cleaner and safer site. A more intensive focus on scheduling recycling and disposal hauling created greater efficiencies" (Bureau of Waste Prevention, 2003). A copy of Consigli Construction's Waste Management Plan is attached in Appendix K. Some of the ideas for composing the waste management plan for this project were inspired from Consigli's plan.

The preliminary waste management plan for the Belmont Street/Route 9 Bridge is outlined below:

Belmont Street/Route 9 Bridge
Waste Management Plan

- It shall be the responsibility of the contractor to ensure that the objectives of this plan are upheld.
- Any questions shall be addressed to the MassHighway's on-site Resident Engineer

Objective:

To reduce the amount of construction debris accumulated during demolition by separating and recycling the recoverable materials.

The main goal is to recycle at least 85% of the construction waste to make use for new projects.

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Plan of Action:

- Disposal of construction materials shall be avoided.
- The general contractor shall assign an employee to administer the waste management plan
- Recycling bins shall be accessible on site.
  - Bins should be clearly labeled based on material type.
  - Steel and concrete shall be separated and placed into respective bins.
- The general contractor is responsible for transporting the material to the appropriate recycling facility.
  - Fees will be negotiated.
- The General Contractor is responsible for compiling reports to track progress.

* Fines shall be applied if guidelines are not adhered to.

4.7 Recycling Conclusion

The overall reconstruction of the Belmont Street/ Route 9 Bridge will be enhanced with the implications of recycling. Recycling will prolong the life-cycle of the bridge materials. The procedure of recycling follows the cradle to the grave approach which assesses the impact of a material from manufacture to disposal. Old components can be utilized to make new components, and when those components reach the end of their lifetime new ones can be fabricated. So at the "grave" stage, materials are not discarded, but reused to make new products.

Another benefit is to use recycled materials to reduce cost and environmental impacts. Byproducts such as fly ash are generally transported to landfills. However, fly ash is beneficial to the concrete industry, and is virtually free because coal producers want to get rid of it. Also, CO2 is reduced since fly ash can substitute for some of the cement needed for concrete mix.

When deciding on which alternative to use, it was evident that the decision needed to be based on cost, location, and availability. The prior sections offer the solutions which meet these criteria. The decision to implement recycled steel, recycled base concrete, and the waste management plan is a preliminary step towards planning for the future.

4.8 Approach to Determining Corrosion Protection Methods

Results from various case studies that investigated material options during new structure construction and effective options for maintenance protection methods were compared to determine economical and sustainable alternatives in corrosion protection. Findings based on these results were then examined to determine the most suitable alternatives for corrosion protection on new construction bridges and maintenance of existing bridges in the New England area.

In order to determine the best corrosion protectant for both new and existing structures, the environmental conditions of the location of the project must first be studied. The location of the bridge can affect the types and amounts of materials to be used in construction and maintenance. The location and design of the bridge can also affect the exposure of components to degradation processes. Also, some construction methods or maintenance systems may not be suitable for all climates and environmental conditions. After the conditions are taken into account, types of rehabilitation methods must be analyzed for that area to determine the best system to use. Once the type of failure is determined, the type of maintenance required to temporarily or permanently repair the problem can be chosen.

4.8.1 Establishing Environmental Conditions for New England

Figure 32 shows the average snowfall in the New England city of Worcester, MA, where the Belmont Street/Route 9 Bridge is located. The darker green line shows that the amount of snowfall in Worcester during the winter months is well above the national average as shown by the light green shading on the graph. In areas that receive large amounts of snowfall, like the New England region, bridge components tend to fatigue faster than areas that don't experience as much precipitation. In drier areas, the bridge deck is not as susceptible to moisture and will most likely not be affected by corrosion as early as bridge decks located in areas that have greater rain and snowfall. The values determined by the study indicate the importance of taking into account the location of a project when determining the type of maintenance and repair it will need in the future.

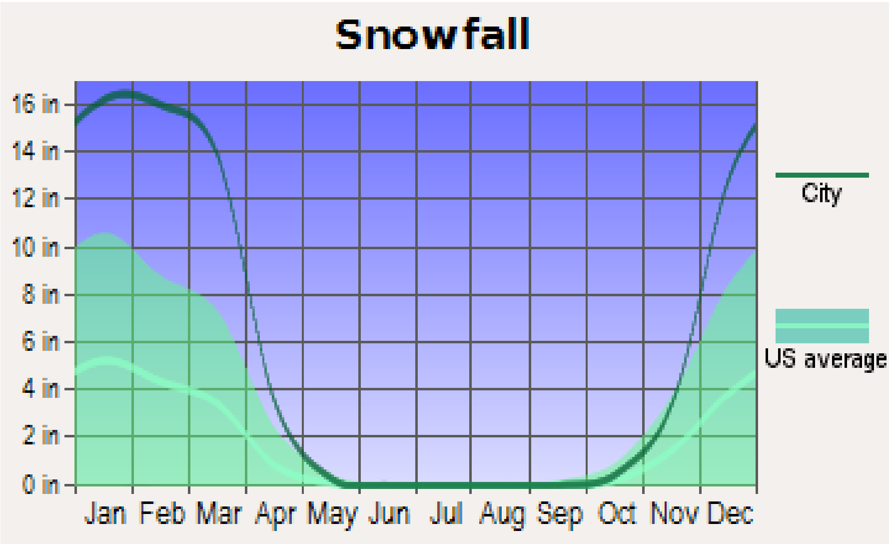


Figure 32: Average snowfall in Worcester, MA based on 2007 readings (taken from http://pics2.city-data.com)

4.8.2 Determination of Rehabilitation Methods

Consideration for the type of method used for bridge maintenance depends on the condition of the existing structure. Maintenance for bridges can be very costly and since funding for bridge maintenance is often scarce, choosing an economical but effective rehabilitation method becomes even more crucial. When determining the type of rehabilitation method to be used on a bridge maintenance project, the following considerations are taken:

- Type of failure
- Intensity of failure
- Adhesion
- Type of coating used

4.8.2.1 Type of Failure

Deterioration of reinforced concrete bridge elements can be caused by cracking, spalling which can lead to advanced stages of corrosion. It is estimated that 150-200 bridges in the United States partially or fully collapse due to increased deterioration which leads to a decrease in strength of the reinforcements (Val, Stewart, & Melchers, 1998). Cracking and spalling allows the steel reinforcement to become exposed to moisture and contaminants which accelerate the rate at which the steel corrodes. There are two types of corrosion that affect the steel rebar, general corrosion and localized corrosion. General corrosion affects large areas of reinforcement at a time while localized corrosion attacks small, concentrated areas of reinforcement. The corrosion of the steel rebar is evidence that the moisture has penetrated beneath the coating system through an existing break in the protectant. If this is not maintained in a timely manner, the rate of corrosion will intensify with the continuous attack of contaminants.

Types of failure of the coating used on concrete reinforcement are most commonly caused by the incorrect application of the protectant at the time of the reinforced concrete formation. Once the original coating is breached, incompatibility with new types of coatings can cause problems with lessened protection of the steel rebar. With the increased development of protective coatings made available, it is more common to see problems with incompatible coatings during maintenance. Often, the types of coatings used to protect the rebar are never recorded, so inspectors have difficulty identifying the original coatings used to determine compatibility with new coats which are applied during maintenance.

4.8.2.2 Intensity of Failure

Bridge inspectors perform visual inspection of bridge elements to determine the level of failure of the member due to deterioration. From their inspections they can determine the extent of the maintenance required. Because of differences in the experience and judgment of inspectors, it is common that there are variances in their inspection reports and therefore, it is common that the ratings of the level of failure can be controversial. The American Society for Testing and Materials (ASTM) has created a system of standards that simplify the process of inspection of coating systems and ensure all inspectors are following the same process during their investigation (Virmani & Clemena, 1998). Table 10 lists the different test methods used to examine the bridge condition. These tests are used to evaluate the degrees of deterioration based on the type of deterioration identified by the inspector. Tests are generally done on site based on visual inspection but at times when further investigation is needed, sample materials can be brought back to labs for extensive testing.

Table 10: Evaluation of degrees of deterioration of bridge deck based on ASTM Standards (taken from astm.com)

ASTM Standard	Description
D610	Test methods for evaluating degree of rusting on painted steel surfaces
D660	Test method for evaluating degree of checking of exterior paints
D661	Test method for evaluating the degree of cracking of exterior paints
D662	Test method for evaluating degree of erosion of exterior paints
D3359	Test method for measuring adhesion by tape test
D4214	Test methods for evaluating the degree of chalking of exterior paint films
D5043	Test methods for field identification of coatings
D5064	Practice for conducting a patch test to assess coating compatibility
D5065	Guide for assessing the condition of aged coatings on steel surfaces

Table 11 uses ASTM codes to assign a rating to the failure of the coating layer so the extent of maintenance needed on the bridge component can be determined. It provides a description of the area subjected to failure followed by a guideline of the appropriate amount of protectant needed to effectively maintain the area.

Table 11: Amount of area to be painted based on ASTM Standards (taken from astm.com)

Corrosion rating	Description	Area to be painted (%)
10	No rust or less than 0.01% rust	0
9	Minute rust, less than 0.03% rust	0
8	Few isolated rust spots, less than 0.1% rust	0
7	Less than 0.3% rust	0
6	Extensive rust spots, less than 1% rust	8
5	Less than 3% rust	18
4	Less than 10%	40
3	Approximately 1/6 of surface rusted	60
2	Approximately 1/3 of surface rusted	100
1	Approximately 1/2 of surface rusted	100
0	Approximately 100% of surface rusted	100

4.8.2.3 Adhesion

Adhesion between the coating and the steel is essential to ensuring the effectiveness of the protectant. A lack of adhesion can result in early failure of the protectant and wasted funds and effort. As new layers of adhesives are needed for the upkeep of maintenance, surface preparation and the additional weight of the new layers can reduce the effect of the original adhesive coating.

4.8.2.4 Type of Coating

The type of coating used during maintenance is limited by the type of original coating used on the component. If the two types of coatings used are not comparable, there will be problems with the adhesion of the system. One method engineers use to determine if the two types of coatings are compatible is a patch test. During this test a section of the existing coating is cleaned, recoated with the new coating then evaluated for failures (Virmani & Clemena, 1998). This test is performed in the field and quality results can be obtained seven days after the application of the new layer of coating (Andrews-Phaedonos, 2006).

4.8.3 Maintenance Strategies

Once the areas needing attention are examined and classified, the maintenance strategy can be established. There are three types of maintenance strategies for coating protection including:

- Spot repair
- Overcoating
- Complete recoating

Some maintenance strategies are more effective than others, while others are more economical. In a world where the cost of maintenance is ever increasing, procedures which are effective while still being economical are desirable. Some protective coatings are used cautiously in bridge maintenance because the chemicals they are made of are detrimental to the environment.

4.8.4 Creation of Corrosion Protection Method Matrix for Existing Bridges

To determine the most suitable method of corrosion protectant, a rubric was made to compare the many alternatives. The rubric allows the user to rate each component on a range from 1 to 5 with 1 being the least optimal rating and 5 being the most optimal rating for the cost, availability, ease of use and service life categories. For the environmental impacts category, 1 is the most optimal rating while 5 is the least optimal rating. Table 12 illustrates the use of the rubric to select a corrosive protectant. The rubric can be used to determine bridge maintenance procedures in various locations by simply changing the ratings of the different criteria to suit the specific bridge being analyzed. Table 12 shows a hypothetical example of how the matrix can be used.

Table 12: Matrix for determining corrosion protectants on an existing bridge

Method for Determining Most Suitable Corrosive Protectant on an Existing Bridge					
Method	**Cost**	**Availability**	**Ease of Use**	**Env. Impacts**	**Service Life**
Method A	2	4	2	1	5
Method B	1	5	3	2	2
Method C	5	3	1	5	2

A description of the criteria for each category is included with the matrix to alleviate any confusion with users and ensure the most suitable rating is given.

Method – includes a brief description of the method or system used for corrosion protection

Cost – how economical is the installation, materials and labor involved in the process? (allow the average cost of complete implementation to range from $10/square foot to $7.00/square foot of cover)

Availability – are the supplies and materials located within a short proximity of the location? (allow the average distance to supplies to be 500 miles)

Ease of Use – is the work required to apply the protectant minimal or extensive? How long does it take for the system to be installed?

Environmental Impacts – does the protectant or process harm the environment in any way? Are the workers who install the system in any kind of health risk?

Service Life – how long can the protectant last in the given environment? (allow the average service life of the bridge with protectant to be 15 years)

Figure 33 shows the scales used to define ratings for each category. It can be noted that the ratings have ranges so users can easily decide on the rating for each category based on their input value. The graphs show that there tends to be a linear relationship between numerical ratings for each of the five categories included in the corrosion protectant selection process.

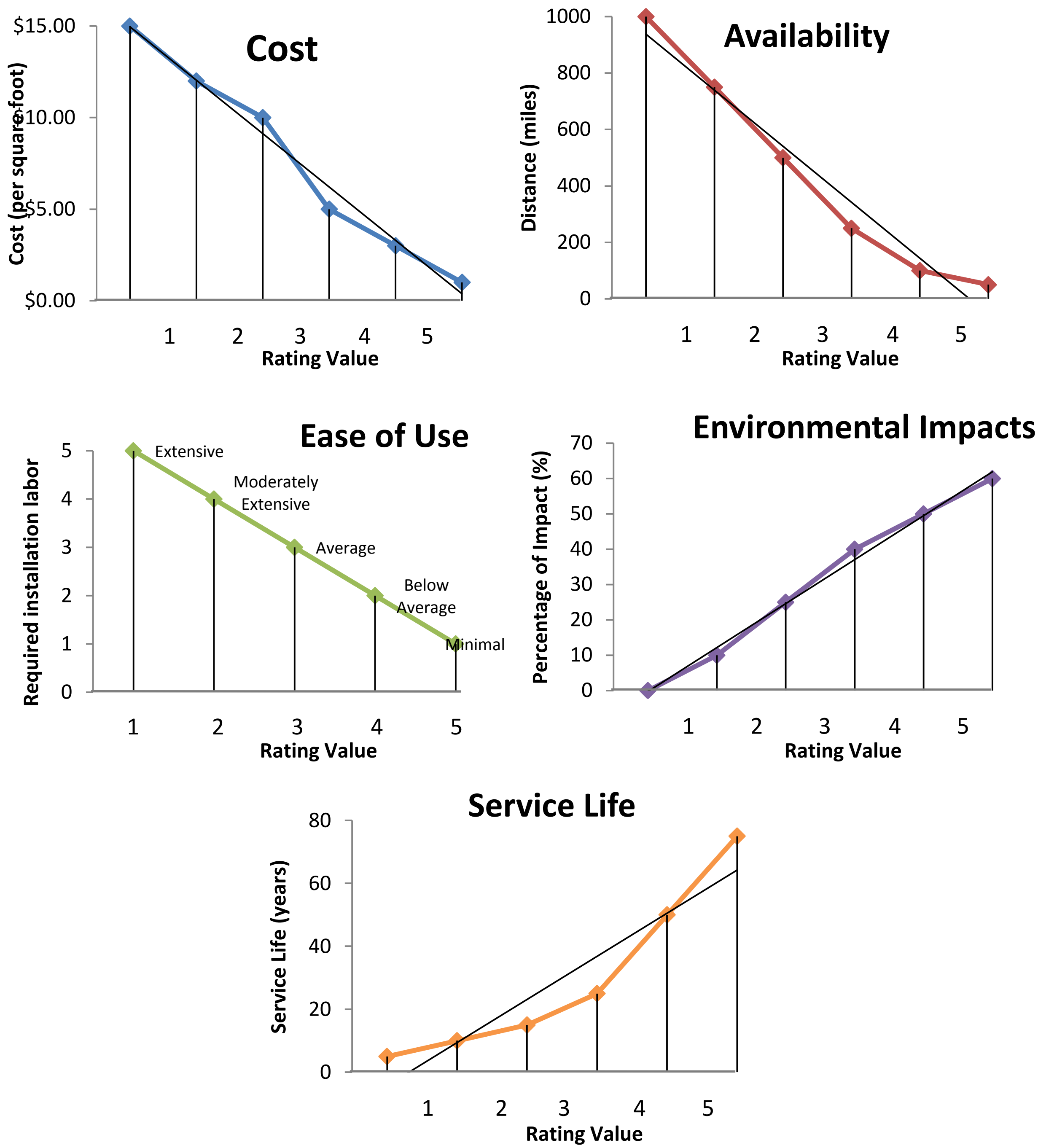


Figure 33: Scales to determine category rating

To determine which option is best, the user can decide if there is certain criterion that are more important than others and if so they can choose based on the comparisons of ratings of those groups. It is important to note that the environmental impacts category is assigned negative values meaning that unlike the other categories, a lower value indicates a better system.

This matrix tool was used to determine which of the alternatives involved in the further study were most desired. In the case of the Belmont Street/Route 9 Bridge, the method of protectant determination will take a particular focus on the ratings of the environmental impacts and service life categories.

4.9 Maintenance Results

In new bridge design there are measures that can be taken during the initial design and construction phase to best select building materials to increase the protection of corrosion. Once an existing bridge becomes susceptible to cracking and corrosion, there are certain maintenance materials and methods that can be used to prolong the service life of the structure.

4.9.1 Alternatives for Protection of New Bridge Construction

The Federal Highway Administration (FHWA) with the participation of the National Institute of Standards and Technology conducted research and testing on design options available during the construction of a new bridge structure. Conclusions were drawn to determine the ideal building materials based on their testing and analysis. These conclusions highlighted four major components including: the thickness of the cover, the quality of the concrete, the use of corrosion inhibiting admixtures, and the utilization of corrosion resistant reinforcement.

4.9.1.1 Concrete Cover Thickness

Typical concrete cover thickness ranges based on State codes and the environmental conditions of the area where the structure is being built. Based on LRFD guidelines, the standard minimum cover thickness is 2.5 inches as used in the bridge re-design (Tonias, 1995). Using an increased cover thickness on the deck will increase the durability of the concrete and increase the amount of time it takes to crack. One issue with increasing the thickness is the increase in price due to the addition of material and labor needed to implement the new cover thickness. Regardless of the thickness of the concrete cover, due to the properties of concrete and the existence of pores in the material, the concrete will inevitably crack in time when subjected to constant use and wear from traveling vehicles. To determine an adequate thickness for the cover, Fick's equation for the second law of diffusion can be used.

$$\left(\frac{\delta Cx}{\delta t}\right) = D\left(\frac{\delta^2 Cx}{\delta^2 \chi}\right)$$

This equation is used to measure the rate of diffusion through the porous material due to the intrusion of chloride in the concrete (Virmani & Clemena, 1998).

Increasing the surface thickness by adding thicker or multiple layers can also increase the strengths of the protection. This method also tends to have a higher initial cost but is compensated for by its longer service life.

4.9.1.2 Concrete Quality

Based on findings from testing of concrete quality of the FHWA, it can be determined that concrete quality does have an effect on the rate at which chloride can penetrate into the concrete and inhibit corrosion. Typical water to cement ratios for concrete components on a bridge can range from 3000 psi to 4000 psi depending on the project. Evidence from testing shows that lower water to cement ratios with good consolidation of the mixtures decreases the air voids in the concrete which reduces the rate of permeability of moisture and contaminants. Figure 34 clearly shows that as the water to cement ratio is decreased, the compressive strength of the concrete has a significant increase. The disadvantage of a better concrete quality lies in the cost. Although a higher quality of concrete will increase the initial amount of time it will take for cracking to occur, based on the properties of concrete, cracking will inevitably occur at some point. Based on this point, the question of increased cost becomes a key area of interest in the investigation of the long term effectiveness of a higher quality concrete.

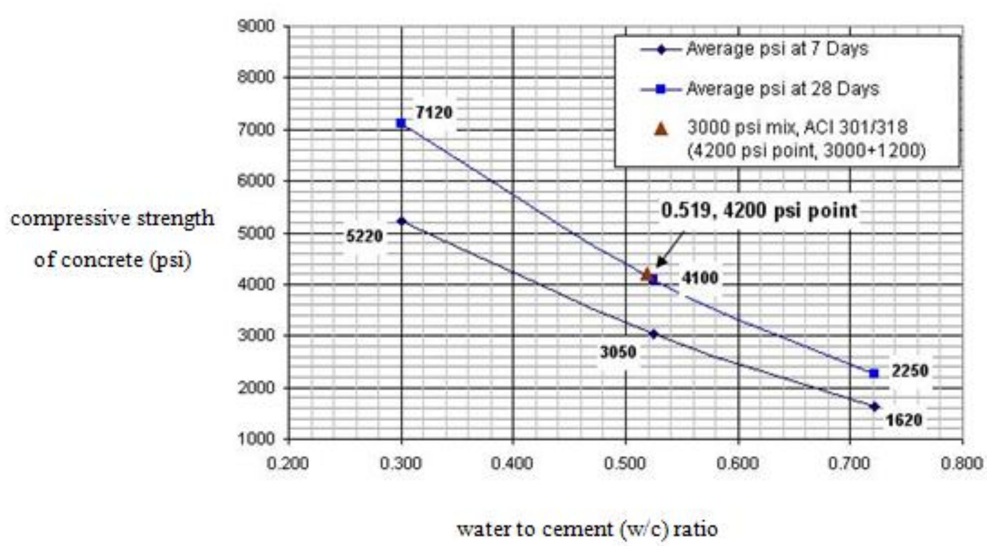


Figure 34: Typical strength vs. water to cement ratio curve (taken from http://www.pensacolatesting.com)

4.9.1.3 Corrosion Resisting Reinforcement

There are several different types of corrosion resisting reinforcement ranging from types of rebar to the variety of protective coatings that are used to cover the rebar. Steel reinforcement is the most common option for bridge design. Two of typical coatings include epoxy coated rebar and galvanized rebar. In the last few decades the use of polyfiber rebar has also been investigated.

4.9.1.3.1 Reinforcement Bar Types

There are several different types of rebar that can be used as reinforcement. The type and coating of the bar can vary in size and material. The use of black steel rebar is conventional in many existing bridges. As many of the state and highway bridges began to suffer from extensive corrosion issues, the authorities found it necessary to investigate more effective methods of protecting bridge reinforcement. Today, engineers have successfully tested many different types of rebar including: epoxy coated steel, galvanized rebar, and more recently the use of polyfiber reinforcement.

4.9.1.3.2 Epoxies

A recent survey conducted by the FHWA showed that the use of epoxy coated rebar in concrete bridge decks is the most common corrosion protection method used by 48 state transportation departments. Among the different types of epoxy coatings, fusion-bonded epoxies tended to be the most preferred system. Based on a cost impact analysis conducted on three bridge decks in Illinois that used epoxy coated rebar for reinforcement, the delivered on site cost of the black steel compared to the epoxy coated rebar was $0.08 higher for the epoxy alternative. Based on the fact that epoxy coated rebar can double the service life of a bridge protected with black steel, the higher initial cost is worth the overall investment. Of the approximate 2.3 billion square feet of bridge deck in the United States, only about 100 million square feet of bridge deck have taken advantage of the value of epoxy coated rebar (Virmani & Clemena, 1998).

4.9.1.3.3 Galvanized Rebar

The FHWA has also performed tests with zinc-coated rebar. Overall results showed although galvanized bars tended to delay the rate of corrosion, the zinc-coating did not prevent it. Some results even showed that once the salt did penetrate the surface of galvanized bar, it began to corrode at a faster rate than the non protected black steel (Virmani & Clemena, 1998).

Figure 35 shows the various layers of hot-dip galvanized coating with their hardness based on the Diamond Pyramid Number (DPN). A higher DPN value indicates a harder material. As noted by the figure, the middle three layers: gamma, delta and zeta are generally harder than the underlying base steel layer. These three layers provide excellent protection against abrasives. The top layer, or Eta layer has a lower hardness, which indicates increased ductility and provides a better impact resistance for the coating. When compared to other coatings, galvanized coatings adhere to the base steel at a magnitude in thousands of pounds per square inch, where typical coatings are only rated at hundreds of pounds per square inch.

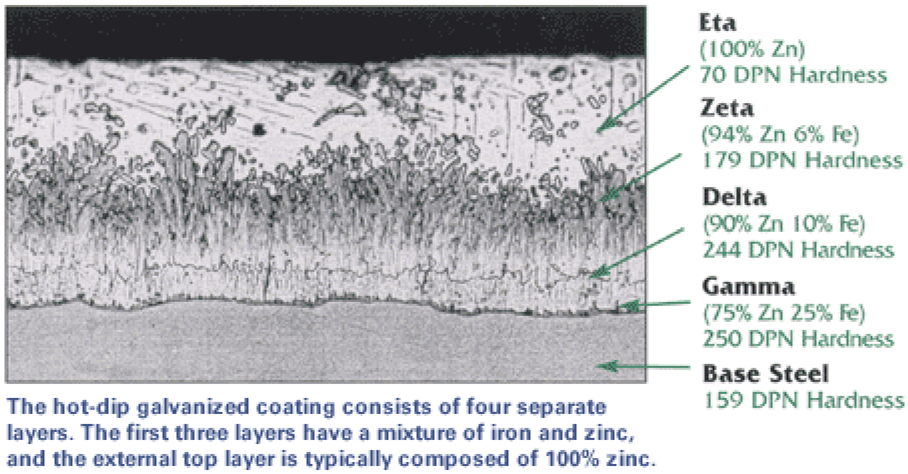


Figure 35: Photomicrograph of a galvanized steel coating cross-section (taken from American Galvanizers Association)

Because the process of galvanizing rebar can be very costly, these findings did not yield optimal results. This process of protection lacks standardization and because of that reason it is hard to obtain laboratory results that can efficiently predict the service life of using galvanized rebar compared to other types of reinforcement.

4.9.1.3.4 Polyfiber Reinforcement

Until recently the use of polyfiber material was not given much consideration as an option for bridge deck reinforcement. Testing has been done to ensure the lightweight material is strong enough to use in bridge design but it is a relatively new material that most civil engineers are not yet used to working with for structural design. A new innovative bridge design was completed in Wisconsin in 2005 which included a fiber-reinforced polymer bridge as shown in the model in Figure 36. A prefabricated plastic grid was used as reinforcement inside the deck instead of steel. The design was tested by engineers at the University of Wisconsin Madison who predict the bridge will last up to twice as long as a typical steel rebar reinforced bridge. Unlike steel, the plastic grid reinforcement is resistant to corrosion and salts and chemicals which can seep into the bridge deck. Other tests showed that the polyfiber materials were more durable in icy winter conditions (Fiber Reinforced Polymer Bridge).

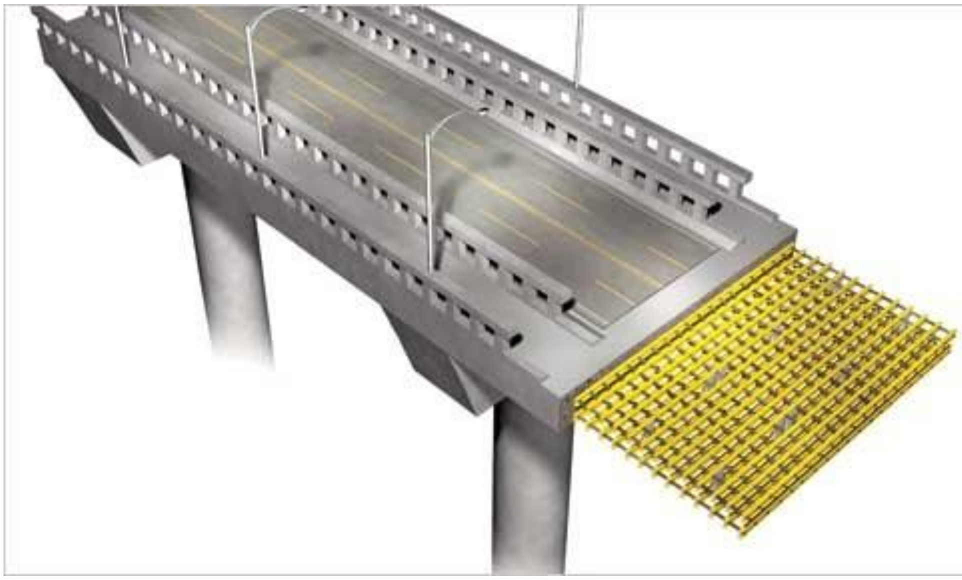


Figure 36: Model of Fiber Reinforced Polymer Bridge (taken from http://www.popsci.com)

4.9.2 Protection of an Existing Bridge

Existing bridges often have challenges associated with their maintenance and repair methods. Unlike new structures where engineers can make decisions about the type of maintenance that will be needed in the future based on the types of materials used, existing bridges have to first be examined to determine which materials were used in the initial design or previous maintenance. The main material that can limit the type of maintenance on a bridge is the type of coating used on the bridge. If the initial coating is not compatible with the type of coating used during maintenance, there can be issues with adhesion. Some systems and protection methods are not compatible with certain types of building materials so compatibility needs to be checked before any maintenance is performed. A greater challenge is faced when records of the coatings used on the surface are not provided. In this instance, a patch test must be performed to analyze the compatibility of the new coating with the unknown existing coating. This is an essential step because if engineers are not careful to provide a full analysis of the existing structure, a lot of money can be wasted on procedures that have no effect or are more detrimental to the structure.

4.9.2.1 Spot Repair

The most cost effective method is the spot repair maintenance technique. This method involves repairing only areas which have become rusted. These areas are removed from the surface before the new surface coating is applied. Other areas which show evidence of minor deterioration are not removed until they reach a more critical level which requires immediate maintenance. Although this method is most economical, in order for it to be fully effective the coatings must have limited amounts of corrosion and have adequate adhesion.

4.9.2.2 Overcoating

For the process of overcoating, all the defective areas of the component are removed. The surface is then cleaned and the entire structure is re-covered with a new, compatible coating. There are two different methods used to clean the surface after the defective areas are removed, an air blowdown technique and a brush-off blasting technique. A few years ago a case study investigating five types of surface coatings were tested using both techniques. Scientists, Kline and Corbett expected the results to show that the brush off blasting technique would provide a higher degree of surface preparation for the new coating application by removing more loose dirt and rust. Instead, their results showed this was not always the case. The results of each test did not warrant using the more expensive blasting technique. The process of overcoating, regardless of surface cleaning technique used can be costly because of the removal of toxic lead-based abrasives which are harmful to the environment (Virmani & Clemena, 1998).

4.9.2.3 Complete Re-coating

For the method of complete recoating of the component, the coating system deteriorates until failure from corrosion is imminent. Once this condition is reached, the entire surface is cleaned, the failed coating system is removed, new rebar is cast and a new coating is applied to all of the components. As with the overcoating technique, a complete recoating can also be a very costly process because of the high cost involved in the removal of lead-contaminated abrasives which were typically used in a lot of older bridge designs.

4.9.2.4 Solvent Cleaning

Solvent cleaning of the surface is effective in removing oil, grease, wax, dirt and contaminants which may have accumulated on the coat. Typical cleaning agents include solvents, vapors, emulsions and alkalis. Although this process works well, it has a negative impact on the environment. For in increased cost, special catchment systems are used to reduce the environmental damage of the chemicals and toxins.

4.9.2.5 Wet Abrasive Cleaning

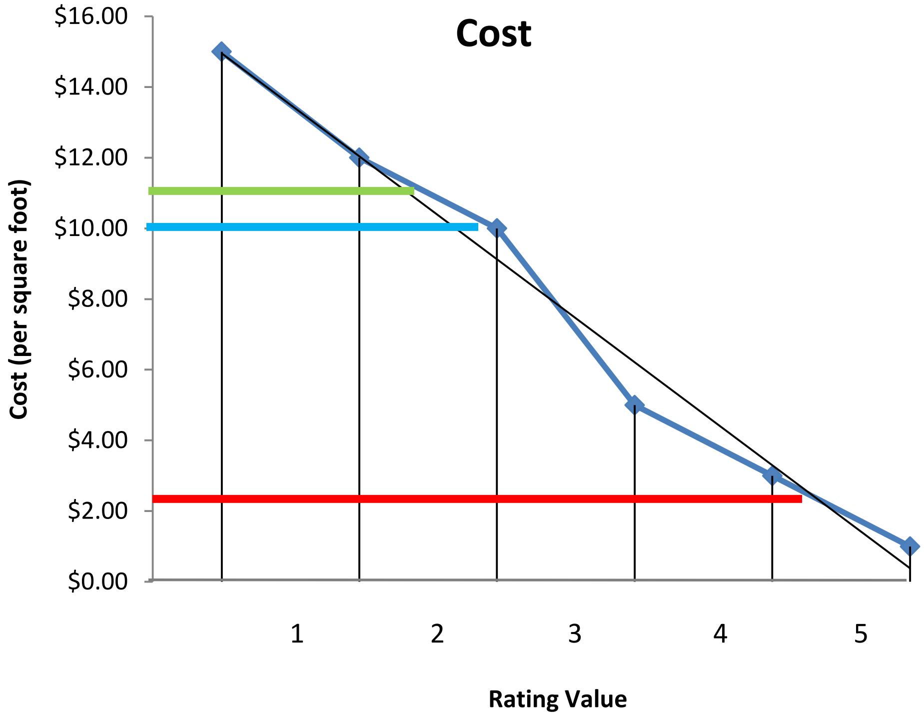
Wet abrasive cleaning provides perhaps the most acceptable results because the process provides very little pollution. One problem with this process is the flash rusting that can occur after the intense blasting. Adding rust inhibitors to the component can prevent the flash rusting from occurring but then makes the system less economical.

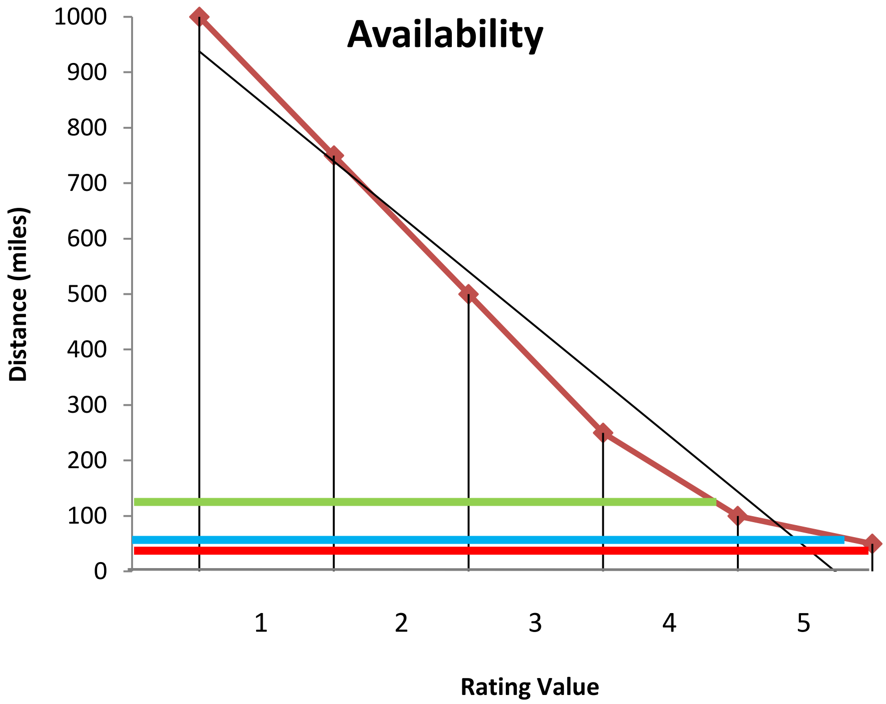
4.9.2.6 Cost Effectiveness of Existing Bridge Maintenance

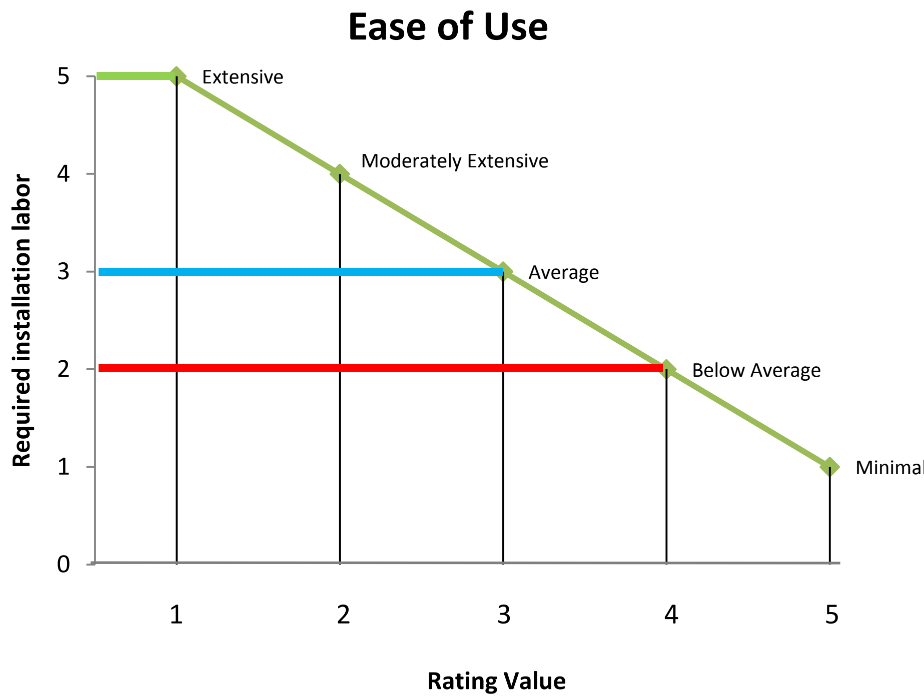
In an effort to be more economical while repairing or recoating an existing bridge, the application methods of the coatings can be taken into consideration. Instead of coating entire structures with the highest strength coating, it is more economical to determine the areas of the structure that are subjected to more severe environmental conditions and the regions that corrode at a slower rate. Using this method, an expensive, more durable coating can be used on the areas which require greater protection and cheaper systems can be used on the lower risk areas of the structure. Although these areas are initially lower costing, by using this method, maintenance is required more frequently which can result in an overall higher maintenance cost.

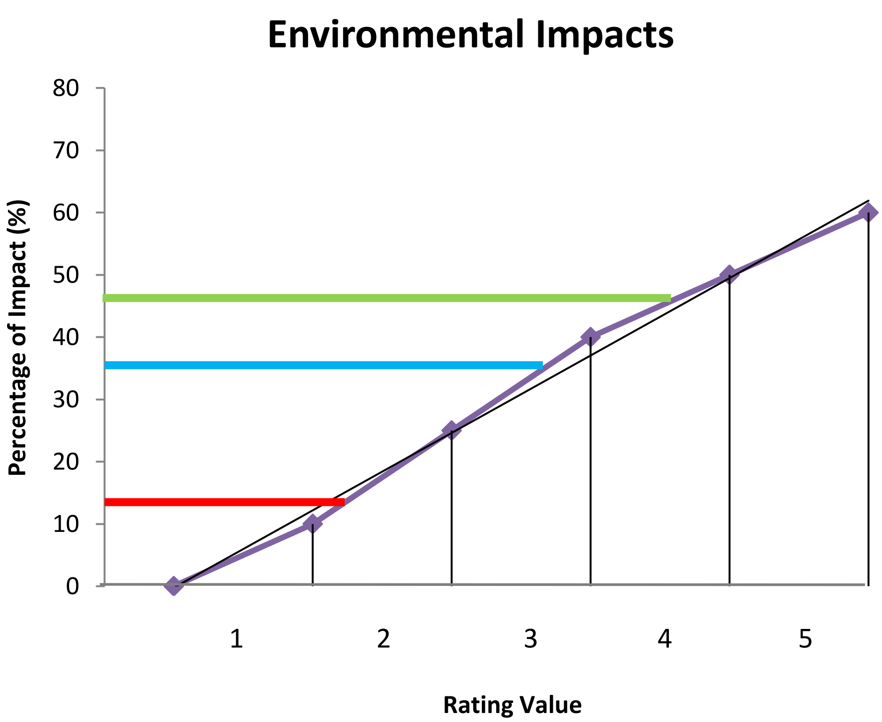
4.10 Determination of Protection System on Belmont Street/Route 9 Bridge

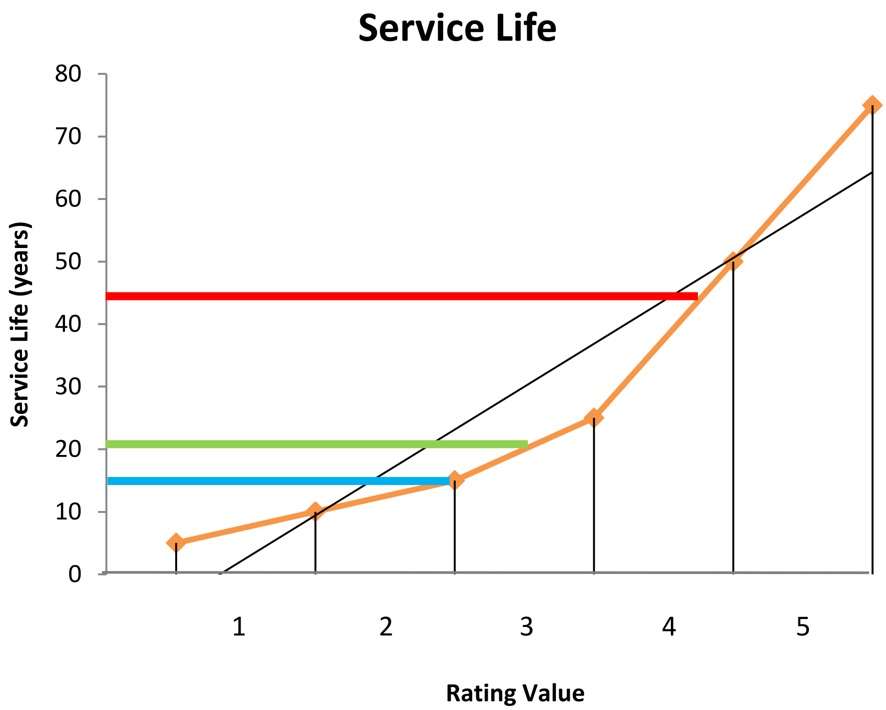
The corrosion protection matrix for existing bridges was used on the Belmont Street/Route 9 Bridge to determine the best protection system. The five categories that were included for investigation were: cost, availability, ease of use, environmental impacts and service life. Three different methods of protectants were compared including an increased cover thickness, a Cathodic protection system and the use of bridge deck epoxy coating. The line colors on the charts correspond to the color that relates to each alternative on the chart.


Cost
Cost (per square foot)
$16.00
$14.00
$12.00
$10.00
$8.00
$6.00
$4.00
$2.00
$0.00
1
2
3
4
5
Rating Value


Availability
Distance (miles)
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
Rating Value


Ease of Use
Required installation labor
Rating Value
Extensive
Moderately Extensive
Average
Below Average
Minimal
0
1
2
3
4
5
1
2
3
4
5


Environmental Impacts
Percentage of Impact (%)
Rating Value
0
10
20
30
40
50
60
70
80
1
2
3
4
5



Method for Determining Most Suitable Corrosive Protectant on an Existing Bridge					
Method	**Cost**	**Availability**	**Ease of Use**	**Env. Impacts**	**Service Life**
Increased Cover Thickness	5	5	4	2	4
Cathodic Protection	2	4	1	4	3
Epoxy Coating	2	5	3	3	2

Rating values for the Belmont Street/Route 9 Bridge were determined based on typical and suggested values discovered for each system during simple research. The rating of each alternative provides a basis for comparison relative to each category.

Applying the matrix to an existing bridge provides useful feedback on the decision system. Overall, the five categories are good measures of what the important factors to consider are when deciding on a corrosion protection method. The high values in the availability category suggest that perhaps a change in the ratings based on distance be investigated. Determining the percentage of environmental impact for each system was hard to measure, therefore a possible change in the way the ratings for that category are determined should also be looked at. The one category that did not assign specific values to each rating level was the ease of use category.

Further research of the impacts of the installation process and experience could create a way to assign quantitative values to the rating levels. As indicated by the application of the preliminary matrix, changes to the way category ratings are determined will produce a better decision system. Creating preliminary decision matrices provides the feedback needed to establish more effective decision making systems.

4.11 Recommendation for Reducing Corrosion

Based on the results obtained from various field and laboratory testing on different types of corrosion protection methods and the costs associated with their effectiveness, recommendations on the best alternative can be made. The best alternative is not necessarily the option that has the lowest initial cost because it may be more economical in the long run to choose the option that is going to be initially more costly but will require less maintenance in the future. Costs associated with bridge maintenance continue to increase as the amount of bridges across the U.S. requiring maintenance is also increasing. In order to ensure the country's infrastructure is safe, it makes sense to start designing structures which will have a longer service life so that we can catch up on maintaining the existing structures that are in desperate need of attention.

The use of epoxy coated rebar has become the standard in bridge reinforcement across the United States. Epoxy coated rebar seems like the most economical alternative based on the increased service life it provides. The FHWA predicted that the average replacement for a bridge deck was $40 per square foot making the potential savings $40/square foot times 100,000,000 of bridge deck equals approximately $4 million in 50 years. If the fact that the remaining 2.3 billion square feet of bridge deck are going to need eventual maintenance to repair the effects of corrosion, it is estimated that over $88 billion in future savings if epoxy coated rebar alternatives are used in the design. This alternative is a lower cost option to providing better protection but there are better alternatives that have been established through recent testing and completed designs (Virmani & Clemena, 1998).

The use of polyfiber reinforcement has increased benefits from most other protection alternatives but it is an extremely costly process. The highlight of a plastic grid reinforcement system is that it is completely resistant to corrosion from the bridge deck, unlike other alternatives that just prolong the time it takes for the reinforcement to corrode. Most other alternatives will increase the service life of the bridge by 20-25 years more than the typical reinforcement system but designing with a polyfiber reinforced system can increase the service life of the bridge by an additional 75 years (Fiber Reinforced Polymer Bridge). The increase of service life reduces the high maintenance costs associated with maintenance workers and equipment. Another financial gain is earned because of the design of the plastic grid reinforcement system. This prefabricated system only takes a day to install and therefore alleviates the costs and aggravations of construction.

An important issue to consider when deciding on the type of maintenance to be used is the possible tradeoffs between improved performance and resource demands for materials required to create new composites and protective coatings. When considering the implementation of plastic grid reinforcement systems, the oil consumption needed to produce the material must be taken into account. Although some of the protection processes seem to increase the service life of the bridge, the required energy to install and maintain these systems must also be looked into. When producing new materials, it is desirable to ensure a use for any byproducts created by the fabrication of the material. It is recommended that the impacts of such tradeoffs are further investigated to determine if the improved performance of the more sustainable alternatives are worth increase in cost and labor.

Innovative designs like polyfiber reinforcement systems can take bridge construction to a higher level. Many countries and a few states have already begun to implement these new systems in their roadway infrastructure. The gains in building with composite materials like plastic outweigh the one major downfall, cost. Especially because building with this type of design is not common, productivity levels will be low making costs high. As more and more state and local transportation agencies start to adopt this type of bridge building, the productivity levels will increase and the cost of the system will decrease. This essential step needs to be taken to improve the maintenance and construction of transportation infrastructure around the world.

5 Stormwater Management

Over the past century, areas of urbanization and development have steadily increased in order to accommodate the nation's demand for apartments, houses, offices, restaurants, and other facilities as the population has continued to grow exponentially. In many ways, this rapid expansion has created tremendous opportunities and technological advancement, yet the sudden increase in impervious surfaces due to development has also created significant environmental issues. One major problem we face today associated with the built environment is controlling the runoff water flowing over these impervious surfaces, also known as stormwater management.

The following chapter explores and identifies methods for improving the current stormwater management system in the area of interest, the Belmont St./Route 9 Bridge, by examining the importance of stormwater management, the standards provided by the state of Massachusetts and the City of Worcester, and investigation of stormwater management techniques. Based on the parameters of the area of interest, alternatives are provided and the process for determining these alternatives if discussed later in the chapter. Lastly, the benefits and impact of these alternatives are discussed.

5.1 Purpose of Stormwater Management

As the amount of parking lots, paved streets, and buildings increase, the amount of absorbent vegetation and soil steadily decrease, leading to an excess of runoff water during periods of heavy rain and snow. Stormwater management systems are used to control the runoff water in the urban environment and are crucial in eliminating problems such as flooding. They also "reduce downstream erosion and water quality degradation and mitigate the adverse effects of changes in land use on the aquatic environment (Glossary of Terms, 2008)."

Figure 37 found below shows the distribution of stormwater in a hydrologic cycle, for either a pervious or impervious surface. In a natural environment, rainwater infiltrates or seeps into the soil and replenishes the groundwater. The vegetation also transpires the rainwater, and a smaller percentage of runoff water becomes overland flow in this scenario. In an urban setting, however, more than half the rainwater is overland flow, and the amount of water infiltrating into the ground drops significantly (Ruby, 2008).

Figure 37: Cycles for Pervious and Impervious Surfaces (taken from http://www.coastal.ca.gov/nps/watercyclefacts.pdf)

5.1.1 Challenges in Stormwater Management

With any stormwater management system, the greatest challenge is to create a plan which disposes or recycles stormwater in an appropriate manner. In an ideal world, the system would accommodate all amounts of runoff water entering the system and would be large enough for a 100-year storm event. Realistically, in almost all cases the budget is the guiding factor. Constraints such as material availability, maintenance, and rainfall patterns are just a few of the factors that must also be considered. In the event that the amount of rainfall exceeds the allowable capacity of the system, an alternative method for this overflow must be formulated. In general, there are only two ways of dealing with the excess rainwater. The first option is to send the overflow to a treatment plant so then it can be properly treated and disposed of without harming the environment. Another alternative is to find a method for reducing the amount of runoff water before it enters the system so that the system never reaches maximum capacity or creates an overflow of untreated water that must be expelled into reservoirs, lakes, and rivers.

5.1.2 Stormwater Management Planning Standards

When creating a stormwater management plan, federal, state, and sometimes regional standards must be addressed. Although almost all standards are based on the national regulations provided by the United States Environmental Protection Agency (USEPA), each state is responsible for regulating municipal stormwater systems. Using various methods of scientific research, USEPA is an organization which establishes environmental goals, objectives and regulations. It is an agency which provides overarching guidelines for environmental protection (About EPA, 2008).

5.1.2.1 Massachusetts Standards

In the state of Massachusetts, the stormwater management standards are provided by the Massachusetts Department of Environmental Protection (MassDEP). The standards were created in 1996 with the intent of improving the water quality and decreasing the amount of water discharged. The standards prohibit the discharge of raw stormwater into wetlands or any other body of water. In area of new development, the peak flow discharge rate must not exceed the existing rate. Similarly, the amount of water infiltrated into the groundwater must stay consistent after development. Also, removal of at least 80% of the contributing total suspended solids must be eliminated during the design of the stormwater management system. Given the situation in which large quantities of pollutant loads are entering the system, measures must be taken to best reduce or eliminate these pollutant load quantities. Lastly, consideration of construction impacts as well the creation of a maintenance plan must also be provided (Volume 1, Chapter 1: The Stormwater Management Standards).

Although the project being investigated is not a new development but a bridge re-design project, these concepts and standards are still important to consider. As a method of sustaining the life of the bridge, reducing the amount of stormwater runoff seeping into the joints and corroding them may prolong the life span of the bridge components. As mentioned above, the standards were developed to reduce the discharge of raw stormwater flowing into wetlands, consider the amount of groundwater infiltration, and reduce the amount of pollutants entering the system. While considering and investigating appropriate alternatives to sustain the bridge, improvement of the current stormwater management plan based on these standards are executed.

5.1.3 Worcester Stormwater Management System

Much of the city’s infrastructure was developed more than ten years ago and portions of piping system implemented during this time period remain today. The system design principles therefore reflect the ideas and practices of the era. In some regions, old brick pipes from the 1800’s, measuring almost eight feet in diameter, can still be found in the city today (Managing Worcester's Combined Sewer System, 2008). The Belmont Street/Route 9 Bridge, for instance, carries two 16” water pipes.

The existing stormwater management plan in Worcester uses two separate systems to treat stormwater. The primary system treats stormwater at the Upper Blackstone treatment plant while the secondary system, a combined sewer system, is utilized during periods of excessive rainfall and snowfall. The combined sewer overflow, which is a mixture of raw water and sewage, is sent to Quinsigamond Avenue Combined Sewer Overflow Treatment Facility (QACSOTF). For both systems, after sufficient treatment, the water is then discharged to the Blackstone River. In the past, the combined sewer overflow ran untreated into the Blackstone River. It wasn't until the eighties that the QACSOTF was built to treat the combined sewer overflow. As shown below in Figure 38, excess stormwater during heavy periods of rain or snow flows directly to the secondary treatment plant and bypasses the primary treatment plant. It is then treated and released into the appropriate body of water, which is the Blackstone River for the Worcester region.

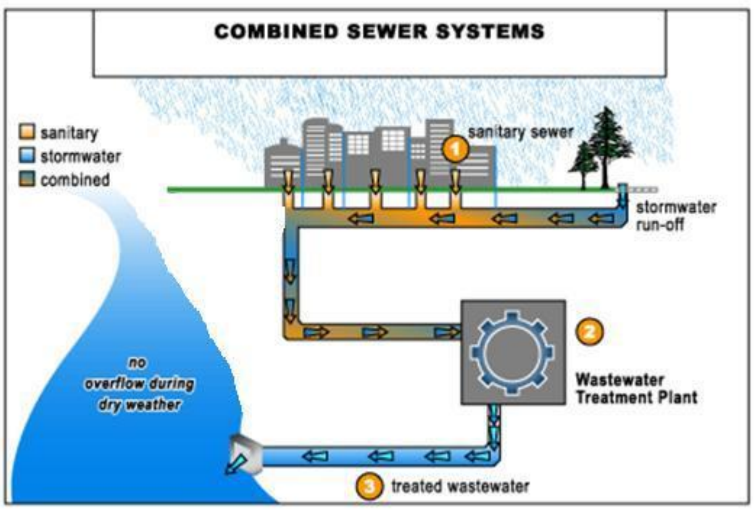


Figure 38: Combined Sewer System (taken from http://www.dcwasa.com)

Based on the current stormwater management system located in the City of Worcester and the state standards, the most effective way for improving the current system and the sustainability of the bridge is to reduce the quantity of water flowing into the storm drains. This reduces the amount of water entering the storm drains and being treated at the treatment plant, as well as prolong the life of the bridge by eliminating a quantity of runoff water flowing over the bridge and corroding the bridge components.

5.1.4 Sustainable Stormwater Techniques

The most effective, practical solution to manage stormwater quantities for this project is to simply reduce the amount of runoff flow entering the storm drains, such that the overall volume entering the system is reduced. Evaporation, evapotranspiration, redirection of runoff water and collection of runoff water are four basic techniques for controlling the volume of excess rainfall. Three sustainable methods that use these simple yet highly effective and economical techniques for reducing runoff flow include rooftop collection systems, runoff collection systems, and fountains.

5.1.4.1 Rainwater Harvesting

A common method used for reducing the amount of runoff water flowing into storm drains or flowing overland is to collect rainwater and use it as an alternative water source. In some cases, large scale systems can even supply enough water for an entire community without the assistance of city water. If transportation of water is an issue, one option is to store the runoff water on site in large tanks to be used during emergencies or to do daily chores. Besides providing people with an essentially cost free water system, collection also helps control the flow of runoff water in urban environments. Issues regarding flooding are significantly reduced by simply removing the leading source of water which causes these floods.

5.1.4.1.1 Rooftop Rainwater Collection

One of the most successful and cost-effective methods of controlling the stormwater volume is a rooftop rainwater collection system. For virtually any type of building, a system can be implemented. Typical rooftops collect rainwater using a gutter but then expel the excess rainwater directly onto an impervious surface or top soil, creating a larger overland flow. Rooftop rainwater collection systems use the same strategy for collecting rainwater, through gutters and downpipes. However, the excess rainwater is redirected into a storage tank located above or below ground, instead of being added to the overland flow volume that enters storm drains. An added benefit to this system is that the rainwater can be used as an alternative water source for domestic activities such as doing laundry, flushing toilets or irrigation. It can also be stored for drier seasons or used for emergencies. Since rooftops are relatively clean surfaces and carry no contaminants, in contrast to a roadway, the rainwater does not need rigorous treatment, prior to use, assuming it is not being consumed. Often times, sedimentation and filtration are the only necessary processes to effectively remove large chunks of debris and leaves.

Additionally, another method for disposing of this rainwater is through infiltration. Instead of capturing the rainwater in a tank or cistern, simply injecting the water beneath the surface soil, into the subsoil, is an equally effective method for reducing stormwater runoff. A rain garden can also be placed at the bottom of the downpipe so that the plants absorb and transpire the excess rainwater collected from the rooftop. An example rainwater collection system can be viewed in Figure 39. This particular system shows a dual collection system, which utilizes both a storage tank and rain garden. Once the collected rainwater fills the tank to a certain volume, the excess rainwater is channeled to the rain garden.

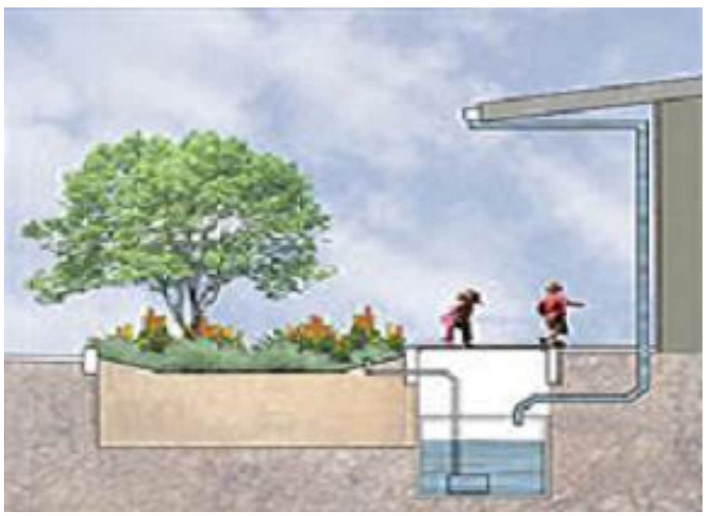


Figure 39: Rooftop Rainwater Collection System (taken from http://www.svrdesign.com/winslow_way.html)

5.1.4.1.2 Runoff Rainwater Collection

Similar to a rooftop system, a runoff rainwater collection system redirects rainwater to reduce the overall volume of water entering the storm drains. This type of system, however, remains at the surface and is collected in manmade detention ponds. When planning a runoff system, it is important to locate the low point of the drainage area for placement of the detention pond. Consideration of pathways for the water to travel and erosion control are two other key components to creating a successful system. As issues of sustainability and environmental impact become increasingly important, finding practical, attractive solutions, such as this, is crucial for participation and interest. As shown in Figure 40, the detention ponds serve as both a practical way to collect excess rainfall effectively, as well as provide an appealing neighborhood focal point.

Figure 40: Runoff Rainwater Collection System (taken from http://svrdesign.com/high_pt.html)

5.1.4.2 Fountains

A final method for utilizing excess runoff water is to implement a fountain. Although they are commonly used for aesthetic purposes in parks or in front of buildings, they are a useful way to decrease runoff volume as well. Collecting runoff water from nearby impervious surfaces such as roadways, sidewalks, or rooftops can be used to supply water fountains, which require significant amounts of water. Since the fountain water evaporates at a constant rate, a sufficient supply of water must be used to keep it fully functioning. For a system like this, it is important to consider the design of a piping system to supply and pump rainwater to the fountain. Depending on the efficiency of the fountain, the cost to implement this system may dictate the appropriateness of this alternative.

After researching the purpose of stormwater management, reviewing stormwater management standards and practices, studying the current stormwater management system used in Worcester, and researching methods for improving stormwater management, the process for improving the current system in the area of interest was explored. Lastly, suggested alternatives and improvements were selected based on the parameters of the area of interest.

5.2 Forming a Stormwater Management Plan

The formation of a new alternative or improvement to the current system must be adjusted based on the parameters provided by the area of interest. The feasibility and economics are two main guiding factors in finding an appropriate solution. To effectively address feasibility and cost, examination of the surrounding environment, consideration of the weather and climate, and adjustment based on the budget is required. The following section shows the process for defining these parameters and selecting an alternative based on these factors.

5.2.1 Weather & Climate

The weather patterns of a region and knowledge of the type of climate can greatly contribute to the creation of a stormwater management plan. These variables help determine the type of solution selected and provide parameters for design once a solution has been chosen. Consideration of rainfall and snowfall of the area is clearly important in determining the amount of runoff. That volume of water estimated is then used to design an appropriate system to maximum effectiveness. A collection system in the Northwest, for example, where rainfall is fairly constant and short periods of torrential downpours are less likely, would be designed differently than a system used in the Northeast, where short periods of heavy rain are more likely.

5.2.2 Rooftop Rainwater Harvesting

In order to determine if rooftop rainwater harvesting would be a beneficial alternative, evaluation of impervious surfaces due to structures, such as office buildings, apartments, hospitals, and schools must be included. When determining the amount of impervious area due to these structures, it is not necessary to calculate the specific surface area contributed by each individual building. Site visits are typically sufficient for generating a rough estimate of impervious area created by structures. Becoming familiar with the amount of surrounding infrastructure and noting the type of structure helps determine the appropriateness of rooftop rainwater collection. Specific structures that should be considered for implementation of a rooftop rainwater system should have large rooftops simply because larger roofs result in a greater volume of water. Therefore, a greater quantity of water can be captured, recycled and then used for other purposes.

Another important element to consider is the use of the recycled water. It is impractical and inefficient to collect the rainwater if it cannot be utilized. Typically, it is not challenging to find a use for the recycled water since it can be used for household chores, watering gardens or irrigation, however, it is essential for design purposes to determine the purpose of the collected water because it helps determine type of system that is selected. Since water collected by rooftop systems is relatively clean, household chores or flushing toilets is good way to utilize this system. If the purpose of the rainwater is to irrigate or water gardens then systems clean water is not essential and a system such as runoff rainwater harvesting may be more appropriate.

5.2.3 Runoff Rainwater Harvesting

When considering runoff rainwater collection, other impervious surfaces besides the rooftops of various structures may be found in concrete or asphalt sidewalks, roadways or parking lots. These are all examples of impervious surfaces that cover the ground, preventing direct absorption of runoff water into the surface soil below. Estimating the amount of impervious surface is critical for addressing the use of runoff rainwater collection. Similar to rooftop rainwater harvesting, site visits, or in some cases, the use of Google Earth is sufficient for estimating the amount of pervious area.

Another important aspect to consider is to examine where the runoff water can be redirected or diverted. Usually this involves determining the lowest point of elevation in a given watershed since runoff water will always flow downhill. Use of topographical maps can determine these low points. Many times this runoff water can be collected in a manmade pond so it can slowly infiltrate into the soil. Determining this low point, however, is essential in determining the feasibility of the alternative. For example, if 90% of a given area is forest but the low point of the region is a developed town, runoff rainwater harvesting is not the best solution. Either the town would be relocated to higher ground or excavation which would entail excessive earthwork would be required for creating a new low point in the area of interest. Either option would be extremely costly and inefficient.

5.2.4 Fountains

Since the implementation of fountains requires a piping system, typically they are more commonly used in urban environments, like rooftop rainwater harvesting. Although fountains are not typically thought of as a tool for stormwater management but rather a piece of artwork, after initial implementation they are a great way to utilize excess runoff water. Often times, fountains are seen as being impractical for the amount of water they require, however, if they utilize water that is of hindrance, they can be aesthetically pleasing, as well as functional.

This section discussed the considerations associated with each stormwater management alternative. Scenarios for the usage of each method were also addressed. The next section evaluates the use of these alternatives in the area of interest surrounding the Belmont Street/Route 9 Bridge. The benefits and challenges with each method are also discussed. Lastly, recommendations for the City of Worcester and discussion of cost are provided.

5.3 Stormwater Management Plan Proposal

Based on the constraints provided by the area of interest, the state standards, and the current system being used, practical solutions and alternatives are evaluated in the following section. As described earlier in greater depth, runoff rainwater harvesting, rooftop rainwater harvesting and fountains are just a few of the many alternatives for improving a stormwater management plan by reducing runoff flow. However, these techniques have proven to be successful in many different scenarios and for this reason were considered for this project.

5.3.1 Weather & Climate

Since the northeast experiences extreme weather changes based on the seasons, developing a system which can withstand large quantities of water is necessary. On the other hand, the system must also be able to withstand periods when it is rarely used. Fortunately, the methods discussed including rooftop and runoff rainwater harvesting and fountains, have no limit for capacity since the overflow can being channeled into the current storm drains if necessary. Although the systems are designed based on the rainfall patterns of region, during a hundred year storm the system is likely to overflow. Even though this is not ideal, it is important to recall that the total amount of water entering the storm drains using these systems will never equate to the amount of runoff flowing into the drains now without these systems. As mentioned, the design of rooftop and rainwater collection systems is adjusted based on the precipitation rate of a region. Similarly fountains can also be adjusted based on the amount of rainwater a region receives and the size and rate of the system can be altered to accommodate different necessities.

5.3.2 Rooftop Rainwater Collection

As stated above, rooftop rainwater collection can only be applied in areas of urban development with structures capable of collecting runoff. Since almost all of the area of interest is developed with structures capable of collecting rooftop rainwater, this is one solution for reducing runoff quantities. The area around the Belmont Street/Route 9 Bridge has numerous buildings surrounding it fit for rooftop rainwater collection. It is suggested that UMass Medical Center Memorial Campus, the church and the apartment complex located just west of the bridge be considered for rooftop rainwater collection shown in the Figure 41.

Figure 41: Map of Area of Interest (taken from http://maps.google.com/maps)

They are structures which can greatly benefit from rooftop collection systems. As shown in Figure 42, the rooftop rainwater can be collected, stored in tanks above or below ground, and then be used to flush toilets or complete other domestic tasks such as laundry. Recycling this water also decreases the runoff water flowing into the storm drains on either side of the bridge. During times of heavy rainfall, these can help prevent the bridge from flooding which can ultimately reduce the amount of water seeping into the joints and components and corroding them.

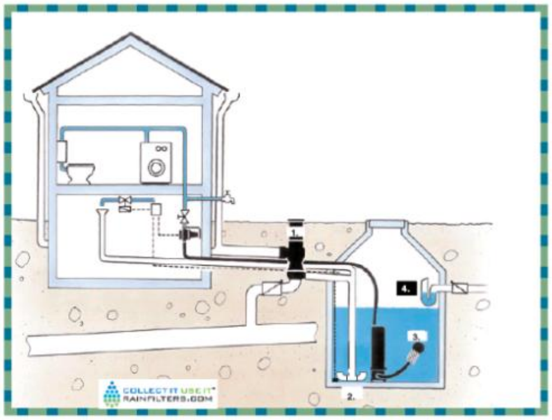


Figure 42: Rooftop Rainwater Harvesting For Flushing Toilets (taken from http://news.cnet.com)

5.3.3 Runoff Rainwater Collection

Although much of the area of interest consists of paved surfaces and developed land, the concept of runoff rainwater collection through use of a detention pond is impractical. Since the entire area is urban developed, the low point of the region cannot be considered for collection. The only other way this system could be beneficial is for the water to be utilized. Unfortunately, the water flowing over paved surfaces collects oil and gas from cars which pollute and contaminate the runoff water. Only after treating the water, can it be used. Providing sufficient treatment of this water would require the use of oil and gas separators and a similar process used at the Blackstone Water Treatment Plant, making the system inefficient. Since the required maintenance would be similar to that of the treatment plant, it is an insufficient solution. Typically, this method is used for collecting runoff water flowing over pervious surfaces because the quantity of water does not contain the same pollutants found in water flowing over roads and impervious surfaces.

5.3.4 Fountains

The number of buildings found in the area of interest makes fountains, like the one shown in Figure 43, a somewhat reasonable solution in reducing the amount of stormwater runoff. Strategic placement of these fountains along the large hill to the east could utilize the large volumes of water flowing down the hill towards the Belmont Street/Route 9 Bridge and Interstate 290. Since the UMass Memorial Hospital is located on this slope and is a facility which could greatly benefit from recycled rainwater, it is suggested that a fountain be placed in front of the building. The recycled rainwater could supply water for flushing toilets throughout the facility without any treatment during times of heavy rainfall. Alternatively, the fountain could be turned off during the hot, humid summer months when water is scarce.

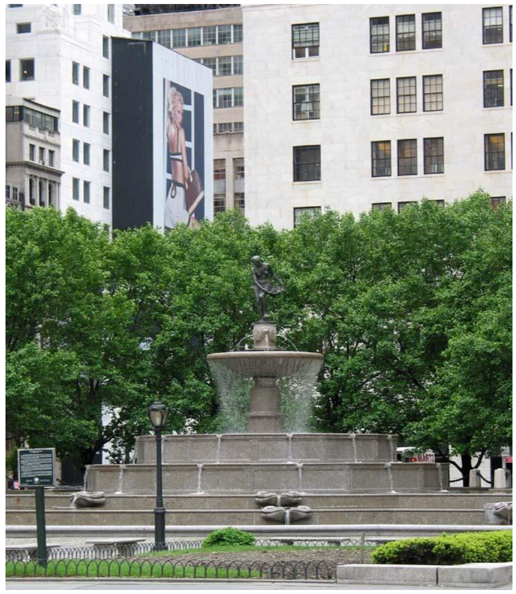


Figure 43: Fountain (taken from http://wirednewyork.com)

After researching the purpose of stormwater management, becoming familiar with the current system, and studying stormwater management standards, it was determined that the simplest way to improve the current system was reduce the runoff flow. The most effective and cost efficient solutions were evaluated and the process for selecting a proposed solution was presented. Based on the parameters of the area of interest, rooftop collection and the use of fountains were both determined to be effective methods for reducing the runoff flow and alleviating the current stormwater management system. The next section discusses further recommendations for the City of Worcester and the cost associated with these alternatives.

5.4 Recommendations for Further Improvement

Although this project only considered the area surrounding the Belmont Street/Route 9 Bridge, a truly effective stormwater management plan alternative must be implemented throughout the City of Worcester. Although implementation of rainwater harvesting systems and fountains can be beneficial in this particular area, in the big picture, significant changes in the amount of runoff flowing into the storm drains and entering the treatment plant will not be seen unless an entire region makes an effort to implement such systems.

It is recommended that these alternatives be considered and evaluated for the entire City of Worcester. If these approaches are not applicable, other ways of reducing the runoff flow may be implemented based on the constraints. Although the results may not be evident from the beginning and the cost of implementation may seem too costly, it is important to consider the long term effects and benefits of these systems.

Above all, cost is the greatest factor or concern of any project. Often times change to fully functioning systems is considered unnecessary and a waste of money. Although there may be significant implementation costs with using the alternatives due to placement of piping systems below the ground, the benefits are not shown in dollar amounts. Instead, water does not flood bridges or roads causing hazardous conditions. Storm drains do not overflow onto the sidewalks and flood the basements of homes. From an environmental and sustainable stand, the surface soil and ground water table are replenished and the use of collected and recycled rainwater provide an alternative water source. Additionally, these systems virtually require no maintenance so after the initial implementation costs, no more money is spent on the system.

6 Transportation & Urban Planning Development

According to the Institute of Transportation Engineers (ITE) *Transportation Planning Handbook*, the practice of transportation planning is intended to improve the conditions between land use and transportation system planning; make planning, design, and operation of transportation services more cohesive; and maintain a balance between transportation-related energy uses. This includes examining "demographic characteristics and travel patterns for a given area" to determine how the transportation system may change over a given time period or under different conditions (Institute of Transportation Engineers, 2008). Thus transportation planning is a vital element to both the design and construction phase of any project.

In order to ensure a traffic plan is adequate for the project site, it is essential to evaluate the existing conditions, study the surrounding area, obtain data pertaining to traffic and transportation, and predict future conditions prior to construction. The objective of this chapter is to identify key factors that affect urban development, methods used to obtain this information, and procedures used to develop a traffic control plan that reflects the data and provides both a constructible and safe approach. In addition the project team will provide a traffic control plan specifically for the Belmont Street/Route 9 Bridge that could be implemented during the construction phase. This plan will be selected from a series of alternatives evaluated based on site constraints, traffic volumes, level of service, etc. and will be compared to the solution suggested by MassHighway.

6.1 Traffic Impact Study

The first step to developing a traffic control plan is obtaining all essential information regarding the current site conditions. Much of this information can be found within a traffic impact access study. A traffic impact access study (TIAS), also known as a traffic impact analysis (TIA), provides information regarding the "present and future impacts of a development on the operation of the surrounding infrastructure and the associated mitigation for such impacts" (Hurwitz, Chase, & Knodler). Such studies are important because they can predict how traffic may change with new development and what types of improvements are necessary in order to maintain safe and desirable traffic conditions. However there are different levels of TIAS that range in detail and complexity. Depending on the type, size, and location of development, a

TIAS may not even be needed (Traffic Impact Studies, 2007). For instance, a TIAS is generally not needed if there will be minimal impacts on the surrounding environment.

6.1.1 TIAS Methods & Procedures

There are several methods that may be used in determining if a TIAS is necessary and to what degree. One approach is to use trip generation data. Trip generation is the "number of inbound and outbound vehicle trips that are expected to be generated by the development during an average day or during peak hour traffic" (Traffic Impact Studies, 2007). This data allows planners to estimate the number of trips that will be generated from a new development. According to the ITE, an in-depth analysis should be completed when 100 or more new inbound or outbound trips are expected during peak hours for a new development. Another approach is to examine the threshold requirements and identify the traffic volumes surrounding the site. In some cases traveling to and from a proposed development may be affected by high traffic volumes on adjacent roads. An example flowchart, developed by the city of Roseville, Ca, illustrates how to determine whether a short-term or long-term traffic study is necessary by evaluating peak hour trip ends. This approach is provided in the Figure 44.

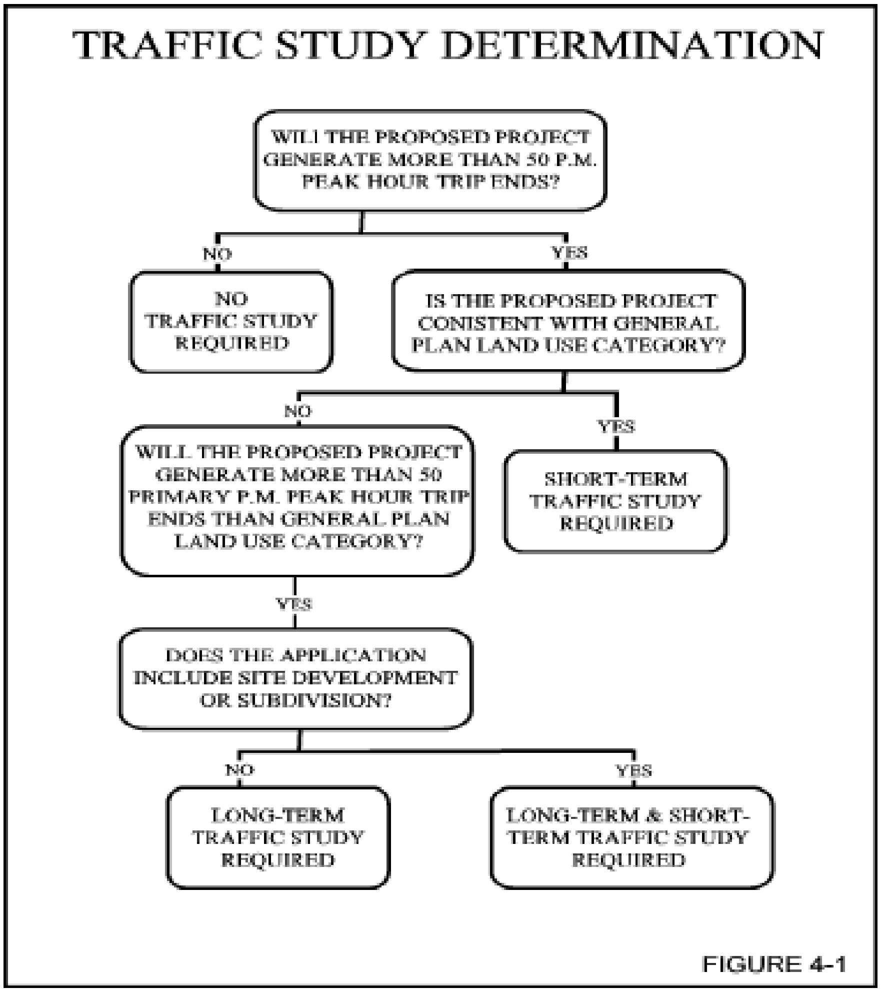


Figure 44: Flowchart showing steps to determining the type of traffic study to be used (taken from http://www.roseville.ca.us/civica/filebank/blobdload.asp?BlobID=2387)

There are several components that make up a traffic study. First and foremost it is necessary to identify the project and provide a background. This includes a description of the proposed development; what it entails, how large it is, and where it is located. Within the description there should also be a vicinity map which locates "subject parcels" and nearby arterials so that the road network is clearly defined. Once this is completed the following information may be gathered: trip generation for peak hours, passerby rates, internal trip capture, existing trips from site, number of peak hour trips, number of trips from other time periods, and average daily trips. This information will help determine how trips are distributed and what arterial units are most critical. Additionally, a level of service (LOS) analysis should be provided for critical arterial units. This includes a list of intersections impacted, current am and pm peak hour counts for each intersection, and current and futures traffic volumes with and without development (Requirements for Traffic Studies with Future Level-of Service Analysis, 2007).

The information gathered in a traffic impact study is important to both engineers and planners. Prior to construction, it is essential to evaluate how the development will affect the surrounding area, what the impacts will be, and what measures should be taken to eliminate problems. By evaluating the traffic impact study, planners can better understand what mitigation measures should take place in order to ensure the construction phase will run smoothly.

6.2 Work Zones

The second step to developing a traffic control plan is understanding the site constraints, where the project takes place, and what rules/regulations must be followed. Depending on the type of work zone, different safety measures and techniques may be required. Work Zones are affected by the type of project, its size, location, and traffic flow. The purpose of evaluating each work zone is to ensure the safety of anyone in or around the work site. This includes motorists, pedestrians, and construction workers.

6.2.1 Work Zone Classifications

In the state of Massachusetts, Public Works Projects are divided into three groups based on the type of setup for the construction zone and the nature of the project. This includes High Speed Roads, Low Traffic High Speed Roads, and Low Speed Roads. High Speed Roads are both divided and undivided Public Roads with a speed limit greater than or equal to 45 miles per hour, Low Traffic High Speed Roads are essentially High Speed Roads except they have a volume less than a maximum of 4000 vehicles per day, and Low Speed Roads are both divided and undivided Public Roads with speeds less than 45 miles per hour (Works). The type of group in which the project falls determines the safety measures that need to be taken during construction.

Work zones are also categorized based on how the construction will progress. Stationary work zones are work activities that exceed one hour but may last for several days in the same location. This includes activities such as paving, sign installation, and bridge repair. In this case the project may require several workers and more equipment to complete the job. Mobile work zones on the other hand refer to work activities that move along the road either intermittently or continuously. This includes litter cleanup, herbicide spraying, sweeping, and painting. For activities that are less demanding, the project may be classified as "rolling slowdown" which means the activity still moves along the road but is less time consuming like picking up debris.

Again, depending on the situation there are different safety measures that should be taken (Washington State Department of Transportation, 2000).

6.2.2 Work Zone Safety

There are four different categories of work zone safety that should be considered in the traffic control plan: work zone, road users, bicyclists, and motorists. Work zone safety considers the area in and around the work site to ensure a safe environment for the workers. Depending on the type of project and what safety devices are used, workers may face the risk of being struck by a moving vehicle. This risk increases with higher volumes of traffic and higher speeds.

Another factor to consider is road user safety which accounts for pedestrian routes, walkways, and crosswalks. There are three main considerations to pedestrian routes. First, pedestrians should be separated from conflicts with construction vehicles, equipment, and operations. Second, they should be separated from conflicts with traffic in or around the work zone. And third, all pedestrians routes should be maintained so that they are as safe, accessible, and convenient as possible.

Similarly, bicyclists should also be separated from conflicts involving traffic, equipment, operations, or any other obstacles in and around the work zone. There are a few different methods to re-routing bicyclists depending on the road conditions. When traffic is traveling between 25 and 30 mph, bicyclists can use the same route as vehicles. In cases where the speed limit is just about 30 mph, it may be possible to reduce the speed of motorists so that bicyclists can still share the road with the vehicles. However, in high speed areas, bicyclists may be instructed to dismount their bikes and follow the pedestrian route. In any case it is important to establish bicycle routes that avoid rough terrain and other hazards including loose gravel, mud, standing water, and raised utility covers.

Lastly, the safety of motorists should also be accounted for. Since motorists are often traveling at high speeds, they require more time to respond to conditions. In order to provide a smooth transition from normal speeds to lower speeds, proper signage should be used to give drivers enough warning. This includes Detour, Road Closed, Police Officer Ahead, Lane Narrows, and Left Lane Closed signs (MassHighway, 2006).

6.3 Traffic Control Plan

The third step to developing a traffic control plan is evaluating the information obtained from the traffic impact study and being able to provide a plan that reflects the safest, most practical solution. Essentially a traffic control plan is a set of drawings and documents that provide a set of rules and guidelines to ensure a safe and fully functional working environment. According to MassHighway, Traffic Management Plans (TMPs) are a result of “work zone traffic control- the planning, design, and preparation of contract documents for modification of the normal traffic and pedestrian patterns during construction” (MassHighway, 2006). The management plan should address issues concerning safety of pedestrians, bicyclists, and motorists traveling through work zones, safety of work crews from surrounding traffic, and any delays or resulting effects of the development on the surrounding area. Such a plan should be developed for the Public Works Project and should include “road detour plans, road closure plans, and plans to mitigate the impact on vehicular and pedestrian traffic outside of the Construction Zone” (Works).

6.3.1 Creating a Traffic Control Plan

A Traffic Control Plan is based on site conditions as defined in the *Manual on Uniform Traffic Control Devices* (MUTCD). Figure 45 is a checklist designed to help produce a traffic control plan.

COMPLETED	ITEM
☐	Determine the duration of work, (Mobile, Short-Term, Intermediate Term/Night)*
☐	Select hours of work to avoid peak periods (refer to work hour chart when applicable).*
☐	Select the appropriate layout(s), using duration, type of roadway, volume, and speed, from guidelines.
☐	Determine any modifications to typical layout(s). • Check decision sight distance • Intersection/driveways • Allow for buffer space free of obstructions
☐	Check the condition of devices (Refer to Quality Standards Booklet).
☐	Install devices beginning with the first device the driver will see. Device spacing as per chart on TCP.
☐	Conduct a drive through to check for problems.
☐	Document temporary traffic control zone, problems and major modifications to the layouts.
☐	Maintain devices while in place.
☐	Complete work.
☐	Remove the devices as soon as work is completed, beginning with the last device placed.

*Utilize the Region Traffic Office Staff to address concerns and questions.

Figure 45: Traffic control plan checklist (taken from http://www.ci.seatac.wa.us/services/workzone.pdf)

The steps involve identifying the scope of the work, when the work is going to be completed, how the project site is laid out, what needs to be considered, what the best solutions are, and what methods are going to be used to implement the traffic control plan (TCP). Since this checklist addresses issues regarding the project site and the scope of the project, this checklist can is only applicable once the TIAS is completed.

6.3.2 Procedures & Devices

A traffic control plan should contain a basic layout of the worksite including the configuration of lanes and placement of signs, barriers, and other devices. Traffic control devices are formally defined as any barrier, message board, warning sign, light, indicator, warning signal, direction sign, curb, street or other traffic markings, mechanical traffic signal systems, including those items located on vehicles, Road Flagger or Police Detail, and any other item or device used to control traffic on a Public Road as a part of the Setup (Works). Depending on the type of project, lane configurations consist of lane narrowing, lane closures, alternating one-way traffic, intermittent closure, the use of shoulders for traffic diversion, and any other alternative routes (MassHighway, 2006). Similarly, depending on the type of project, different signs, barriers, and devices may be required. For instance, portable changeable message signs are recommended for high speed, high volume roadways or in work zones that require highly visible message signs. On the other hand, flashing arrow boards are required for all lane closures or multi-lane roads excluding shoulder closures. There is also a wide variety of traffic barriers that can be implemented. This includes traffic drums, water filled barriers, concrete barriers, and barricades. For projects that occur on freeways, traffic drums may be a safe alternative. However, if the project is long term stationary work in areas with high traffic volumes, concrete barriers may be safer (Washington State Department of Transportation, 2000).

If traffic control devices are not sufficient enough to protect construction workers from moving vehicles, a traffic control plan can also suggest the use of police details and flaggers to help direct and control traffic within the work zone. Police officers will be able to enforce the speed limits so that all vehicles move through the work zone at an acceptable speed. Similarly flaggers can help mitigate any congestion that may be caused by the construction to ensure traffic is still flowing. In either case however, the officer or flagger should remain visible to oncoming traffic and avoid standing in the road if at all possible (Washington State Department of Transportation, 2000).

In order to fully develop a traffic control plan, information that serves as a guide and regulations regarding the use of different devices and details can be found in the *Manual on Uniform Traffic Control Devices* (MUTCD) and in MassHighway's *Standard Details and Drawing for the Development of Traffic Management Plans* (MassHighway, 2006). Figure 46 is an example of a standard detail developed for a long term stationary work zone. The figure shows the types of signs required, the placement of the signs, and the layout of the work zone. The work zone should provide adequate shoulder taper and enough buffer space to fully protect the construction workers.

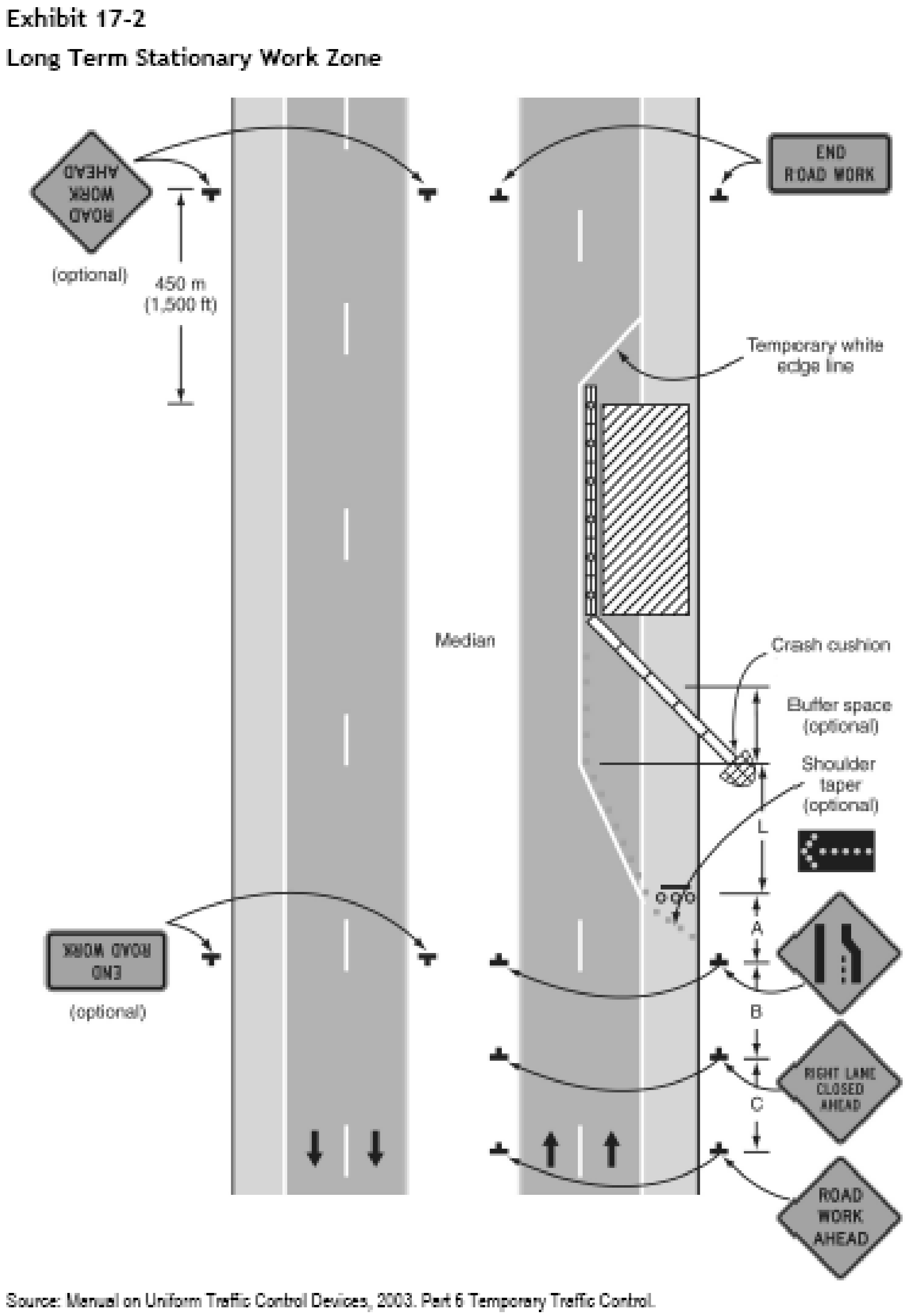


Figure 46: Long-term stationary work zone (taken from http://www.mhd.state.ma.us/downloads/designGuide/CH_17.pdf)

6.3.3 Effectiveness of Traffic Control Plan

In order to ensure the traffic control plan is carried out efficiently, a designated traffic control officer should be assigned to the job to help implement the control plan. They shall serve as the coordinator of the project and be knowledgeable in traffic control principals. They need to be able to identify the work location, posted speed limit, traffic volume and pattern, the type of work that is being performed, and the potential impact the work may have on the existing traffic. Further, it is their responsibility to ensure proper setup, tear down, and repositions of all devices used; to conduct daily inspections of the devices; and to make sure all construction workers have the proper training, and that personal protective equipment is both distributed and used amongst all workers (Force). However, in addition to the traffic control officer's responsibilities, it is also the responsibility of anyone in or around the work zone to be aware of their surroundings and remain cautious in order to avoid major accidents (Washington State Department of Transportation, 2000).

6.4 Key Concepts

The overall goal of the traffic control plan is to ensure the safety of anyone in or around the work zone. By using information gathered from the TIAS and evaluating the impacts the construction will have on the surrounding area, proper safety measure can be taken to alleviate congestion and ensure the work zone is both functional and safe. The types of devices used and the safety measures taken are dependent upon the type of work zone, the site constraints, how heavy the traffic is flowing and at what speeds, etc. Thus in order to ensure construction is safe and manageable and all rules and regulations are met, a traffic control plan should be developed prior to construction. The following section utilizes the ideas discussed above in order to create a Traffic Control Plan specific to the Belmont Street/Route 9 Bridge.

6.5 Belmont Street/Route 9 Bridge Traffic Control Plan

It has already been stated that traffic control plans are designed to provide safe work environments. However, on a larger scale, since this project aims to produce the most sustainable and cost effective design, the traffic control plan should consider sustainable alternatives. By taking a more economical design approach, it is possible to alleviate congestion and reduce emissions from idling vehicles. Thus, the project team will investigate several alternatives and propose a traffic control plan specific to the Belmont Street/Route 9 Bridge.

6.5.1 Considerations

A traffic control plan for a short term rehabilitation project is slightly different than a long term development project. Many of the techniques addressed in the previous section are associated with development projects involving long term usage patterns. For instance, if a new mall was being built directly off a major highway, an in depth Traffic Impact Study would have to be completed prior to establishing a traffic control plan. The traffic impact study would identify both the present and future impacts of development based on the collected data. This data includes trip generation, am and pm peak hour counts, and traffic volumes. However, for a short term rehabilitation project, most of the information obtained from an impact study is already available.

Ideally the Belmont Street/Route 9 traffic control plan should consider the information obtained from a traffic impact study. However, due to lack of data and resources, a traffic impact study was not factored into the evaluation.

Additional information considered for long term development projects includes the type of work zone associated with the project site, the four areas of work zone safety, and the types of procedures and devices that should be used. These considerations are also applicable for short term rehabilitation projects.

For the Belmont Street/Route 9 Bridge specifically, the project site is located within a low speed road (less than 45 mph) with high traffic volumes. The objective of the traffic control plan is to ensure the safety for anyone in or around the work site. This includes construction workers, road users, bicyclists, and motorists. To make certain the work zone remains safe and functionally, the proper control devices will be implemented according to MassHighway’s regulations.

6.5.2 Approach

The proposed traffic control plan will be selected from four different alternatives ranked on the basis of four main criteria. The alternatives include completely closing the bridge to traffic, leaving one lane open with one-way traffic, leaving one lane open but with alternating traffic, or having two lanes open with traffic flowing both ways. Each alternative is evaluated based on emergency access, flow of traffic, safety, and efficiency. Evaluation is on a scale of 1 to 5, with 1 being the least acceptable and 5 being the most acceptable.

The evaluation criteria was selected based on relevance and importance to the decision making process. Considering UMass Memorial Hospital is located approximately 0.2 miles from the Belmont Street/Route 9 Bridge, maintaining access to emergency vehicles is a major consideration (GoogleMaps). Figure 47 shows the exact location of the project site with respect to UMass Memorial Hospital:

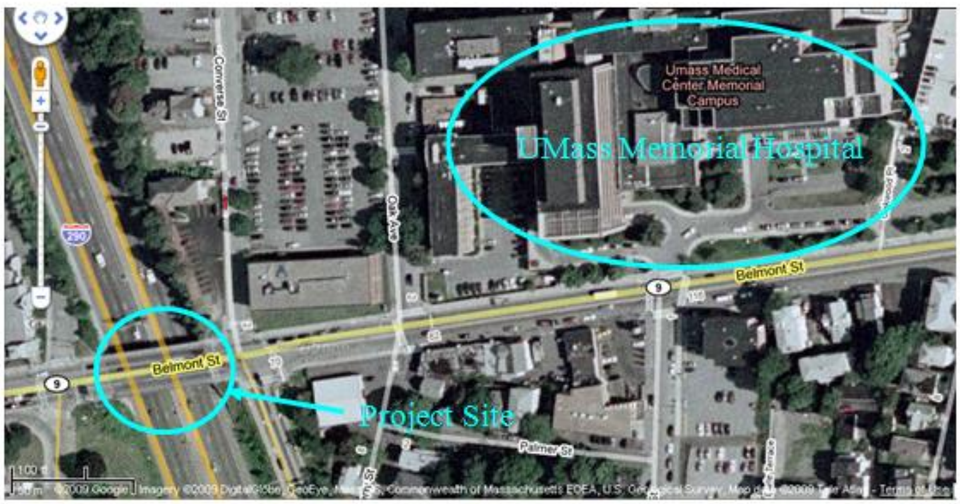


Figure 47: Emergency access (taken from Google Maps)

Similarly, Route 9 is a major east-west access road so it is important to consider how the construction will affect the flow of traffic. A traffic control plan should be designed to reduce the amount of congestion that may occur due to construction. At the very least traffic needs to be able to circulate in a continuous east-west or west-east pattern. Additionally, as stated before, one of the major reasons for developing a traffic control plan is to ensure the safety of anyone in and around the work site, making safety another key factor. It is important that drivers and pedestrians have clear instruction of where to go, who has the right of way, when they may proceed, etc. in order to eliminate any confusion that may arise due to construction. Lastly, considering how efficient the alternative will be accounts for the duration of construction, scheduling, and certain time related costs associated with the project including equipment rental and labor.

The alternative with the highest ranked score forms the foundation of the traffic control plan. Once this is established the remainder of the traffic control plan can be developed. This includes the implementation of traffic devices, signs, police details, and other control devices or techniques that are appropriate for the project site and scope of the work.

6.5.3 Analysis

The following framework is designed to provide a systematic approach to selecting a basic layout for a traffic control plan. As part of the framework, a rubric is established to objectively assess and score each criterion. The rubrics are outlined in the Table 13–Table 16.

Table 13: Emergency access criteria

1	Access is completely closed off to all emergency vehicles
2	Access to emergency vehicles is extremely limited and unsafe
3	Emergency vehicles may proceed with caution
4	Emergency vehicles may proceed safely, but timing may be delayed
5	Emergency vehicles may proceed safely and in a timely manner

Table 14: Flow of traffic criteria

1	Access is completely closed off to all vehicles. Expect detours and delays.
2	Access is limited to one direction. Expect delays, detours, and/or heavy congestion
3	Vehicles may proceed with caution in both directions. Expect delays and congestion
4	Vehicles may proceed safely with minor delays and congestion
5	Vehicles may proceed safely and in a timely manner

Table 15: Safety criteria

1	Conditions are unsafe to vehicles, pedestrians, and/or workers
2	Conditions are safe for workers, but undesirable for vehicles and pedestrians
3	Conditions are safe for pedestrians and workers, but unsafe for vehicles
4	Conditions are acceptable for vehicles, pedestrians, and workers, but anyone passing through the work zone must proceed with caution
5	Conditions are safe for anyone in and around the project site

Table 16: Efficiency criteria

1	The layout of the construction site is not ideal. The project is expected to be completed in several phases over several years
2	The layout of the construction site is acceptable, but the time required to complete the project is not ideal.
3	The time required to complete the project is acceptable, but the construction site is not ideal.
4	Both the time to complete the project and the layout of the site is acceptable. Construction may still be required to be completed in two or more phases
5	Both the time to complete the project and the layout of the site is ideal. Construction may occur all in one phase

With the assigned ranking system, each Alternative is evaluated in Table 17-Table 20.

Table 17: Alternative 1 – Bridge Closed

Criteria	Ranking	Comments
Emergency Access	1	Unless a temporary bridge is installed, this alternative would not be adequate for emergency access considering it would restrict emergency vehicles from traveling to and from the hospital.
Flow of Traffic	1	This would cause a major disruption in the flow of traffic for vehicles traveling on both I290 and Rt. 9. Vehicles that typically take exit 17 off I290 and turn left would have to find an alternative route to get to their destination as well as vehicles that travel eastbound across the bridge.
Safety	5	Closing the bridge would create a barrier between outside traffic and construction workers which greatly reduces the risk of accidents.
Efficiency	5	Closing the bridge would not only reduce the time required to complete the project, but it would also maximize the space available for construction making this the most efficient alternative.

Table 18: Alternative 2 – One way, one lane

Criteria	Ranking	Comments
Emergency Access	2	With traffic only flowing in one direction, emergency access vehicles would have to find an alternative route when traveling to and from accidents that occur westbound on Rt.9.
Flow of Traffic	2	Despite the fact this alternative would allow traffic to circulate, the flow of traffic would not be sufficient enough considering Rt.9 is heavily traveled in both directions even when four lanes are operating.
Safety	4	Vehicles would have to travel slowly through the work zone, obey safety rules, and be cautious of their surroundings while traveling across the bridge.
Efficiency	4	With only one lane operating, more of the bridge can undergo construction at one time, but the project would still have to be completed in stages.

Table 19: Alternative 3 – One lane, alternating traffic

Criteria	Ranking	Comments
Emergency Access	3	Emergency vehicles will be able to travel to and from the Hospital, but must travel slowly and wait to cross considering traffic is alternating.
Flow of Traffic	3	Traffic is free to flow both directions, but with only one lane operating, delays and heavy congestion may be expected.
Safety	2	With one lane open and alternating traffic, without a traffic officer or signal lights, vehicles may have a difficult time crossing through the project site. These conditions may increase the chance of accidents and cause unsafe conditions for both drivers and pedestrians.
Efficiency	4	With one lane operating, a greater portion of the bridge is available to be worked on at one time. Thus both the time required to complete the project and the layout of the construction site is acceptable.

Table 20: Alternative 4 – Two lanes, one each way

Criteria	Ranking	Comments
Emergency Access	4	With two lanes operating and traffic flowing in both directions, emergency vehicles should have enough room to safely travel through the project site. However, without the use of all four lanes, the area is likely to become congested, forcing emergency vehicles to proceed slowly.
Flow of Traffic	4	Traffic is free to flow in both directions, but there may be some delays due to significant amount congestion without having four lanes operating.
Safety	4	Since two lanes are open, allowing for traffic to move in both directions, both vehicles and pedestrians are able to safely travel through the project site, but should remain cautious of their surroundings.
Efficiency	3	Having two lanes open reduces the space available for construction resulting in a less desirable work zone. The time to complete the project, however, though slightly longer is still acceptable.

Table 21 provides a summary of the evaluations:

Table 21: Summary of results

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Emergency Access	1	2	3	4
Flow of Traffic	1	2	3	4
Safety	5	4	2	4
Efficiency	5	4	4	3
Totals	**12**	**12**	**12**	**15**

Based on the results, as you reduce the number of operating lanes, and decrease the time required to complete the project, the project is both safer and more efficient. However, as you increase the number of operating lanes, and extend the time required to complete the project, there is better access to emergency vehicles and through traffic. Thus, in terms of overall performance, these two cases end up counteracting one another causing Alternative 1, 2, and 3 to all have a ranked score of 12, and Alternative 4 to have a ranked score of 15, making Alternative 4 the best solution.

6.5.4 Recommendations

Based on the ranking method, Alternative 4 has the best overall performance. Thus, the design of the traffic control plan for the Belmont Street/Route 9 Bridge will allow for two lanes of operating traffic so vehicles can flow in both directions. With the basic layout established, additional measure can be taken to complete the site layout. To help protect construction workers from moving traffic, some form of barrier should be used. For a stationary work zone that encounters high volumes of traffic, either traffic drums or a concrete barrier will be sufficient. Additionally, warning signs, guide signs, and regulatory signs shall be positioned, in accordance with MassHighway, to ensure vehicles are aware that construction will be taking place. Signs such as “Multiple Lanes Closed”, “Road Work”, and “Turn Prohibition (left)” are all appropriate examples for this project.

MassHighway has developed standard details and drawings to help standardize the different types of traffic control plans. These drawings can be used as templates for the majority of work zone layouts. Figure 48 has been taken from the Manual on Uniform Traffic Control Devices (MUTCD) provided by MassHighway. It illustrates the layout of a Partial Bridge Closure Stage

One Stage Two (Switch to other Side), similar to that of the Belmont Street/Route 9 Bridge, and will be used as a reference for the traffic control plan.

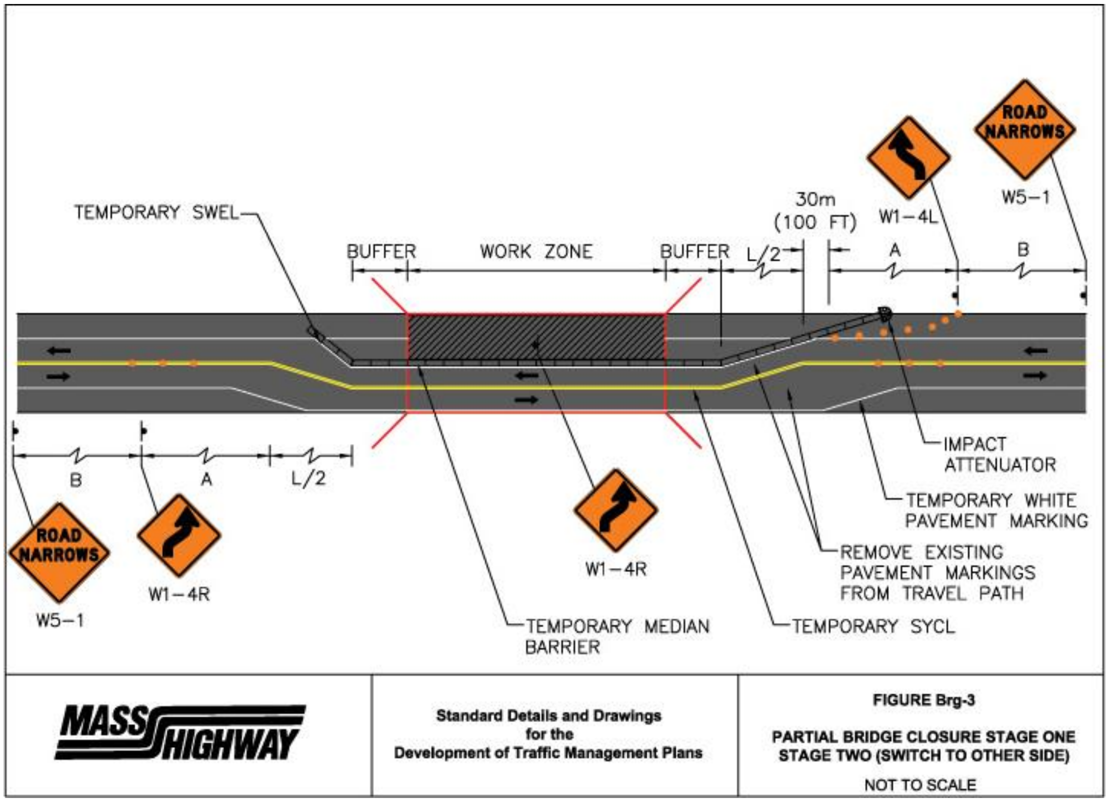


Figure 48: MassHighway standard detail (taken from MassHighway)

This however is only one portion of the traffic control plan. Aside from planning how the site will be laid out, it is also important to consider how the site will function. Since there will only be two lanes operating, one way to reduce congestion is by restricting turning movements. One suggestion from Mark Johnson and Joe Frawley at MassHighway was to prohibit vehicles from turning left off exit 17 of I290. They also suggested prohibiting vehicles from traveling westbound over the bridge and turning left on to I290. The following Figures illustrate the movements that will be allowed and restricted. The blue lines in Figure 49 represent movements that are allowed, and the red lines in Figure 50 represent movements that are restricted:

Figure 49: Allowed movements (taken from Google Maps)

Figure 50: Restricted movements (taken from Google Maps)

By limiting these movements, the amount of traffic traveling through the work site will be reduced, while still allowing for vehicles to travel directly westbound and eastbound. As for vehicles forced to find an alternative route, one possible solution is to redirect traffic towards Washington Square which may be accessed from either Summer Street or Shrewsbury Street. Vehicles could then either enter/exit I290 using exits 15 or 16 instead of exit 17. Figure 51 shows the proposed detour:

Figure 51: Detour 1 (taken from Google Maps)

Another solution is to redirect traffic towards Lincoln Square and use exit 18 to enter/exit I290. Figure 52 is provided to illustrate the detour:

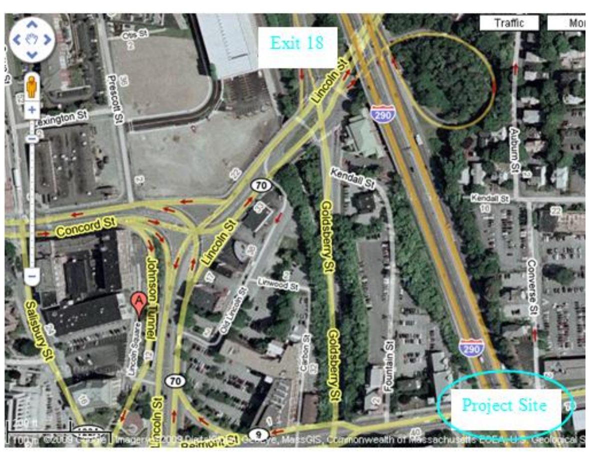


Figure 52: Detour 2 (taken from Google Maps)

Either way these exits are close in proximity, so re-routing traffic shouldn't cause any major inconveniences or delays. Thus, depending on where the traffic is traveling from and where the traffic is traveling to, there are several alternatives for vehicles to travel around the work site.

Although the recommended traffic control plan is based on the preformed analysis, there are additional devices and procedures that may be implemented to enhance the performance of the plan. Whether or not they are applicable, they may still be an option. One advancement is installing a temporary bridge next to the existing bridge. This allows the bridge to be closed without disrupting the flow of traffic. Despite being a costly alternative, this will allow construction to be safer and more efficient. However, considering the location of the Belmont Street/ Route 9 Bridge, there isn't enough space to install a temporary bridge. Figure 53 provides an aerial view of the area surrounding the project site:

Figure 53: Project site layout (taken from Google Maps)

Another advancement is to install a signal preemption system to allow emergency vehicles to have the right of way. Based on the criteria for the analysis, this will help to increase the ranking value of Emergency Access and Safety. Not only will this system help during construction, but it can also be used when the bridge is fully operating.

As stated earlier, these advancements may not be applicable to this project, but they should still be considered. Thus, in terms of developing a traffic control plan, assume neither the temporary bridge nor the preemption system will be installed. Figure 54 is a basic Traffic Control Plan that can be implemented for the Belmont Street/Route 9 Bridge:

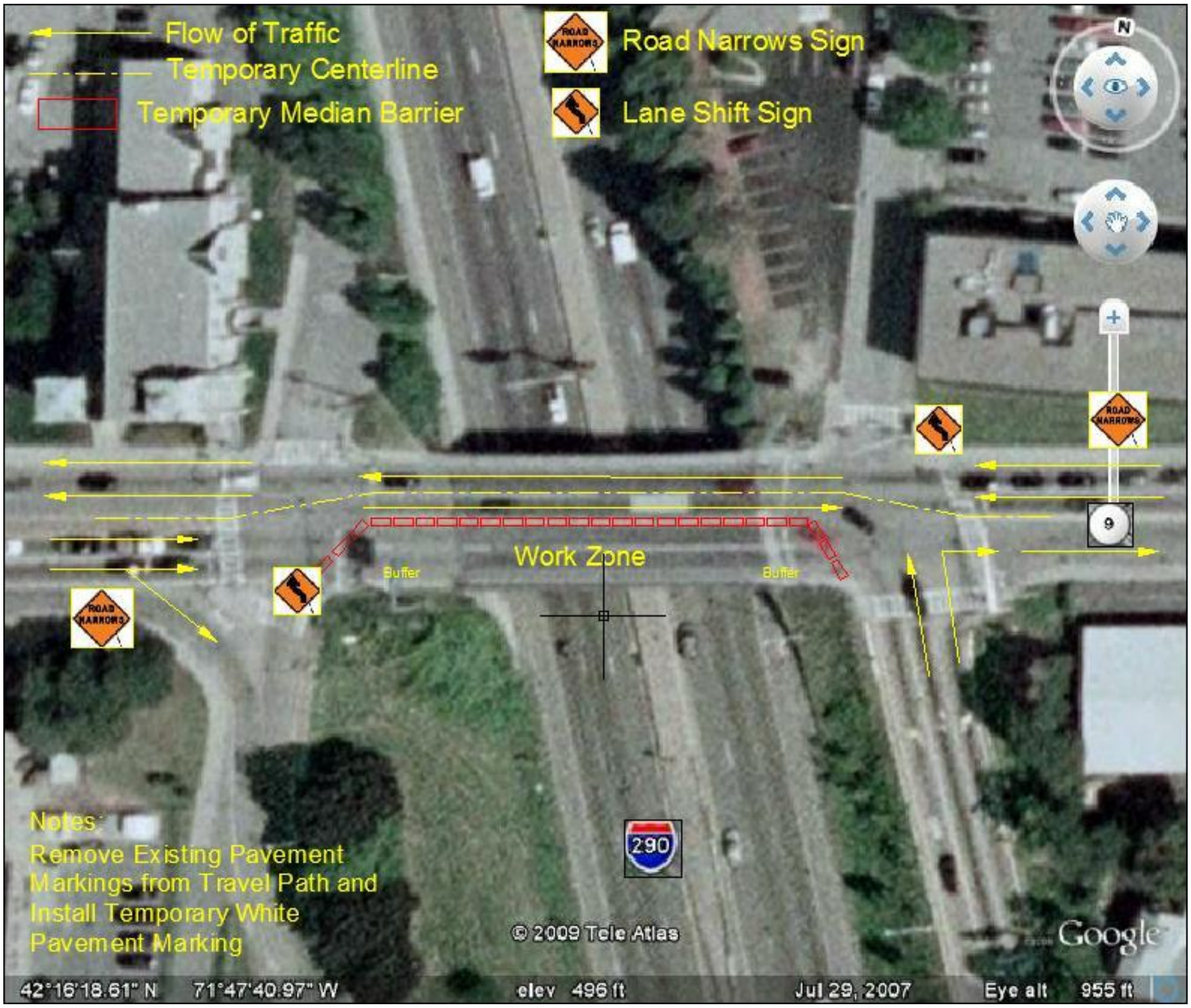


Figure 54: Belmont Street/Route 9 traffic control plan – Stage 1

This plan illustrates the movement of traffic, how the lanes will shift, and where the work zone is located. With appropriate signs and devices installed, vehicles should be able to safely travel in and out of the work site without harming the construction workers. In terms of a sustainable design, by allowing traffic to flow in both directions and by limiting turning directions, the amount of congestion and idling cars can be reduced.

6.6 Cost Analysis

There are two primary costs associated with a traffic control plan. The first is the cost for each traffic control bid item used in the design. This includes the cost of devices such as traffic drums and signs, the cost of hired control officers, and the cost of removing and replacing existing elements. The cost of these items can become very expensive, especially for a large scale project. The cost of each item can range anywhere from $2.70 per day for Barricade Warning Lights (High Intensity) to $50.00 per hour for a Uniformed Flagger (Traffic Control Officer) or $95.00 each for traffic drums (Connecticut Department of Transportation). All three of these items can be used for the Belmont Street/Route 9 Traffic Control Plan.

The second cost associate with a traffic control plan is more of an indirect cost related to how the design of the control plan affects the overall construction. In the case of the Belmont Street/Route 9 Bridge, the traffic control plan was designed to allow two lanes of operating traffic while the other two lanes were designated as the work zone. Depending on the site layout, the amount of space available for storing equipment and managing the site affects the total cost of the project. For instance, had the traffic control plan been designed to have three lanes of operating traffic, the amount of space available to perform work and store equipment may not be sufficient. Instead, in order to provide enough room for construction workers, additional space may need to be rented for offsite storage.

In addition to limiting the space available for work and storage, by increasing the amount of functional lanes during construction, the total area that can be worked on at a give time is decreased. As a result, the duration of the project may be extended as much as another whole year. Thus, the total cost of items that are dependent on time will increase significantly. This includes all items with an hourly rate, daily rate, or even a monthly rate.

In sum, the cost of the traffic control plan is associated with both direct and indirect costs. Not only does the design affect the types of devices used, but it also affects the duration of the project and the space available to work in. Thus, the design of a traffic control plan should provide a safe and sustainable solution while minimizing the costs of additional bid items and space requirements. In the case of the Belmont Street/Route 9 Bridge, the selected design, which provides two lanes of operating traffic, is both sustainable because it allows traffic to flow regularly and cost effective because it allows an optimal amount of space for construction without extending the duration of the project.

6.7 Conclusion

The objective of this section was to identify what a traffic control plan consists of and how one may go about designing such a plan. As identified earlier, the types of devices used and the layout of the site depends on the type of work zone, where the project takes place, and the flow rate of traffic in and around the area. In terms of the Belmont Street/Route 9 Bridge, four separate alternatives were evaluated to determine the most economical approach. The recommended traffic control plan accounts for the alternative with the highest ranked score, which in this case was Alternative 4. With the use of MassHighway Standard Details, Google Earth, and AutoCAD, a traffic control plan drawn specifically for this project was presented.

7 Sustainable Bridge Design

Sustainable design is the future of heavy construction projects. In a country that is suffering from an economic crisis, the fact that structures such as bridges are requiring increased amounts of maintenance is not helping relieve any financial burden. Maintaining and rehabilitating bridges is a costly process which includes labor, equipment, and material expenses. Because there is no standard practice in performing bridge maintenance across the U.S., sometimes it is difficult for engineers to determine when a structure is in need of repair. For this reason, many structures become unstable or deficient making them unsafe to the general public. Engineers can not catch up with the increasing maintenance demands so many bridges are left untouched. This action can put bridges into a very critical state and can even cause injuries or in worst cases death, like the 2007 bridge collapse on Interstate 35 in Minneapolis, Minnesota (Design News). By transitioning into a system that uses more sustainable designs and building materials, it is possible to build better structures that will not suffer from serious damages due to the effects of corrosion. The initial transition will be very costly but it can be justified by the idea that the bridges will not need repairs as soon or as often as bridges that are built with typical materials used today. Also, if new construction has an increased service life, engineers will have the opportunity to repair existing critical bridges without having to worry about additional maintenance cases being added to their workload. It is important for engineers to consider the life-cycle cost of new systems and building materials to decide if they are worth the increased cost.

Design is beginning to evolve from typical practice to more innovative practice which incorporates the use of sustainable and recyclable materials. Example of how design is changing is the emergence of the LEED certification system in building and the Architecture 2030 Challenge to reduce the contribution of global warming from the building sector. Guidelines such as these have not yet been created for bridge design. As the world becomes more conscious of its responsibility to reduce the amount of negative environmental impacts during building construction, it is essential to have specifications for all types of construction including bridges and other infrastructure systems.

7.1 LEED Building Standards

The project team, by using the LEED building specifications as a guideline, was able to create a similar type of guidelines to use for bridge construction. LEED has become a universal building guideline for sustainable building that has been adopted by several state and local governments across the country. The development of LEED rating systems is due to the collaborative efforts of several practitioners and experts in the construction and building industry. This allows a committee to evaluate the guidelines and enable them to have an open appeals process if changes to the guideline are deemed necessary (LEED Project Certification).

The intent of the preliminary bridge sustainability rating system is to allow a basis for developing an accepted sustainable guideline for bridge designs. The implementation of such a system could have a serious affect on the environment much like that of the LEED building system. With the adoption of a new system, LEED can extend their boundaries into other areas of structural design.

7.2 Existing Sustainable Bridge Designs

Recently engineers have made a conscious effort to include the idea of sustainable design in their new, innovative bridge projects. Many countries around the world including the United States have experimented with using recyclable materials, alternative design practices and other ideas that lead toward a more sustainable design advancement. Although there currently is not a set of standards or guidelines for engineers to follow, by investigating the new types of design that are emerging around the world, engineers can start to describe an initial set of standards for sustainable bridge design. A few states that have made significant advances in sustainable bridge design are Oregon, Maine, Wisconsin, and Illinois.

7.2.1 Wind Turbine Powered Bridge in Oregon

In Oregon, design proposals for one new project will include the addition of wind turbines. The $4 billion dollar project would use wind turbines to generate power that could be used for the bridge lights or operation of tollbooths (Rivera). One of the problems of implementing such a new design on a bridge is that it is difficult to measure how much power the system will generate and if the system will provide a sufficient amount of payback to justify the new construction. The addition of such a system will require the structure to have a higher capacity to accommodate the additional weight of the system. As the required capacity of the bridge increases, the cost of building materials also increases. Some concerned people think a bridge with turbines will be an eyesore so multiple designs have been created to alleviate the apprehension. Figure 55 shows a design with vertical spinning turbines in the center of the bridge. The thought behind this unique project is that it will showcase the regions commitment to leadership in sustainability (Rivera).

Figure 55: New Interstate 5 bridge crossing over the Columbia River shows vertical wind turbines in blue (taken from http://www.oregonlive.com/environment)

The second design shown in Figure 56 features a flat design with helix shaped turbines erected in transparent cylinders that are mounted approximately 10 feet above the roadway.

Figure 56: Flat Interstate 5 bridge design with wind turbine mounted along the bridge, similar to a sculpture design (taken from http://www.oregonlive.com/environment)

Many people are still skeptical about the new design which tends to happen when a new, innovative system or design is introduced without much proof that it will eventually be worth the initial investment. The project is still in the process of being presented to the public and addressing concerns. A final design has not been agreed upon and no date to start building has been set at this point (Rivera).

7.2.2 Recycled Road Sub-base on Bridge in Maine

In Sabattus, Maine over 2 million scrap tires were made into 6-inch rubber chips and used as a replacement for traditional crushed rock in a road sub-base on a 2003 bridge project. The 2 million scrap tires equate to about 19,000 tons of rubber chips. The cleanup site was located only 10 miles away from the project site in Bowdoin, Maine, so transportation and delivery of the reusable material was minimal. At one point the Bowdoin site had between 8-10 million scrap tires. Since Maine has made an effort to reuse the rubber in various construction projects across the state, Bowdoin now has between 1.5 to 2 million scrap tires. Of the five sites that had over 1 million scrap tires each, Maine had currently cleared all but one by using the waste. In 2001 over 40 million scrap tires were used in civil engineering projects across the U.S. The use of the shredded tire chips is also more economical than using typical material such as crushed rocks. For a project that was estimated to cost over $1 million for traditional fill, Maine spent only $507,600, almost half the cost by reusing a material that served the same purpose as the crushed rock (Truini). Other states such as California have also put extensive effort in reusing scrap tires. In the late nineties California recycled 64.5% of its scrap tire stockpile. Some of these tires were shredded into rubber chips that were used in several civil engineering projects in the state. It is estimated that California could potentially increase its annual recycled tire use to approximately 6 million scraps from its current 1 to 2 million scrap use in just civil engineering projects (Anonymous).

7.2.3 Reinforced Poly-Fiber Grid System in Wisconsin Bridge Deck

A bridge in Fond du Luc, Wisconsin was built using a fiber-reinforced polymer grid system to replace traditional steel rebar reinforcement. Because the polymer material is resistant to corrosion, engineers estimate that a design using this system will provide an additional 35 to 40 years of service life to the bridge. This doubles the typical span for which bridges require maintenance and repair. Figure 57 shows the installation of the plastic grid system on the Wisconsin bridge. The grid system is prefabricated so it can easily be brought to the site and installed much faster than typical reinforcement systems. Cranes are used to rapidly lay the grids in place which eliminates costs associated with laborers and equipment (ASM International). The engineers believe that these reasons justify the approximate 35% higher cost difference than the typical steel rebar reinforced bridge deck (Fiber Reinforced Polymer Bridge).

Figure 57: Polymer grid system being laid into bridge deck by a crane (taken from http://www.engr.wisc.edu)

7.2.4 Eco-Friendly Bridge in Chicago, Illinois

A plan to develop a green space along Chicago's Monroe harbor includes the addition of a semi-circular bridge given the name "Eco-Bridge". The reason for this design is to provide a breakwater where residents and tourists can spend time sailing or rowing in the calm water. The bridge itself will also have recreational space to include public parks and fountains. The design spans two miles and connects the city center to Grant Park as shown in Figure 58. To showcase Chicago's commitment to building with sustainable design, wind turbines located along the bridge would be incorporated in the final design. The project is estimated to cost $1 billion but since there is no funding for the project yet, no date has been set to start construction (Rogers). Cities like Chicago that attract millions of tourists a year can really use their initiative in sustainable bridge design to increase awareness about the importance of choosing to build structures that follow more sustainable standards.

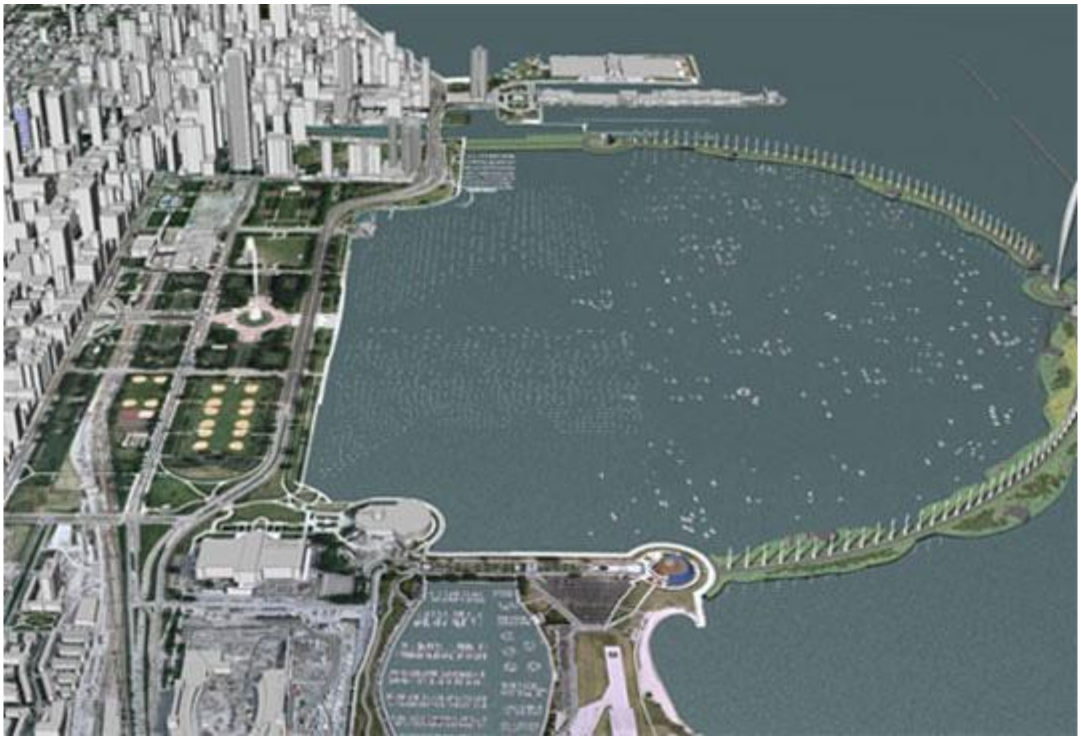


Figure 58: Arial model of proposed "Eco-Friendly" bridge on Chicago harbor (taken from http://earthfirst.com)

7.3 Creation of Sustainable Bridge Design Guidelines in Bridge Construction

In order to create a guideline to bridge building with sustainable design, the LEED building certifications were used as a model approach. The components of bridge design differ from those of building design so changes were made to different categories and criteria as necessary. The guidelines were broken up into five main categories including: materials & resources, design based on durability and maintenance, sustainable site, alternative utilities and reduction of environmental impacts. Each category was assigned a maximum value for the amount of points that can be obtained if the criterion is followed as shown in Figure 59. By adding up the total points from each category, much like that of the LEED certification process, it can be determined which certification level the design achieved (U.S. Green Building Council). The mock-up guidelines include four different levels that range from a level of minimum certification to Platinum certification. Points range from a low score of 18 to 23 to the highest level of recognition, the Platinum certification which receives between 38 to 49 points.

Sustainable Bridge Design Point Rating System

Materials & Resources (13 pts maximum)

- Constructed of recycled materials from preexisting structures (3 pts)
- Use of waste byproducts integrated into road sub-base (1 pt)
- Reuse of scrap metal railings and guardrails from rehabilitation projects (1 pt)
- Corrosion protection system is in use (2 pts)
- Use of prefabricated materials (2 pts)
- Timely and appropriate application of protective coatings (1 pt)
- Materials can be reused if they need to be replaced (2 pts)
- Use of various byproducts to enhance strength of concrete (1 pt)

Design Considerations (7 pts maximum)

- Avoid use of movement joints (1 pt)
- Design is integral from one abutment to the other (1 pt)
- Addition of arching action (1 pt)
- Locating steel reinforcement at center of slab with thickened cover (1 pt)
- Use of glass fire reinforced plastic reinforcement bars (2 pts)
- Use of higher strength concrete (1 pt)

Sustainable Site (12 pts maximum)

- Construction activity pollution prevention plan (3 pts)
- Ability to be maintained while still remaining in service (1 pt)
- Located near large public buildings such as hospitals, hotels, apartment buildings, etc. (1 pt)
- Surrounding area provides space for water storage tanks (1 pt)
- Located near bus stop for use of public transportation (1 pt)
- Roof covers bridge (1 pt)
- Located nearby existing traffic route (2 pt)
- Does not affect historical locations (1 pt)
- Provides area for HOV lanes (1 pt)

Alternative Utilities (9 pts maximum)

- Implementation of wind turbines to produce natural energy (3 pts)
- Use of rainwater harvesting collection and storage system (3 pts)
- Electricity generated powers bridges lighting system (3 pts)

Reduction of Traffic Pollution (8 pts maximum)

- Provides adequate space for pedestrian/bike path (2 pts)
- Motion sensors on traffic lights (1 pt)
- Automatic toll sensors (1 pt)
- Reduced toll price for hybrid cars (2 pts)
- Include option for mass transit (2 pts)

Certification Levels
Certified: (18 - 23 pts)
Silver: (24 - 28 pts)
Gold: (29 – 37 pts)
Platinum: (38 – 49 pts)

Figure 59: Preliminary sustainable bridge design point rating guidelines

7.4 Sustainable Bridge Design Guideline Recommendation

Ideally, a sustainable bridge design guideline similar to the LEED building design guideline should be produced to encourage engineers to take a more sustainable approach to their designs. The guideline could be included as an extension of the LEED program to extend sustainable design standards and alternatives to other infrastructure systems. The project team developed a preliminary guideline for sustainable bridge design to recommend implementing. The guidelines are organized into categories and awarded a point value based on the impact of the alternative on the environment.

Based on the preliminary guidelines from Figure 59, it can be noted that the two categories of particular emphasis are Materials & Resources and Sustainable Site by the fact that the most points can be achieved in these categories. For example, the guidelines encourage engineers to make a conscious effort to build with less raw materials and more reusable materials. Also, the guidelines try to promote the use of public transportation and carpooling to reduce emissions caused by idol traffic. A brief description of each category which includes the impact of other suggestions is included with the guidelines to ensure the understanding of the criteria. Full points are allotted for each guideline that is met based on an established criterion of typical building guidelines. No partial points will be awarded.

7.4.1 Materials & Resources

Materials and Resources focuses on the idea of reducing the amount of raw materials used in a new construction project. If raw materials are needed for various components, then it is important to ensure that they can be reused on another project if removed or repaired in the future. Recycled materials like waste concrete or scrap metal from railings of guardrails can be collected from the demolition during maintenance of surrounding structures. Other byproducts like scrap tires can be reduced into small pellets and integrated into a road sub-base. Industrial byproducts such as fly ash and silica fume can be added to concrete mixtures to increase the strength of the material. In order to reduce the amount of time before maintenance is needed, corrosion protection systems must be installed in the design. This can be as simple as including epoxy coated rebar instead of non-coated reinforcement. Protected steel is more effective than plain rebar because the protective coating is more resistant to corrosion, therefore lasts longer. During maintenance it is important that the correct protective coatings are applied appropriately and as often as necessary to uphold the integrity of the design. If steel reinforcement is used, locating it in the center of the member and increasing the size of the reinforcement could reduce the amount of individual rebar used; reducing the locations corrosion can occur.

Another consideration that must be taken into account for a sustainable design is the use of local materials. During construction, if the bridge location is within 500 miles of the prefabrication sites, it can decrease the emissions of large service trucks that deliver the parts. Also, an increase in the amount of prefabricated materials used in a design can reduce the amount of time heavy equipment is needed for installation. This is beneficial because it reduces the cost of equipment as well as the amount of pollution created by the machine engines. It is important to note that this is not effective if the prefabricated components are located far distances from the project location because then the environmental impact of the large trucks needed to deliver the components would outweigh the benefit of having a prefabricated design. The amount and type of materials used in a bridge design can have a significant effect on the environment if certain considerations are not taken to reduce their affects.

7.4.2 Design Durability & Maintenance

There are several areas on a bridge that engineers can pay special attention to during the design stages. If certain considerations are taken the durability of the design can be increased and the required maintenance can be reduced. Simple design considerations like ensuring the superstructure is integral from one abutment across the span of the bridge to the other can reduce issues of cracking caused by an uneven deck. Because joints are generally areas of concern on a bridge, avoiding the use of joints can produce a better design. Designing with the addition of an arch system can reduce the amount of reinforcing steel needed in the design which would eliminate the possibility of failure due to corrosion. Alternatively, designs could incorporate the use of reinforcement that is resistant to corrosion such as polyfiber reinforcement. Other resign considerations such as using a higher strength concrete will increase the durability of the component and extend its lifespan. A large part of sustainability is based on the final design of the bridge and its strength. Also, since maintenance is a very costly process which effects the environment, creating a design that reduces the amount of future maintenance needed on the bridge is optimal.

7.4.3 Sustainable Site

A significant area of recent concern is the amount of pollution caused by large shipping trucks, heavy equipment needed for construction and maintenance of various projects, and high volumes of traffic traveling on the roadways. Efforts to reduce pollution caused by traffic have already taken affect. Any approved construction plan should present a pollution prevention plan with the designs. In addition to a pollution prevention plan, points will be earned if the bridge is located on a preexisting roadway rather than require new roadway development and construction. Other ways to reduce car emissions are to incorporate the use of high occupancy-vehicle (HOV) lanes on the road or highway that the bridge connects or to have stops along the route of the bridge to encourage public transportation. It is important to ensure the bridge can remain in service during routine maintenance so that traffic plans that increase driver's routine or daily trips don't have to be altered. Another alternative is to build a covered bridge. This will increase the protection of the bridge deck from areas which experience heavy rain and snowfall. Lastly, similar to buildings, the construction of bridges must not obstruct surrounding historic structures or locations. For new construction choosing a sustainable site for a bridge project can play a large role in making the entire structure more sustainable.

7.4.4 Alternative Utilities

The key to success in sustainability is innovation in design. There are multiple ways to incorporate alternative utilities into a bridge design. Including a rainwater harvesting collection and storage system could provide usable rainwater to many surrounding places. Points can be gained by instituting a rainwater storage system and water storage tanks. This option could be used in conjunction with the LEED building points systems to award local building such as hospitals, apartments, hotels, etc. points for the use of the rainwater system. Also including wind turbines in the design could produce natural energy that could be used to generate electricity on and around the bridge. There are still many innovative designs that have not yet been attempted or included in a bridge design. As sustainability becomes more important, these new alternatives will begin to emerge rapidly.

7.4.5 Reduction of Traffic Pollution

There are many ways negative environmental impacts can be reduced in a bridge design. Points can be gained by providing space for pedestrian or bikes along the bridge path. On the connecting roads of the bridge, if tolls are included, traffic congestion can be alleviated by the addition of automatic toll sensors. Another alternative would be to charge a reduced toll price for hybrid cars to reward hybrid users for the environmentally conscious purchase. On highways especially if an option for mass transit is provided, it can also help reduce the amount of sitting traffic in highly traveled areas. In areas where there are intersections located at the ends of a bridge, sensors can be included on the traffic lights so vehicles are not stopped when there is no oncoming traffic in the opposite direction. By attempting to keep an even flow of traffic, vehicle emissions can be significantly reduced from non moving traffic.

The point values for The Sustainable Bridge Design Point Rating are broken down by category and the guideline includes the point ranges for the different levels of certification. Although the categories differ from LEED's sustainable building design categories, points are distributed similar to LEED's procedure.

7.5 Sustainable Bridge Designs of the Future

As engineers in different countries continue to experiment with the use of materials and resources, design considerations, sustainable sites, alternative utilities and the reduction of environmental impacts in sustainable design, eventually a set of standards similar to the LEED Building Criteria will be created for bridges. There are endless possibilities to design more sustainable structures in order to reduce the financial burden of maintenance and repair on bridges and increase the durability and service life of new construction.

7.5.1 Feasibility of Implementing Sustainable Bridge Designs

In order to investigate the feasibility of implementing a guideline similar to the one created for sustainable bridge design, a test bridge was rated using the new point system. The bridge used for the sample test was the proposed Eco-Bridge in Chicago. In Table 22 the design is awarded points in each category to determine if the design could meet enough requirements to be gain certification. Available options that could easily be incorporated in the design are highlighted in yellow to indicate the requirement will be met.

Table 22: Point rating system for bridge design

Certification Levels
Certified: (18 - 23 pts)
Silver: (24 - 28 pts)
Gold: (29 – 37 pts)
Platinum: (38 – 50 pts)

Materials & Resources	
Constructed of recycled materials from preexisting structures	3 pts
Use of waste byproducts integrated into road sub-base	1 pt
Reuse of scrap metal railings and guardrails from rehabilitation projects	1 pt
Corrosion protection system is in use	2 pts
Within 500 mile radius of prefabrication factories	2 pts
Timely and appropriate application of protective coatings	1 pt
Materials can be reused if they need to be replaced	2 pts
Use of various byproducts to enhance strength of concrete	1 pt
TOTAL	12

Design Considerations	
Avoid use of movement joints	1 pt
Design is integral from one abutment to the other	1 pt
Addition of arching action	1 pt
Locating steel reinforcement at center of slab with thickened cover	1 pt
Use of glass fire reinforced plastic reinforcement bars	2 pts
Use of higher strength concrete	1 pt
TOTAL	2

Sustainable Sites	
Construction activity pollution prevention plan	3 pts
Ability to be maintained while still remaining in service	1 pt
Located near large public buildings such as hospitals, hotels, apartment buildings, etc.	1 pt
Surrounding area provides space for water storage tanks	1 pt
Located near bus stop for use of public transportation	1 pt
Roof covers bridge	1 pt
Located nearby existing traffic route	2 pt
Does not affect historical locations	1 pt
Provides area for HOV lanes	1 pt
TOTAL	4

Alternative Utilities	
Implementation of wind turbines to produce natural energy	3 pts
Use of rainwater harvesting collection and storage system	3 pts
Electricity generated powers bridges lighting system	3 pts
TOTAL	3

Reduction of Traffic Pollution	
Provides adequate space for pedestrian/bike path	2 pts
Motion sensors on traffic lights	1 pt
Automatic toll sensors	1 pt
Reduced toll price for hybrid cars	2 pts
Include option for mass transit	2 pts
TOTAL	2

Table 23: Summary table of sustainable point totals

Criteria	Maximum Total Points	Total Awarded Points
Materials & Resources	13	12
Design Considerations	7	2
Sustainable Site	12	4
Alternative Utilities	9	3
Reduction of Traffic Pollution	8	2
MAXIMUM TOTAL POINTS: 49		**GRAND POINTS TOTAL: 23**

With a grand total of 23 points, the Eco-Bridge falls into the general certified level as shown in Table 23. The preliminary guidelines suggest that there are challenges involved with creating a list of sustainable criterion. Based on the point system, it seems as though it is not difficult to meet the criteria for the materials and resources category. This could suggest that the guidelines are too broad or that they are too easy to achieve. This could indicate that these guidelines are already included in most buildings or that they are not hard to incorporate in new designs. The lower point values in the other categories suggest that the design must be more innovative to gain additional points. This suggests that perhaps the guidelines are too focused and should be broader. Although there should be established guidelines to determine what is considered a sustainable alternative and what is not, reaching a level of certification should be attainable. Because the Eco-Bridge only gained a certified honor, it suggests that more can be done in sustainable design.

The application of this guideline provides feedback to possible alterations that could result in a better certification system. One thing that can be noted from the scheme is the lower point value in the reduction of traffic pollution category. When taking a look at the breakdown of criteria, it suggests that not all bridges have the same opportunity to meet the guidelines. For example, the suggestions about tolls and mass transit assume a large bridge to be used in the study. Generally small bridges do not include tolls; therefore they cannot be awarded points based on categories that involve alternative toll options. Another example of this can be seen in the Sustainable Site category which considers the use of HOV lanes. Similarly, HOV lanes are rarely used on small bridges such as highway overpasses, which are generally not wide enough to provide additional lanes. These implications suggest that perhaps more specific guidelines should be established for different bridge sizes based on amount of lanes and length of bridge. This would allow for dissimilar bridges to have the same possibility of achieving certification and therefore larger bridges would not be given an advantage.

As engineers create and test new designs, the criteria rubric can be altered to suggest new practices that are efficient and sustainable. Before a standard in sustainable design in bridge construction can be established like in building construction, the first step must be taken to introduce guidelines for engineers to follow. Once sustainable design becomes a routine practice, the need for guidelines and criteria will not be as eminent.

7.5.2 Costs Associated with the Implementation of Sustainable Bridge Designs

In most cases, there are extremely high costs associated with sustainable building versus costs of conventional construction. An increased initial cost is common because many sustainable designs are new and innovative; therefore they are often complicated and complex designs. Productability of the materials and systems used in the design may be lower, giving it a higher cost. Since many people are skeptical about the value of a multi-million or even billion dollar structure, engineers must investigate the payback given by using more sustainable materials and practices to justify the increase in initial cost. For example, if a reinforced polymer grid reinforcement system can add 30 to 40 years of service life on a bridge, is the added construction cost of this system offset by savings in equipment and labor in the future. These are the types of questions that taxpayers want answered before they are on board with large scale, innovative sustainable bridge projects.

8 Life-Cycle Cost Analysis

According to the US Department of Transportation Federal Highway Administration, life-cycle cost analysis is a "process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment (Kane, 1996)." Since bridges are a long term investment the goal was to create a sustainable design where aspects were addressed to further the serviceability of the bridge. For the re-design of the Belmont Street/Route 9 Bridge specifically, a construction cost estimate and a bridge management system were produced to provide insight into the implications of a life-cycle cost.

8.1 Background

The following section presents background information on the primary factors which influence the cost of bridge projects. The cost estimate section discusses the general guidelines and methods incorporated into producing a cost estimate. The maintenance section discusses the costs associated with repair and maintenance procedures.

8.1.1 Construction Costs

Prior to commencement of a construction project, a preliminary cost estimate is formulated to assist in identifying the scope and budget of the project. Along the duration of the project, additional cost estimates are conducted at various stages to ensure the cost of the project is within budget. Generally the cost estimate includes all of the elements associated with the project. The more comprehensive the estimate is, the better the results (SCDOT, 2006).

An estimator typically follows particular guidelines in order to produce a precise, yet comprehensive, cost estimate. The first step is to identify project elements and quantities then pursue completion of cost data needed to construct an estimate. Then an estimator should consult historical data to assign costs. Such information can be accessed from a database usually sustained by the respective state department of transportation. The database enables the cost estimator to allocate unit prices based on costs of similar projects and geographical locations. Unit prices depend on many factors, and the most relevant are listed below.

• Geographic location (e.g., urban/rural, engineering district)
• Similarity to recent bridge projects
• Inflation (adjustments to past prices to reflect the current year);
• Reliability of recent construction cost data
• Recent trends in cost of materials, labor, and equipment
• Anticipated difficulty of construction
• Project size relative to size of similar projects
• Proposed project schedule
• Anticipated construction staging
• Expected environmental problems (e.g., hazardous wastes, wetlands)
• Use of experimental materials and engineering judgment
(SCDOT, 2006).

It is important to estimate for the broad spectrum of areas related to each construction project. In addition to unit costs for the structural components, additional project fees need to be regarded. The further areas of cost for a bridge project are approach, mobilization, and removal and disposal of existing bridge elements. The project approach includes areas such as a traffic control plan and provisions for replacement of utilities. Sometimes a separate cost estimate is prepared by the transportation department to provide the cost of implementing a detour plan. Mobilization costs include projected fees for preparation of work and transfer of equipment, supplies, and the workforce back and forth from the project site. The removal and demolishment of existing bridge components incur a smaller amount of costs, but are intrinsic to the total cost estimate (SCDOT, 2006). Figure 60 illustrates the average breakdown of costs associated with bridge projects according to the Texas Department of Transportation. Approximately 55.0% of the cost is produced from construction of the bridge, 30.0% from the approach of the project, 10% for the mobilization, and 5.0% for the removal of existing components (TXDOT, 2007).

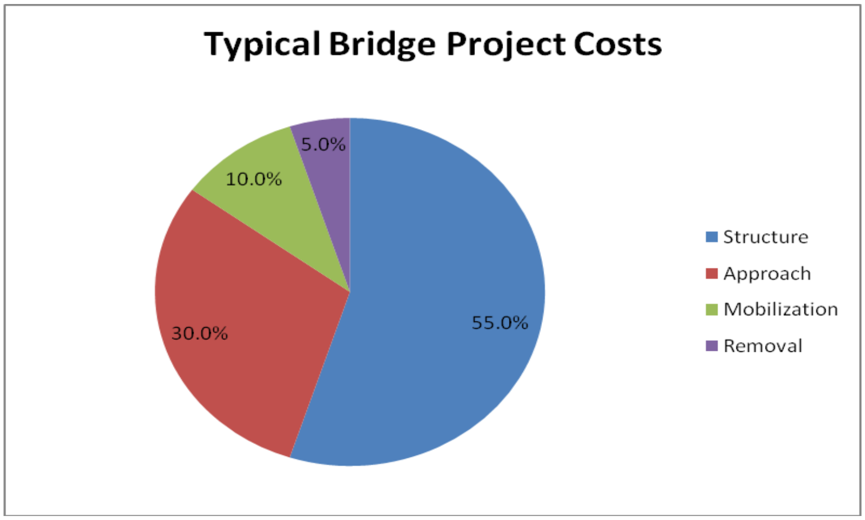


Figure 60: Pie Chart of Average Breakdown of Costs for Bridge Projects (TXDOT, 2007).

Furthermore, there are indirect costs attributed to each project such as on-site offices, temporary utilities and employee salaries. After the final estimate is completed, contingency costs are generally appended as well. Contingency costs account for uncertainties in the design and for unforeseen emergencies. The additional contingency cost is usually 10% to 15% of the final estimate (SCDOT, 2006). Due to the above mentioned factors, and various other considerations, cost estimating is not an exact science and requires experience and practice.

8.1.2 Maintenance

Estimating the direct cost of material, labor, and equipment required for construction is only one aspect of determining the long term cost of a project. In order to produce a realistic life-cycle cost analysis, the cost associated with rehabilitating and maintaining the structure over the duration of its service life was also considered. For instance, there may be a less expensive design which uses a low grade concrete, but will contribute to corrosion of the reinforcing steel area faster. In this case, by paying more money up front and using a higher strength concrete that is more resilient, it is possible to save money in the future if the structure is easier to maintain. Thus, maintenance considerations are equally as important as the cost of construction. However, the problem with evaluating maintenance costs is that it is difficult to place a numerical value on maintenance and repairs with limited data and resources. Not to mention most repairs are performed on a case by case basis, so aside from routine inspections, maintenance occurs at a variable rate. Thus, this section aims to identify the different costs associated with maintenance in order to propose a bridge management plan specific to the Belmont Street/ Route 9 Bridge.

8.1.2.1 Types of Maintenance

Some forms of maintenance are minor compared to others, but may occur more frequently. This includes repairing minor cracks and potholes, resurfacing/resealing surfaces, repainting surfaces, and repairing curbs, handrails, and sidewalks (MoDOT Engineering). This also includes maintenance procedures such as cleaning trash, removing snow, distributing road salts, or sweeping the road surfaces. Aside from the general upkeep of the structure, most of these repairs are caused by general wear and tear of the materials.

Even though minor repairs contribute to extending the service life of the structure, there are additional maintenance activities that have a greater impact on service life. These repairs are typically more in depth, but occur less frequently. This includes repairing bent or damaged steel beams, repairing cracked or spalled concrete, repairing or installing new expansion joints, repairing bridge decks, maintaining proper drainage, restoring or replacing bearings, repairing or replacing approach slabs, and repairing bridge beam ends (American Association for State Highway and Transportation Officials). Again these damages are caused by wear and tear of the materials, but also from the lack of performing routine maintenance on design details that contribute to degradation. If a management system was implemented, it may be possible to extend the service life of the structure and prevent these damages from occurring.

Over time structures are bound to weaken and deteriorate. Since they are constantly subjected to load factors such as chemicals and varying weather conditions, it is important to be aware of the different types of debris and sediment collecting on the surface. Figure 61 lists the various pollutants that are deposited onto the structure through stormwater and runoff:

Table 1. Highway Runoff Constituents and Their Primary Sources (US EPA, 1993)	
Constituent	**Primary Sources**
Particulates	Pavement wear, vehicles, atmosphere
Nitrogen, Phosphorus	Atmosphere, roadside fertilizer application
Lead	Tire wear, automobile exhaust
Zinc	Tire wear, motor oil, grease
Iron	Auto body rust, steel highway structures, moving engine parts
Copper	Metal plating, brake lining wear, moving engine parts, bearing and bushing wear, fungicides and insecticides
Cadmium	Tire wear, roadside insecticide application
Chromium	Metal plating, moving engine parts, brake lining wear
Nickel	Diesel fuel and gasoline, lubricating oil, metal plating, brake lining wear, asphalt paving
Manganese	Moving engine parts
Cyanide	Anticake compound used to keep deicing salt granular
Sodium, Calcium, Chloride	Deicing salts
Sulphate	Roadway beds, fuel, deicing salts
Petroleum	Spills, leaks, or blow-by of motor lubricants, antifreeze and hydraulic fluids, asphalt surface leachate

Figure 61: Road pollutants (Stormwater Center)

It is apparent that there are a wide variety of constituents that come in contact with the structure. Thus, by maintaining road surfaces and keeping the structure clean, the negative effects caused by the discharge of stormwater can be reduced. This may be achieved by properly applying road salts, sweeping and vacuuming heavily traveled roadways, and restricting the use of herbicides and pesticides used in certain locations (Stormwater Center).

8.1.2.2 Cost of Maintenance

Regardless of the type of repair, the cost of maintaining a structure can accumulate quickly. Washington State Department of Transportation (WSDOT) provides estimated rates for both labor and equipment associated with maintenance. The costs according to WSDOT are summarized in Figure 62. This includes Maintenance Technicians for Traffic Control and Repair, $40/hour/person; Bridge Inspectors, $50/hour/person; Man Lift, $16/hour; Pickup, $5/hour; and Vans, $4/hour. Considering the total costs associated with inspections, the employment of technicians, inspectors, and equipment sums up to roughly $240 per structure annually (Wisconsin Department of Transportation). Since the costs of materials vary, this estimate does not assign a numerical value to the materials.

Structural Inspections

Work Activity	Qty	Details	Cost
Labor	4	Maintenance Technician for Traffic Control	$640
	2	Bridge Inspector (Structural Engineer)	$400
Equipment	1	Man Lift Truck	$64
	1	Pickup	$20
	2	Van	$32
	1	Truck-Mounted Impact Attenuator	$12
		Total Cost per Structure (every 5 years)	**$1,200**
		Total Cost per Structure (annually)	**$240**

Figure 62: Inspection costs (taken from Wisconsin Department of Transportation)

The underlying problem with performing routine maintenance is the issue of obtaining money. Money is often budgeted towards deficient structures since they have higher priority. However, by taking a proactive approach to preserve the structure instead of waiting until the structure is in critical condition, the cost of maintenance is far less than the cost of complete rehabilitation.

A study was completed by Dave Westerling, an associate professor at Merrimack, for the Longfellow Bridge, built in 1909, which connects Boston and Cambridge, Massachusetts. The study investigates the cost of deferred maintenance associated with the bridge and how performing regular maintenance can reduce the amount of costly repairs. To illustrate this, Westerling applied the concept of annual reinvestment to the following three scenarios. Scenario 1- Annually invest 1% of the bridge's capital cost in a maintenance program, Scenario 2- Annually invest 2.5% of the bridge's capital cost in a maintenance program, and Scenario 3- No annual maintenance program but a major rehabilitation in 1959 followed by another facelift in 2002 (Westerling and Poftak).

Figure 63 estimates the total savings over the 100 year life of the Longfellow Bridge by using a small percentage of funds for maintenance and repairs for each scenario:

	Scenario 1 (1%)	**Scenario 2 (2.5%)**	**Scenario 3 (0)**
Maintenance Cost	$62.7M	$156.8M	$23.5M
Current Cost to Rehab	$80.0M	$40.0M	$200.0M
Total Cost to Return Bridge to Good Repair	$142.7M	$196.8M	$223.5M
Estimated Savings from Maintenance	**$80.8M**	**$26.7M**	**N/A**

Figure 63: Summary of Maintenance Scenarios (% asset value spent yearly on maintenance) (Westerling & Poftak, 2007)

From the figure above, it is evident that by maintaining the structure it is possible to save as much as $80.8M over its lifespan. Comparatively, in the case of the Belmont Street/Route 9 Bridge, it may be beneficial to apply an annual reinvestment to increase savings.

If funding for repairs is delayed, the state will then have to fund for replacements (Massachusetts Infrastructure Investment Coalition). Considering the cost of repairs is typically less than the cost of replacements, a good way to budget for maintenance is by "requiring agencies to expend operating funds equal to 2 percent of asset replacement value on maintenance, establishing a Facilities Maintenance Reserve Fund, and utilize budgetary surpluses to perform pay-as-you-go maintenance," (Westerling and Poftak). To ensure the money set aside is put towards maintenance, it is best to avoid prioritizing new projects over maintenance and political incentives that discourage money being used on maintenance (Westerling and Poftak).

According to De Sitter's 'Law of Fives', "if maintenance is not performed, then repairs equaling five times the maintenance costs are required; if the repairs are not made, the rehabilitation costs will be five times the repair costs," (Westerling and Poftak). Additionally, money spent on maintenance early in the life of the structure is more effective than money spent at the end of its life. Thus, it is better to perform regular maintenance throughout the life of the structure.

8.2 Methodology

A life-cycle cost analysis was conducted to determine the most feasible design components for the Belmont Street/Route 9 Bridge based on economic considerations. Life-cycle cost includes the initial construction of the bridge as well as provisions for repair and maintenance. The estimate quantifies material, equipment, and labor costs, and considers the implications of maintenance.

8.2.1 Construction Cost Estimate

Donald P. Wurst, a Professional Engineer from Weston & Sampson Engineers, gave insight into the estimating process. He stated, "In Connecticut, as with many other states, we bid projects with pay items and unit prices. Each item has an estimated quantity. Then a unit price is applied to that to get the estimated construction cost" (Wurst, 2008). A similar approach was taken to formulate a cost estimate for the Belmont Street/Route 9 Bridge. The first step was to make a spreadsheet with a detailed list of the design components and assign a unit cost to each. In order to allocate unit costs, the *RS Mean's Construction Book for Heavy Equipment* was consulted. The *RS Mean's* manual illustrates costs which include materials, labor, and equipment. For the purpose of this project overhead and profit expenses were not considered.

After all unit values were determined, quantities of each item needed to be established, and these quantities were measured consistent with the unit cost. Some items were priced per entity, other were priced per cubic yard or square yard, while some items were priced per square foot. To complete the cost estimate, the quantity of each item was multiplied by the unit cost and rounded to the nearest $100 or $1000, depending on the value. Then a summation of the cost of each item was calculated to determine the total cost of the project. The calculations for separate bridge components are illustrated in Appendix L. An excerpt of the calculations is shown in Table 24.

Table 24: Bridge Component Quantity Calculations

Deck Slab- 8"

Length (ft)	Width (ft)	Unit (SF)
131	48	6288.00

Bituminous Concrete Wearing Surface

Length (ft)	Width (ft)	Depth (ft)	Unit (CY)
131	48	0.21	48.52

An aspect which took more consideration was assigning unit costs to different girder sizes. In addition to investigating the total cost of the bridge the objective was to select an economical girder size. The *RS Mean's* handbook only supplied values for girders up to a nominal depth of thirty-six inches. The majority of the girders considered for this analysis entailed the utilization of wide flange beams with a nominal depth of forty inches. After, investigation it was evident that the costs were based on the weight of steel in pounds per linear foot. The nominal depth of the beam did not significantly affect the cost. To estimate the unit prices a graph was devised based on a wide flange girder with a thirty-six inch nominal depth and varying weights. It was produced with the values supplied in the *RS Mean*'s Handbook. Figure 64 includes a graph of cost based on girder weight is plotted below. Notice that the prices follow an increasing linear trend.

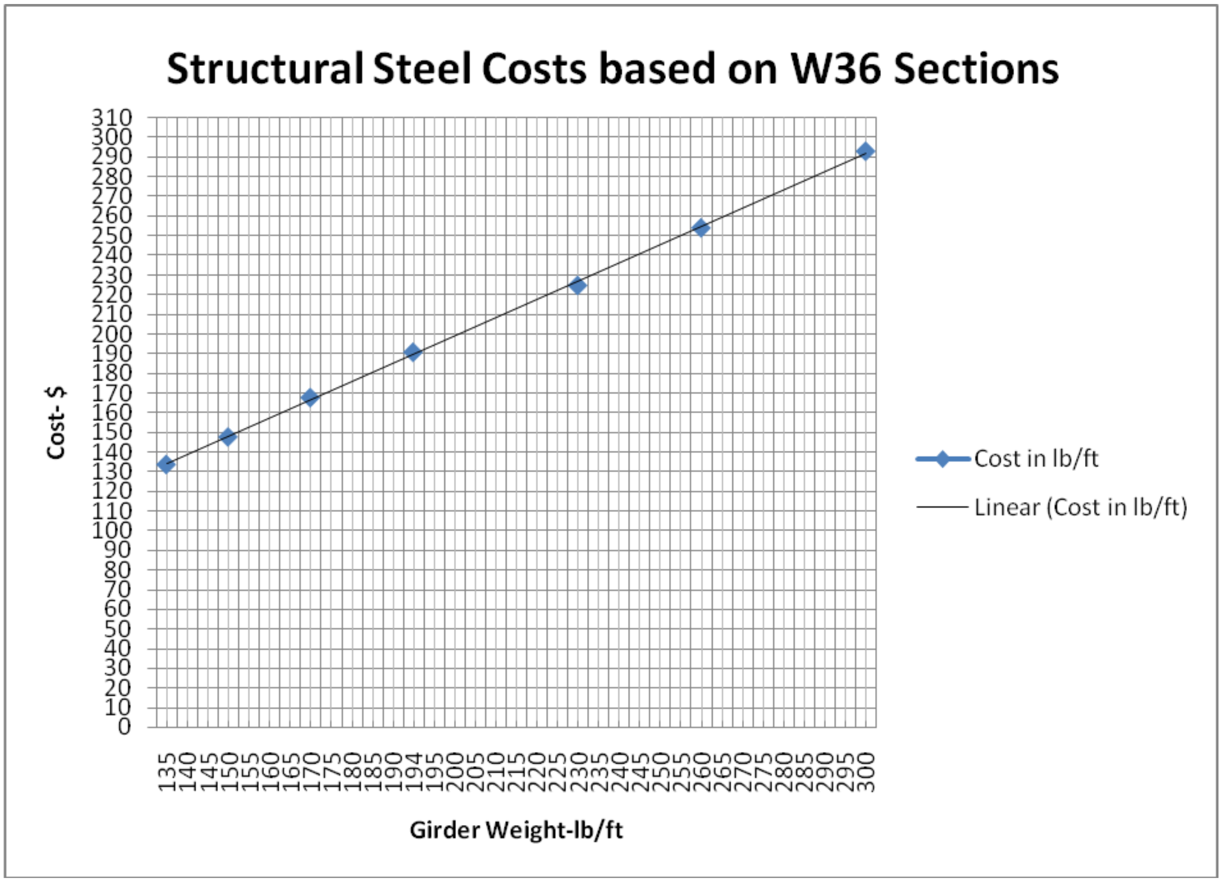


Figure 64: Cost of girders based on weight

Values were assigned based on the cost function of cost per weight. The prices were assumed to be to the nearest dollar since it would be difficult to distinguish cent values. For example a W40x199 was estimated to cost $197.00. Cost assignments for various girder sizes may be viewed in Appendix L. The least expensive girder design was used for the overall cost estimate. Due to this method of estimating cost, the cost allocation may not be as accurate as real world applications, but it still provides a suitable reference.

Once the values were assigned to each girder size then a cost estimate for solely the girders was performed. This preliminary cost estimate only assessed the cost of different girders sizes and accounted for shear connectors as well. This cost analysis will be displayed in the results section. After the costs were calculated, the most economical girder and shear connector option was chosen and included in the overall cost analysis.

The overall cost estimate was formulated to provide a base for considering the financial implications of bridge design. Cost per unit for some items was not found in the *RS Mean's* manual due to the fact that the handbook is based more on construction of buildings. This influenced the overall accuracy of the cost data. The accuracy of the estimate was also limited by amount of obtainable design data. For example, the dimensions of the wingwalls and abutments were approximated because the exact dimensions were not known. For simplicity they were assumed to be pre-cast structures to make sure a conservative amount of concrete and reinforcement was included.

Due to the lack of data and resources, the construction estimate provided is only a base cost of the major components that were designed for. The following list contains additional elements which would be included in a comprehensive cost estimate:

Additional Material Costs:

- Equipment and labor costs for Bearings
- Foundation elements such as piles and footings
- Parapets
- Abutments
- Additional reinforcement such as lateral bracing
- Miscellaneous steel work such as welding or bolting
- Temporary drainage structures, and drainage protection used during construction

Site Costs:

- Preliminary site investigation
- Clearing and grubbing
- Demolition and removal of existing structure components
- Excavation
- Backfilling
- Curing and finishing of concrete structures

Additional Project Costs:

- Design Fees
- Subcontractor Fees
- Indirect Costs: temporary offices and utilities
- Overhead and Profit
- Inflation and Interest Rates
- Contingencies or Special Provisions
- Traffic Control Plan
    - Pavement markings, signage, traffic barriers
- Police Detail
- Inspection Costs

8.2.2 Bridge Management System

Although a cost estimate provides insight to how much a project may initially cost, it does not account for the service life of the structure. Thus in order to provide an accurate life-cycle cost analysis, the cost of repair and maintenance was considered. However, since there was an absence of data available for the Belmont Street/ Route 9 Bridge, the cost of maintenance was discussed, but an actual numerical value was not assigned to the maintenance portion. Instead, a bridge management system was suggested in order to improve the quality and service life of the bridge once construction has taken place.

According to the *AASHTO Manual for Bridge Maintenance*, "Most problems can be prevented or minimized by timely preventative maintenance for bridges," (American Association for State Highway and Transportation Officials). As discussed in the background section, there are several factors that affect the overall performance of the structure. This includes the construction materials used; the quality of construction; the details of the design; and natural occurrences of the atmospheric environment such as fire, fatigue, earthquakes, and floods (Harding, Parke and Ryall).

Thus, a bridge management system is designed to manage the inspection, analysis, and maintenance of the bridge for as long as the bridge is functional. In order to establish a bridge management system, the following steps should be taken: 1. Determine activities, 2. Determine data set which includes material, load-bearing, and condition data as well as maintenance strategies, 3. Perform ranking and Budgeting, and 4. Describe the contents of the activity (Harding, Parke and Ryall).

The bridge management system presented is modeled from an existing system created by the New York State Department of Transportation. The system provides a method to determining whether maintenance, rehabilitation, or reconstruction is required. From that the proper steps can be taken to fix the problem. This process can be used specifically for the Belmont Street/Route 9 Bridge to ensure the appropriate maintenance procedures take place. The system also provides a list of maintenance and repairs ranked according to their cost. Since there are certain operations that provide a better value for your money, this list illustrates which activities are cost effective.

8.3 Results

The life-cycle cost analysis provides insight into the overall cost of the bridge while considering future maintenance costs and procedures. There are several components incorporated in the estimated construction cost of a project, but as stated earlier, due to limited design data and cost information the estimate is provided for only a portion of the project. Further investigation of the design of the bridge as well as additional sources of cost data would lead to a more accurate estimate. In addition, a bridge management system is provided to help control the costs of future repairs. By implementing such a system and performing routine maintenance, less money will be spent on serious repairs. The information obtained from the cost estimate and maintenance considerations will be used to recommend an economical design.

8.3.1 Construction Cost Estimate

In order to achieve a cost effective design several alternatives were assessed. The first measure was determining the most feasible girder selection for the design. The results yielded that a partial composite design would be the most appropriate option because of the reduced cost attributed to the reduced amount of shear connectors. The full cost analysis for the girder selection can be found in Appendix D. Table 25 summarizes the cost for each girder size based on the varying location of the plastic neutral axis locations and the number of studs required. The final selection is highlighted in yellow.

Table 25: Summary of girder costs

GIRDER SIZE	PNA	NO. STUDS	TOTAL
	0	224	$ 417,535.36
	2	193	$ 416,895.52
	3	161	$ 416,235.04
W40x199	4	128	$ 415,553.92
	0	238	$ 440,880.32
	2	206	$ 440,219.84
	3	174	$ 439,559.36
W40x211	4	142	$ 438,898.88
	0	243	$ 449,367.52
	2	207	$ 448,624.48
	3	170	$ 447,860.80
W40x215	4	133	$ 447,097.12
	0	265	$ 487,549.60
	2	229	$ 486,806.56
	3	193	$ 486,063.52
W40x235	4	157	$ 485,320.48
	0	279	$ 506,702.56
	2	236	$ 505,815.04
	3	193	$ 504,927.52
W36x247	4	150	$ 504,040.00

Based on this table the W40x199 is the most practical design girder for this project. The girders shall be constructed as partially composite meaning the plastic neutral axis of the girders will descend into the steel of the beam rather than within the concrete slab. Partial composite design will reduce the composite capacity of the girders as well as reduce the overall cost. It is important to note that this option still retains enough capacity to pass strength and serviceability inspections. Each girder section will require 128 shear studs to prevent the tendency of the girders and concrete slab from shearing. In conclusion, the W40x199 (128) is the most economical decision with a total cost of approximately $416,000.00. This selection is included in the overall life-cycle cost analysis of the bridge.

The final cost estimate was completed for the principal components of the bridge. This includes basic components of the superstructure, substructure, and deck. A description of each item is delineated with respective unit costs followed by a summation of total costs. An excerpt of the cost estimate is illustrated in Table 26.

Table 26: Cost Estimate

DECK				
CONCRETE IN PLACE-REGULAR CONCRETE 8" SLAB	SF	6288.00	$ 3.00	$ 19,000.00
GRANITE CURBING 6"x18"	LF	262	$ 17.01	$ 4,000.00
BITUMINOUS CONCRETE 2.5" THICK	LF	48.52	$ 5.50	$ 300.00
SIDEWALK 6" THICK	SF	1048	$ 3.57	$ 4,000.00
FENCE CHAIN LINK INDUSTRIAL 9 GA. ALUMINIZED	LF	262	$ 18.38	$ 5,000.00
BRIDGE RAILINGS STEEL, GALV PIPE, 3 LINE W/ SCREEN	LF	262	$ 303.76	$ 80,000.00
ASPHALTIC CONCRETE PAVEMENT, HIGHWYS 4"	SY	698.67	$ 8.06	$ 6,000.00
SUPERSTRUCTURE				
ROLLED STEEL BEAM GIRDER	LF			$ 416,000.00
BEARING WITH ELASTOMERIC PADS	EA	32	$ 3,000.00	$ 96,000.00
SUBSTRUCTURE				
PREFABRICATED ABUTMENT	CY	494.81	$ 263.10	$ 130,000.00
PREFABRICATED WINGWALL	CY	910.52	$ 327.75	$ 298,000.00
COLUMNS REINFORCING IN PLACE 24"-36" DIAMETER	TONS	16.40	$ 1,555.00	$ 26,000.00
			TOTAL COST:	$ 1,058,300.00

As depicted in the excerpt above, the anticipated construction cost is $1,058,300.00. This value is significantly lower in comparison to the projected estimate from MassHighway. MassHighway proposes that total construction cost will be $6,627,470.00. The primary reason for the contrast in results is due to the fact there was a limitations in the scope of the design and the cost data. For some areas of the project it was not possible to allocate costs without additional design and cost data. For the purpose of this project, a rough estimate provides an acceptable amount of information and insight to the basic costs associated with the bridge. Despite the fact the estimate only addresses certain elements pertaining to the bridge; it introduces the process of devising a preliminary cost estimate.

8.3.2 Bridge Management System

A bridge management system provides a means for managing the design, construction, operation, and maintenance of a bridge. The goal is to ensure the condition of the bridge is both safe and functional while providing cost effective solutions to maintaining the structure. A complete evaluation includes collection of inventory data, thorough inspection, assessment of conditions and strength, repair or replacement, and prioritization based on the budgeted funds (Michigan Government).

Figure 65 is a model taken from the New York State Department of Transportation. The figure illustrates a rational method for determining the type of maintenance required and the necessary actions that should be taken. This model can be implemented for the Belmont Street/Route 9 Bridge.

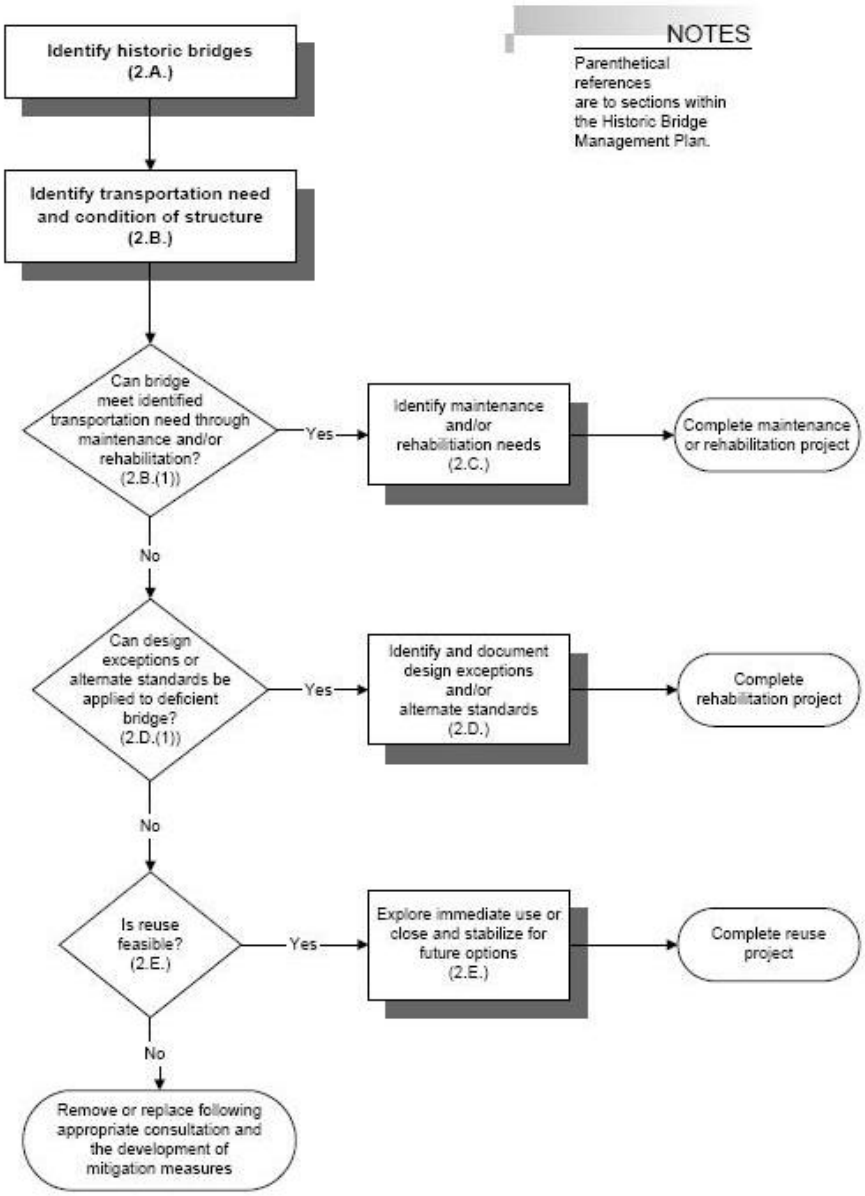


Figure 65: Bridge management system (taken from New York State Deparment of Transporation and Federal Highway Administration, 2002)

The following evaluation in Table 27 is an example of how the flowchart above can be used for the design of this project:

Table 27: Application of NYSDOT flowchart

Step 1	Identify historic bridges	Belmont Street/Route 9 Bridge
Step 2	Identify transportation need and condition of structure	This bridge is located in a heavily populated area and experiences high traffic volumes. According to MassHighway this bridge is currently rated structurally deficient.
Step 3	Can bridge meet identified transportation need through maintenance and/or rehabilitation	Yes the rehabilitation will provide more capacity for traffic.
Step 4	Identify maintenance and/or rehabilitation needs	Since this bridge is structurally deficient, all elements should be re-designed. Routine maintenance should be preformed to increase the service life of the bridge.
Step 5	Complete maintenance or rehabilitation project.	___________________

According to this evaluation it is evident that this project requires rehabilitation. However, once rehabilitation is completed, routine maintenance should be conducted to prevent or minimize the need for costly maintenance and repairs. Figure 66, also created by the New York State Department of Transportation, provides a list of various maintenance activities in order of how much they cost.

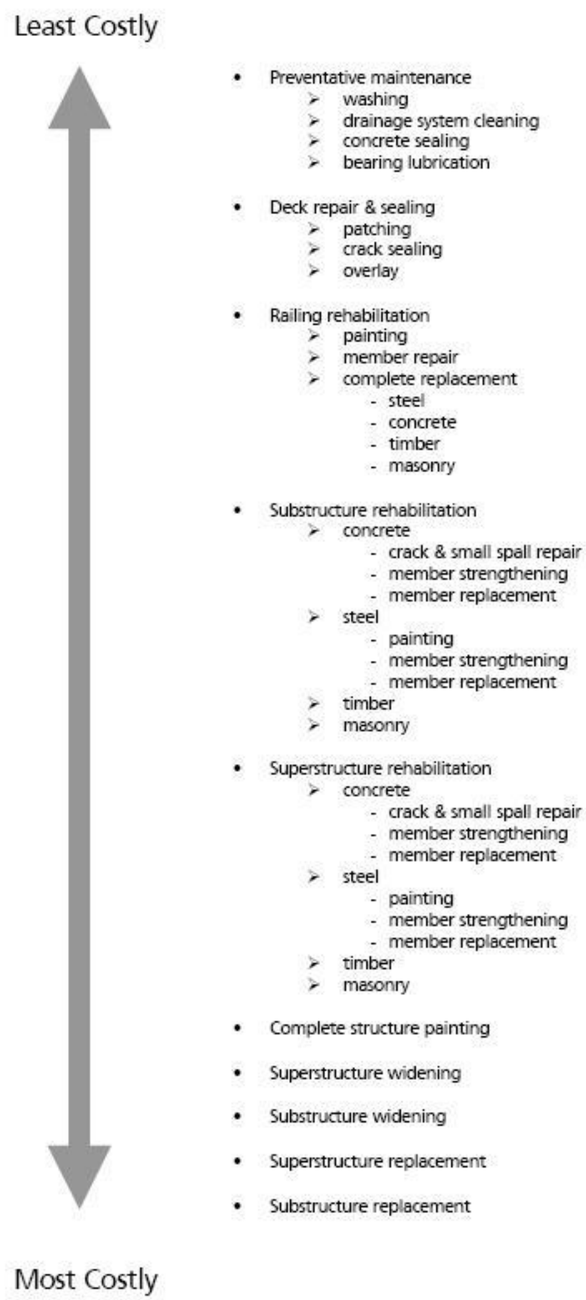


Figure 66: Maintenance operations (taken from New York State Deparment of Transporation and Federal Highway Administration, 2002)

Based on the figure, there are various routine maintenance operations that are cost effective. Among these operations are cleaning of drainage channels and other bridge components, as well repairing cracks and replacing sealants. To reduce long term maintenance costs and extend the life of the structure, the Belmont Street/Route 9 Bridge should utilize the methods at the top of the list to minimize the need to perform operations shown at the bottom of the list.

Performing regular maintenance will greatly reduce the life-cycle cost of the bridge while improving the quality and performance. Figure 67 illustrates the effects of maintenance activities on the condition of the bridge over an extended period of time. The blue line represents the condition of the bridge without maintenance and the black line represents the condition of the bridge with maintenance.

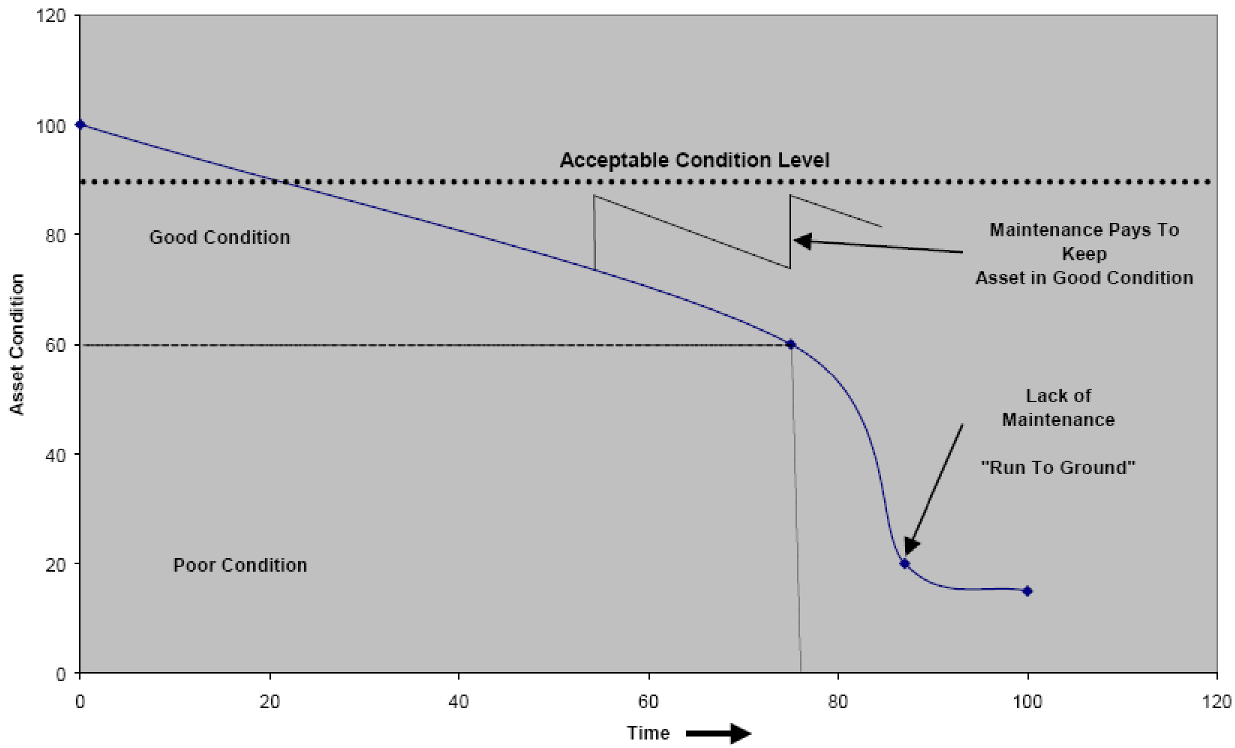


Figure 67: Effects of maintenance (Westerling & Poftak)

It is evident that as time progresses, maintenance "pays to keep asset in good condition," (Westerling and Poftak). Thus, the implementation of this system will not only provide a means for keeping the bridge in good condition, but by utilizing low cost operations, this system can enhance the quality and service life of the bridge.

As part of a comprehensive bridge management system, computer software and monitoring systems can be used to provide more accurate data for assessment and decision making. Since inspections do not occur on a daily basis, and most repairs occur depending on necessity, it is difficult to evaluate the condition of the structure at any point in time. Instead of relying on manual inspections and physical reports, it may be beneficial to implement an electronic monitoring system. A monitoring system is capable of providing data on structural integrity and wear that may contribute to bridge life and stress assessment data and information regarding the performance of the design and materials (American Association for State Highway and Transportation Officials). With more information available at any given time, problems can be detected earlier and repairs can be made sooner. Not only does this data help with the detection of problems, but it increases the accuracy of the bridge management system by regularly providing input data. This gained knowledge makes it possible to prevent serious problems before they occur. These types of systems have also proven to save money budgeted towards repairs since they detect problems before they become serious (American Association for State Highway and Transportation Officials). In Connecticut alone, after installing monitoring systems on 11 bridges, roughly $2.7 million has been saved by performing early repairs that wouldn't have been detected without the monitoring systems (American Association for State Highway and Transportation Officials). Therefore, in conjunction with the management plan, implementing monitoring systems and using computer software can increase the amount of savings.

8.4 Summary

The evaluation of life-cycle costs is an important aspect to consider committing to a project design. Just because the cost of materials and construction is a least cost option does not mean the design is the best investment. By considering costs related to design, purchasing/leasing, constructing/installing, operating, maintaining, repairing, and disposing, one can provide an estimated cost associated with the life of the structure.

In terms of the Belmont Street/Route 9 Bridge, the cost estimate completed totaled approximately $1,058,300.00. This estimate is comparably low to MassHighway's estimate of nearly $6 million, but excludes several elements that would increase the cost of the project. Such exceptions include the approach, mobilization, removal of existing structure, and contingencies. These costs however are only the initial design costs and do not account for the service life of the bridge.

To maximize the lifespan of the bridge, a management system should be implemented to regulate routine maintenance and guide low cost maintenance activities that increase the quality of the structure. This system was modeled from the New York State Department of Transportation and provides a rational method for determining whether maintenance, rehabilitation, or reconstruction is required. A list of cost effective operations is also provided. In addition, a monitoring system is capable of providing stress assessment and performance data should be installed. Unlike routine inspection which typically occurs on an annual basis, monitoring systems constantly assesses the condition of the structure. Thus these systems can detect problems when they are still minor and easy to fix. By preserving and maintaining the structure before it becomes “structurally deficient”, money can be saved, and the life of the bridge can be extended (Massachusetts Infrastructure Investment Coalition)**.**

9 Project Conclusions

The purpose of this project was to investigate the process to re-design a typical highway overpass and to promote sustainability by exploring strategies to extend service life and reduce maintenance cost. The sustainable alternatives addressed in this project are recycled materials and methods, use of corrosion protectants, stormwater management system, and a traffic control plan. In addition a life-cycle cost analysis was performed and a bridge management system was suggested to maintain the quality of the bridge over time. The case study used for the project is the Belmont Street/Route 9 Bridge located in Worcester, MA which has been deemed structurally deficient.

The preliminary design process required the re-design of components which were no longer considered adequate based on review of bridge inspection reports. New options were explored and analyzed for the concrete deck slab, rolled steel girders, and the reinforced concrete columns within the pier. These components were designed based on LRFD standards. In order to select the most feasible components, considerations such as capacity and cost were taken into account. Capacity was accounted for in the design and analysis of various members. The software application RISA 2-D, assisted in the iterative calculations for the design of the deck slab and girder sizes. With the assistance of Microsoft Excel, the project team created a bridge design worksheet template that may prove helpful to future projects. The templates were established to eliminate the process of repetitive hand calculations, and allow for adjustments in the design.

The cost was addressed by composing a construction cost estimate based on individual unit costs. When information on members was not obtainable, values were assumed based on dimensions of components from similar projects. The cost estimate gave insight into the estimating process and what it entails. Decision to select components for the final design was based on the most economical products with sufficient strength. The construction cost estimate evolved into a life-cycle cost analysis, with the inclusion repair and maintenance procedures. A bridge management system was created that can be used to improve the quality and service life of the bridge once construction has commenced.

The supplementary features of the design are the sustainable alternatives. Sustainability is a timely field which promotes planning for future generations. New technologies and discoveries were recommended to incorporate the ideals of sustainability. The specific alternatives that were examined include alternative building materials and protectants, stormwater management, a traffic control plan, and a bridge management system. An in depth background chapter was written for each feature. The knowledge gained from the background was utilized to assess the alternatives and recommend the most effective selections.

The results from the *Alternative Building Materials and Protectants* yielded that different materials would improve the durability and cost of the design. For example a new technology of polymer reinforcement has better resistance to corrosion than typical steel reinforcement. The polymer or plastic reinforcement is lighter and reduces time of construction because it is shipped as a prefabricated grid. Another alternative which can substitute for a typical building material is recycled concrete aggregate which reduces the cost of construction. Byproducts such as fly ash are essentially free and can also be added to concrete mixes to enhance the strength of concrete. Implementation of such products will increase the lifetime of the structure as well as reduce environmental impacts associate with relying on new raw materials.

An innovative technology for collection of rainwater is a harvesting system. Two types of collection systems would be beneficial for the bridge by decreasing the water flowing into storm drains and reduce water infiltrating the deck joints. Proposed alternatives are a rooftop rainwater collection system or a fountain. Both systems are efficient methods of reducing runoff flow. In addition, the collected water would not have to be filtered, and it can be used to flush toilets or aid in other tasks such as watering or irrigating lawns and landscaping. The recycled water would be especially advantageous for UMass Medical Center Memorial Campus, and a nearby church, and apartment complex. It is recommended that the City of Worcester implement a city wide rainwater harvesting system.

The final sustainable alternative presented in this project is a traffic control plan specifically devised for the Belmont Street/Route 9 Bridge. The plan was developed through identification and evaluation of the detour alternatives based on the reconstruction of the bridge. The final decision was selected based on the criteria of emergency access, flow of traffic, safety, and efficiency. The solution allows for two lanes of operating traffic so vehicles could flow in both directions. Implementation of a traffic control plan contributes to sustainability by alleviating congestion and reducing vehicle emissions.

Knowledge gained about sustainable alternatives was utilized to formulate a framework which would promote the implementation of these concepts. The project team formulated a recommendation guideline for sustainable bridge design. The framework is similar to the LEED green building rating system. It is recommended that an actual LEED rating system should be established for bridges. This would account for sustainability, and increase the service life of bridges while reducing maintenance.

A LEED rating system would be especially beneficial since America's infrastructure is starting to decline. The American Society of Civil Engineers (ASCE) released the *2009 Report Card for America's Infrastructure* and bridges were graded with a "C" or mediocre score. Approximately 26% or roughly one in four bridges, are considered structurally deficient or structurally obsolete, and these numbers are rising in urban areas. According to ASCE, "A $17 billion annual investment is needed to substantially improve current bridge conditions. Currently, only $10.5 billion is spent annually on the construction and maintenance of bridges (ASCE, 2009)." It is necessary for the United States to strategically invest in infrastructure. The money can be used to implement new technologies which would account for less structurally deficient and obsolete bridges in the future.

The main recommendation that emerges from this project is that a pilot study should be conducted by the Federal Highway Association to see if the service life of a bridge produced with sustainable alternative components would be extended. The sustainable technologies discussed in this project could be used aspects for the design. The bridge design should include some variation of a rainwater harvesting system, a traffic control plan, a bridge management plan, and utilization of alternative or recycled materials and corrosion protectants. Ideally, the bridge would be put in service so that maintenance and repair costs could be monitored.

Utilization of monitoring technologies could compile performance data and facilitate condition assessment.

A project of this sort may be fairly extensive, but it could be used to observe if an initial escalated cost to implement new technologies would actually decrease the total cost of construction because repair and maintenance would be reduced. However it is important to consider the impact of a construction project on the community since they bear the cost of construction and maintenance as well as environmental impact such as stormwater problems. The outcomes of the study are projected to yield positive results. Sustainable alternatives should extend the lifetime of bridges as well as reduce cost and environmental impacts. Positive results may persuade the bridge construction agency to convert to LEED practices. In all, this project could be used as a basis for further study on providing for a safe and sustainable future.

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13 Appendices

Appendix A: Project Proposal

Worcester Polytechnic Institute

Project Number: LDA-0902

Proposal:
The Reconstruction of a Highway Overpass

A Major Qualifying Project Report:
submitted to the Faculty of
the WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements
for the Degree of Bachelor of Science by

Nicole Maglione

____

Sara Migdal

____

Jocelyn Moody

____

Justine Ziobron

____

Date: October 16, 2008

Approved by:

Professor Leonard Albano, Major Advisor

____

Table of Contents

1 Problem Statement 1

2 Scope 1

2.1 Design 2

2.2 Corrosion 3

2.3 Rooftop Rainwater Collection System 3

2.4 Recyclable Building Materials 4

2.5 Construction Phase Detour Route 5

2.6 Life-Cycle Cost 6

3 Capstone Design 6

3.1 Economic 7

3.2 Environmental 7

3.3 Sustainability 7

3.4 Constructability 8

3.5 Ethical 8

3.6 Health and Safety 8

4 Deliverables 9

5 Schedule 10

6 Bibliography 11

Problem Statement

Many of the new reconstruction projects that have surfaced across the United States involve the refurbishment of bridges. In the state of Massachusetts alone, there are currently 588 bridges considered to be structurally deficient which represents approximately ten percent of the traveled bridges in the entire state (100 Busiest Structurally Deficient Bridges). A local overpass of specific concern shown in Figure 1, located in Worcester, Massachusetts, is the Belmont Street/Route 9 Bridge which spans over Interstate-290. The goal of the project team is to propose a sustainable bridge design based on life-cycle cost analysis to provide the most feasible solution for the Belmont Street/Route 9 Bridge.

Figure 1: The existing Belmont Street/Route 9 overpass

1 Scope

Currently the United States is on the forefront of making the transition to sustainable development. Sustainability can be defined as **"meeting the needs of the present without compromising the ability of future generations to meet their own needs"** (Sustainability, 2008). The aim of the project team is to design a bridge that is dependable as well as sustainable for the future. Figure 2 illustrates that the main focus of the project, a sustainable bridge re-design for the Belmont Street/Route 9 highway overpass. The design alternatives branching off from the main design incorporate innovative sustainability practices and will be analyzed in greater depth. The tasks listed within the scope show the objectives necessary to complete the entire sustainable re-design.

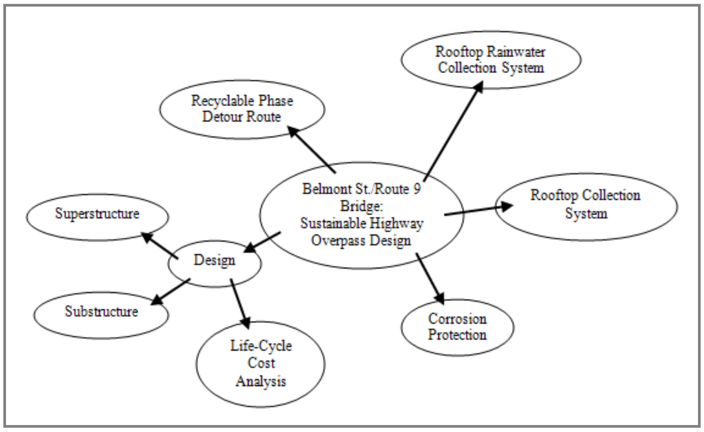

Figure 2: Flowchart showing the key components that will be addressed in the project

1.1 Design

When re-designing a bridge, many different aspects must be considered by the engineers. To ensure a successful reconstruction, engineers must determine the factors contributing to the deficiency of the bridge in order to promote longevity. As bridges age, their components need to be maintained in order to preserve the structural stability of the overpass. When bridges are not maintained on a regular cycle, they become structurally deficient. Bridge design specifications help to ensure the sufficiency of bridges and are available to the general public, typically from the states department of transportation.

The project team will accomplish the following objectives in order to complete the re-design for the Belmont Street/Route 9 Bridge:

- Examine how to define a deficient bridge
- Obtain bridge specifications
- Determine dead and live loads
- Determine materials of each component
- Determine limit states for each component
- Determine size of bridge components to provide required integrity
- Model design using Revit Structures and link to Google Earth geographic location

The project team will use ASSHTO LFRD Bridge Design specifications in order to complete the tasks listed above. Included in the guidelines provided by the LFRD design specifications, factor of safety values will be incorporated to ensure the design of safe structures.

1.2 Corrosion

Concrete, whether prestressed, precast or reinforced is a major material used in the construction of a bridge. Like most building materials concrete is affected by weather conditions, continuous traffic, maintenance and chemicals. In areas of high rainfall or snow accumulation, concrete commonly corrodes or begins to crack and chip away. Deterioration is caused by chemical reactions with the surrounding materials. This can create a problem with the stability of the bridge over time. Based on their location, components that are made of concrete usually have an expected life span. The life span can be defined as the estimated time before the original component is deemed unstable.

The following list of tasks will be completed by the project team to determine the effect of incorporating corrosive protectants and sealants:

- Determine how corrosion occurs
- Research the impact of corrosion
- Examine types of protectants for research
  - Linseed oil
  - Rubber and silicon resins
  - Epoxy based sealants
- Consider non-chemical alternatives
- Determine most sustainable method and approach

The project team will analyze the expected life-cycle cost of the bridge protectants. The bridge will be designed such that the life span of the new design will surpass the life span of the current structure by reducing corrosion and selecting effective materials while reducing the maintenance and delaying future replacement. In doing this, the re-design will be more sustainable and reduce the negative impacts on the environment.

1.3 Rooftop Rainwater Collection System

In emerging method used for reducing the amount of runoff water flowing into storm drains or flowing overland is to collect rainwater and use it as an alternative water source. In regions which lack water, communities can utilize collected rainwater where rainfall is more plentiful. In some cases, large scale systems can even supply enough water for an entire community without the assistance of city water. Another option is to store the runoff water on site in large tanks to be used during emergencies or drier times of the year. Besides providing people with a low-cost water system, collection also helps control the flow of runoff water in urban environments. Issues regarding flooding are significantly reduced by simply removing the leading source of water which causes these floods.

A rainwater collection system will be included in the bridge re-design and the following objectives will be addressed:

- Review covered bridge designs
- Design rooftop, storage, and transportation system for collection
  - Collect rainfall data
  - Determine volume of runoff water
  - Determine flow rate of runoff water
- Analyze impact of roof system on bridge structure

The project team will consider the feasibility of recycling runoff rainwater. The collection system will benefit the environment as well as make the re-design of the bridge more sustainable by providing an alternative water source, reducing the amount of runoff water flowing into storm drains, and extending the life of the bridge by ultimately reducing the amount of maintenance. Implementing a system such as this can also reduce the direct impact of rainfall and snowfall, thereby broadening the longevity of the bridge and making it more sustainable.

1.4 Recyclable Building Materials

Renovation projects generally include a demolition and construction phase where a mass amount of waste accumulates. In the past, the waste was simply transported off-site and disposed of in landfills. This process incurred greater costs; economically and environmentally. The new reality of using recycled materials has significantly reduced the amount of waste produced. Materials such as concrete and steel can be salvaged from existing infrastructure and re-used to make new and improved products.

The following tasks will be accomplished to establish the practicability of using more sustainable and environmentally friendly materials:

- Research types of recycled/alternative materials
  - Recycled concrete
  - Recycled steel
- Determine availability of recycled materials based on location
- Select appropriate recycled material

One key element that will be focused on during the material selection process is constructability, which is a measure of the feasibility of the project. One contributing factor to the constructability is the site location which may impact the availability of certain materials. Using recycled materials also addresses sustainability and the environment. In an effort to increase the ecological awareness and reduce environmental impacts during construction, the project team will also investigate designing with innovative recyclable materials.

1.5 Construction Phase Detour Route

An important factor to the design and construction of any major project involves the evaluation of the surrounding area. Prominent regions of concern include the location of the project, who the project will affect, and the constraints of the project. In bridge design especially, one of the most important influences during construction is the surrounding traffic. For instance, in heavily populated areas, professionals need to consider re-routing traffic prior to construction so that the surrounding area can function relatively normally. Thus, the project team will identify the different services that are available along with any procedures or methods to conduct traffic studies and evaluate the traffic flows over major bridges. More specifically, the project team plans to develop a proposed traffic control plan that could be implemented during the construction phase of the Belmont Street/Route 9 Bridge in Worcester, Massachusetts.

When evaluating the area of interest, the following will be considered to determine the most effective alternative construction route:

- Research similar detour projects
- Obtain traffic count based on area of interest
- Gain understanding of site surrounding area
    - Major routes
    - Residential areas
    - Business areas
    - Emergency access route
    - Intersections
- Determine constraints and parameters
- Propose detour solution during construction with the aid of AutoCAD and GIS
- Compare solution with MassHighway's proposed solution

The suggested traffic route will consider both constructability and safety. One factor of the constructability of the project relies upon the location of interest and the traffic flowing through the construction site. Since the area surrounding the Belmont Street/Route 9 Bridge is heavily traveled, traffic routes must be altered to ease the constructability of the project. Also, providing awareness of the new traffic patterns during building is essential to ensure the safety and health of both the members of the community and the workers involved in the construction.

1.6 Life-Cycle Cost

According to the US Department of Transportation Federal Highway Administration, life-cycle cost analysis is a "process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment (Kane, 1996)." Since bridges are a long term investment, the project team aims to develop a bridge design that can withstand all such elements so that the costs for construction, maintenance and repairs will be minimized and the need for complete replacement and rehabilitation will be reduced.

One of the main objectives of the project is to provide a feasible yet cost effective solution to the currently deteriorating bridge on Belmont Street/Route 9. In order to complete this, the project intends to conduct a cost analysis of all materials for implementing the suggested solution. The cost of corrosion protectants for maintenance, a rainwater collection system, as well as alternative and recycled building materials will be estimated in the cost analysis. The proposed design will then reflect the best combination of materials that will help extend the life expectancy and cost of the bridge.

2 Capstone Design

In fulfillment of the Major Qualifying Project, it is also necessary to complete a capstone design. According to the Accreditation Board of Engineering and Technology (ABET) under General Criterion 4, "students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political" (Criteria for Accrediting Engineering Programs, 2007). In compliance with this requirement, the project will consider economic, environmental, sustainability, constructability, ethical, and health and safety constraints.

Economic

Since the amount of funding for projects is limited, the design elements of a construction project should be both practical and affordable. In order to ensure that the project stays within budget, the types of materials that are going to be used and the cost of construction will be assessed. Thus the project team will conduct a life-cycle cost analysis of all the building materials to determine which are the most feasible and cost effective.

Environmental

In recent years, environmental impacts have become an increasing concern, especially in the field of engineering and construction. It is becoming more of a necessity to protect the surrounding natural environmental to prepare for a sustainable future. In doing so, the project team will consider the use of recyclable materials that can be incorporated in the final design. The project team will also investigate the use of a rooftop rainwater collection system with the intent of providing an alternative water source that helps reduce storm runoff.

Sustainability

Sustainable design is an innovative practice which is necessary to promote economic growth while conducting practices that benefit the environment. When considering sustainability, the project team plans to analyze the expected life span of the bridge, as well as provide include innovate sustainability alternatives to reduce the carbon footprint. This will be accomplished by implementing a rooftop collection system to store and reuse stormwater. Also, the use of recycled adaptations of traditional building materials such as recycled steel and concrete will be incorporated in the design. The project team will extend the life span of the structure incorporating protective sealants or non-chemical based alternatives to reduce corrosion.

Constructability

Constructability is a standard which defines the feasibility and ease of a design. Such a standard is dependent upon the cost and availability of materials. It is also dependent upon the surrounding area and any constraints that may limit the actual construction of the project. Prior to making any final decisions, the project team will examine different materials and alternatives in order to produce the most practical design. The project team will also identify the impacts the surrounding traffic will have on the construction of the project in order to determine appropriate mitigation measures.

Ethical

According to the civil engineering code of ethics, civil engineers are obligated to "use their knowledge and skill for the enhancement of human welfare and the environment; be honest and impartial and serving with fidelity the public, their employers and clients; strive to increase the competence and prestige of the engineering profession; and support the professional and technical societies of their disciplines" (Code of Ethics, 2006). With this in mind, it is the goal of the project team to construct an innovative, modern solution that is economically and ecologically advantageous by applying the fundamental civil engineering principles studied at WPI.

Health and Safety

The most important parameter when re-designing the bridge will be safety. Although, cost and sustainability are negotiable based on the budget, health and safety are fixed variables and cannot be altered. All propositions and alternatives proposed will consider safety to be the guiding factor in the analysis. In the guidelines provided by the LFRD design specifications, factor of safety values will be incorporated in the calculations to ensure the structure is built to accommodate uncertainties in the design process. Prior to construction, the project team will propose a traffic control plan to provide a safe environment for workers and travelers.

Deliverables

Upon completion of this project, a re-design of the highway overpass that crosses above I-290 will be created and will include the selection of construction materials based on an extensive comparative analysis. Calculations of external design loads and internal forces, component sizes and component strengths, based on the *AASHTO LRFD Bridge Design Specifications* will be included in the final report to justify the design. With the assistance of software like Microsoft Excel, the project team can create a bridge design worksheet template that may prove helpful to future projects.

These findings will all be incorporated in a final written report which presents all aspects of the highway overpass design. The final design will be modeled using software programs like AutoCAD and Revit Structures. Using the new technology of GIS, the bridge design can then be linked to Google Earth to show an approximation of the final design in its geographic location. All of the aforementioned assessments will finally be presented to professionals, educators and colleagues.

3 Schedule

The project team has compiled a schedule of the anticipated timeline of the project. Since this is a three-course equivalent project it will span over three consecutive seven-week terms. At the end of each term, the project team will present a submittal including all tasks completed in the term. The following chart displayed in Figure 3 shows the approximate durations of the main activities.

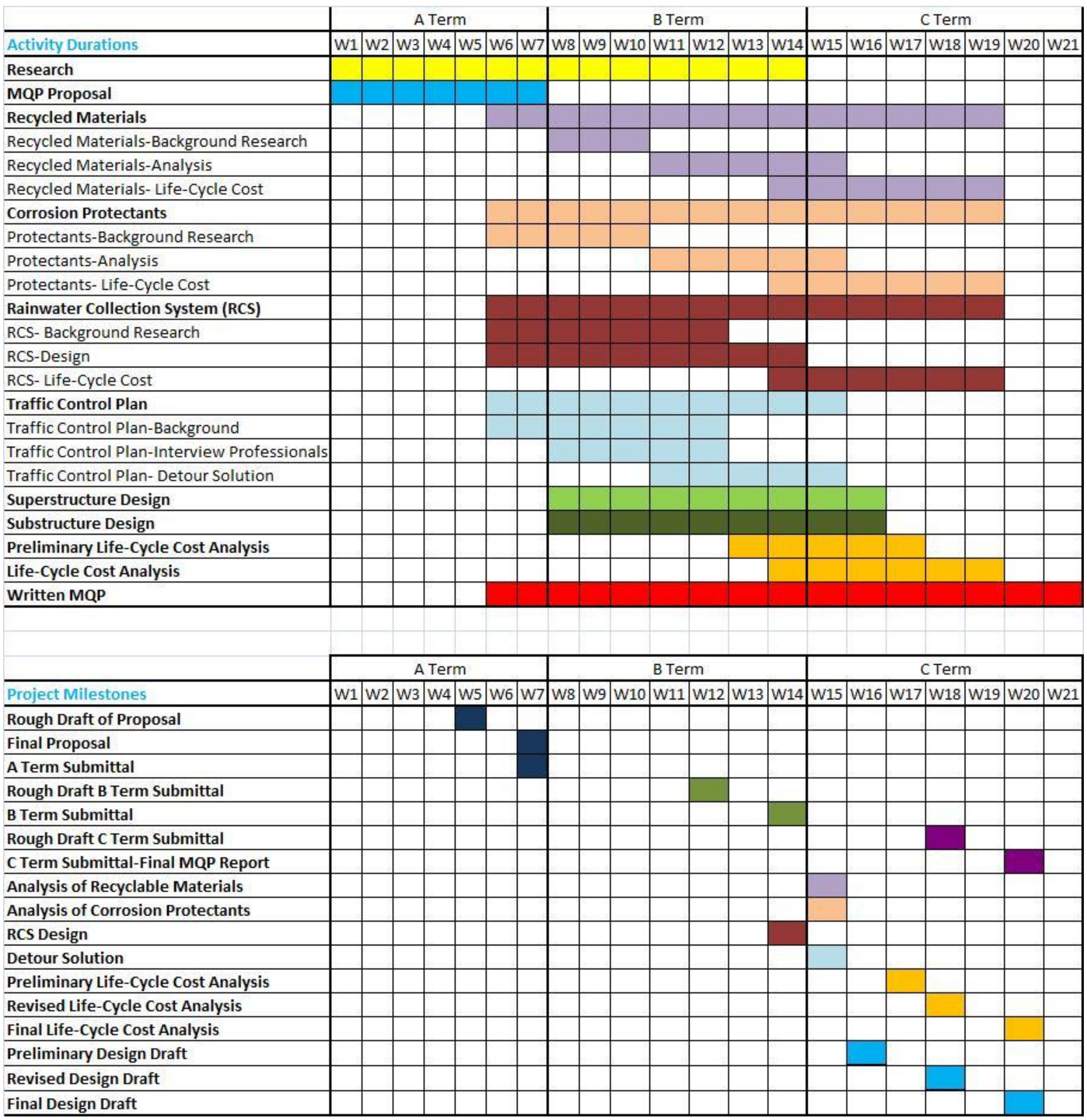

Figure 3: The durations of project tasks and submittals over the three term span

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Appendix B: MassHighway 2008 Structures Field Report

MASSACHUSETTS HIGHWAY DEPARTMENT
STRUCTURES INSPECTION FIELD REPORT
ROUTINE & SPECIAL MEMBER INSPECTION

2-DIST	B.I.N.	BR. DEPT. NO.
03	1L2	W-44-094

CITY/TOWN: WORCESTER	8.-STRUCTURE NO.: W44094-1L2-MHD-NBI	11-Kilo. POINT: 156.701	41-STATUS: P:POSTED	90-ROUTINE INSP. DATE: JUN 26, 2008
07-FACILITY CARRIED: ST 9 BELMONT ST	MEMORIAL NAME/LOCAL NAME:	27-YR BUILT: 1958	106-YR REBUILT: 0000	YR REHAB'D (NON 106): 0000
06-FEATURES INTERSECTED: I 290	26-FUNCTIONAL CLASS: Urban Arterial	DIST. BRIDGE INSPECTION ENGINEER: L. A. Gauthier		
43-STRUCTURE TYPE: 302 : Steel Stringer/Girder	22-OWNER: State Highway Agency; 21-MAINTAINER: State Highway Agency	TEAM LEADER: R. C. Angell		
107-DECK TYPE: 1 : Concrete Cast-in-Place	WEATHER: Cloudy; TEMP. (air): 19°C	TEAM MEMBERS: R. ORLANDO RO		

ITEM 58 — DECK: 5

		DEF
1. Wearing Surface	5	S-P
2. Deck Condition	5	S-P
3. Stay in place forms	N	-
4. Curbs	6	M-P
5. Median	N	-
6. Sidewalks	5	S-A
7. Parapets	6	M-P
8. Railing	6	S-P
9. Anti Missile Fence	7	-
10. Drainage System	N	-
11. Lighting Standards	N	-
12. Utilities	6	M-P
13. Deck Joints	4	S-A
14.	N	-
15.	N	-
16.	N	-

CURB REVEAL (In millimeters): N 215, S 200

APPROACHES

		DEF
a. Appr. Pavement Condition	5	M-P
b. Appr. Roadway Settlement	6	M-P
c. Appr. Sidewalk Settlement	6	M-P
d.	N	-

OVERHEAD SIGNS (Attached to bridge) (Y/N): N

		DEF
a. Condition of Welds	N	-
b. Condition of Bolts	N	-
c. Condition of Signs	N	-

ITEM 59 — SUPERSTRUCTURE: 4

		DEF
1. Stringers	4	S-P
2. Floorbeams	N	-
3. Floor System Bracing	N	-
4. Girders or Beams	N	-
5. Trusses - General	N	-
a. Upper Chords	N	-
b. Lower Chords	N	-
c. Web Members	N	-
d. Lateral Bracing	N	-
e. Sway Bracings	N	-
f. Portals	N	-
g. End Posts	N	-
6. Pin & Hangers	N	-
7. Conn Plt's, Gussets & Angles	4	S-P
8. Cover Plates	5	S-P
9. Bearing Devices	5	S-P
10. Diaphragms/Cross Frames	4	S-P
11. Rivets & Bolts	5	S-P
12. Welds	5	S-P
13. Member Alignment	4	S-P
14. Paint/Coating	4	S-P
15.	N	-

Year Painted: N

COLLISION DAMAGE: *Please explain*
None ( ) Minor ( ) Moderate ( ) Severe (X)

LOAD DEFLECTION: *Please explain*
None ( ) Minor (X) Moderate ( ) Severe ( )

LOAD VIBRATION: *Please explain*
None ( ) Minor (X) Moderate ( ) Severe ( )

Any Fracture Critical Member: (Y/N) N

Any Cracks: (Y/N) N

ITEM 60 — SUBSTRUCTURE: 5

	Dive	Cur		DEF
1. Abutments			5	
a. Pedestals	N	N		-
b. Bridge Seats	N	5		M-P
c. Backwalls	N	4		S-P
d. Breastwalls	N	6		M-P
e. Wingwalls	N	6		M-P
f. Slope Paving/Rip-Rap	N	N		-
g. Pointing	N	N		-
h. Footings	N	H		-
i. Piles	N	N		-
j. Scour	N	N		-
k. Settlement	N	6		-
l.	N	N		-
m.	N	N		-
2. Piers or Bents			5	
a. Pedestals	N	N		-
b. Caps	N	5		S-P
c. Columns	N	5		S-P
d. Stems/Webs/Pierwalls	N	N		-
e. Pointing	N	N		-
f. Footing	N	H		-
g. Piles	N	N		-
h. Scour	N	N		-
i. Settlement	N	7		-
j.	N	N		-
k.	N	N		-
3. Pile Bents			N	
a. Pile Caps	N	N		-
b. Piles	N	N		-
c. Diagonal Bracing	N	N		-
d. Horizontal Bracing	N	N		-
e. Fasteners	N	N		-

UNDERMINING (Y/N) If YES please explain: N

COLLISION DAMAGE:
None (X) Minor ( ) Moderate ( ) Severe ( )

SCOUR: *Please explain*
None (X) Minor ( ) Moderate ( ) Severe ( )

I-60 (Dive Report): N *I-60 (This Report):* 5

93B-U/W (DIVE) Insp 00/00/00

X=UNKNOWN N=NOT APPLICABLE H=HIDDEN/INACCESSIBLE R=REMOVED

RTN(1)7-96

CITY/TOWN	B.I.N.	BR. DEPT. NO.	8.-STRUCTURE NO.	INSPECTION DATE
WORCESTER	1L2	W-44-094	W44094-1L2-MHD-NBI	JUN 26, 2008

ITEM 61 CHANNEL & CHANNEL PROTECTION — N

	Dive	Cur	DEF
1. Channel Scour	N	N	-
2. Embankment Erosion	N	N	-
3. Debris	N	N	-
4. Vegetation	N	N	-
5. Utilities	N	N	-
6. Rip-Rap/Slope Protection	N	N	-
7. Aggradation	N	N	-
8. Fender System	N	N	-

STREAM FLOW VELOCITY: Tidal ( ) High ( ) Moderate ( ) Low ( ) None (X)

ITEM 61 (Dive Report): N ITEM 61 (This Report): N

93b-U/W INSP. DATE: 00/00/00

ITEM 36 TRAFFIC SAFETY

	36	COND	DEF
A. Bridge Railing	0	6	S-P
B. Transitions	0	0	S-A
C. Approach Guardrail	0	0	S-A
D. Approach Guardrail Ends	0	0	S-A

WEIGHT POSTING Not Applicable [ ]

	H	3	3S2	Single
Actual Posting	20	25	40	N
Recommended Posting	20	25	40	N

Waived Date: 00/00/00 EJDMT Date: 00/00/00

	At bridge E	At bridge W	Other Advance E	Other Advance W
Signs In Place (Y=Yes, N=No, NR=NotRequired)	Y	N	N	N
Legibility/Visibility	7 / 7			

CLEARANCE POSTING

Not Applicable [X]

	N ft	N in	S ft	S in	meter
Actual Field Measurement	14	11	14	11	4.54
Posted Clearance		0		0	

	At bridge N	At bridge S	Advance N	Advance S
Signs In Place (Y=Yes, N=No, NR=NotRequired)				
Legibility/Visibility				

ACCESSIBILITY (Y/N/P)

	Needed	Used
Lift Bucket	Y	Y
Ladder	P	N
Boat	N	N
Waders	N	N
Inspector 50	N	N
Rigging	N	N
Staging	N	N
Traffic Control	Y	Y
RR Flagger	N	N
Police	Y	Y
Other:		
	N	N

TOTAL HOURS 8

PLANS (Y/N) Y

(V.C.R.) (Y/N) N

TAPE#:

List of field tests performed:

RATING

Rating Report (Y/N): Y

Date: 02/01/1997

Inspection data at time of existing rating

I58: 7 I59: 4 I60: 6 Date: 09/27/1995

(To be filled out by DBIE)

Request for Rating or Rerating (Y/N): N

If YES please give priority: HIGH ( ) MEDIUM ( ) LOW ( )

REASON: NO

CONDITION RATING GUIDE (For Items 58, 59, 60 and 61)

	CODE	CONDITION	DEFECTS
	N	NOT APPLICABLE	
G	9	EXCELLENT	Excellent condition.
G	8	VERY GOOD	No problem noted.
G	7	GOOD	Some minor problems.
F	6	SATISFACTORY	Structural elements show some minor deterioration.
F	5	FAIR	All primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
P	4	POOR	Advance section loss, deterioration, spalling or scour.
P	3	SERIOUS	Loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
C	2	CRITICAL	Advance deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
C	1	"IMMINENT" FAILURE	Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put it back in light service.
	0	FAILED	Out of service - beyond corrective action.

DEFICIENCY REPORTING GUIDE

DEFICIENCY: A defect in a structure that requires corrective action.

CATEGORIES OF DEFICIENCIES:

M= Minor Deficiency- Deficiencies which are minor in nature, generally do not impact the structural integrity of the bridge and could easily be repaired. Examples include but are not limited to: Spalled concrete, Minor pot holes, Minor corrosion of steel, Minor scouring, Clogged drainage, etc.

S= Severe/Major Deficiency- Deficiencies which are more extensive in nature and need more planning and effort to repair. Examples include but are not limited to: Moderate to major deterioration in concrete, Exposed and corroded rebars, Considerable settlement, Considerable scouring or undermining, Moderate to extensive corrosion to structural steel with measurable loss of section, etc.

C-S= Critical Structural Deficiency - A deficiency in a structural element of a bridge that poses an extreme unsafe condition due to the failure or imminent failure of the element which will affect the structural integrity of the bridge.

C-H= Critical Hazard Deficiency - A deficiency in a component or element of a bridge that poses an extreme hazard or unsafe condition to the public, but does not impair the structural integrity of the bridge. Examples include but are not limited to: Loose concrete hanging down over traffic or pedestrians, A hole in a sidewalk that may cause injuries to pedestrians, Missing section of bridge railing, etc.

URGENCY OF REPAIR:

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RTB(2)04-07

MASSACHUSETTS HIGHWAY DEPARTMENT
STRUCTURES INSPECTION FIELD REPORT
ROUTINE & SPECIAL MEMBER INSPECTION

2-DIST	B.I.N.	BR. DEPT. NO.
03	1L2	W-44-094

CITY/TOWN	8.-STRUCTURE NO.	11-Kilo. POINT	90-ROUTINE INSP. DATE	93*-SPEC. MEMB. INSP. D
WORCESTER	W44094-1L2-MHD-NBI	156.701	Jun 26, 2008	Jun 26, 2008

07-FACILITY CARRIED	MEMORIAL NAME/LOCAL NAME	27-YR BUILT	106-YR REBUILT	*YR REHAB'D (NON 106)
ST 9 BELMONT ST		1958	0000	0000

06-FEATURES INTERSECTED: I 290
26-FUNCTIONAL CLASS: Urban Arterial
DIST. BRIDGE INSPECTION ENGINEER: L. A. Gauthier
43-STRUCTURE TYPE: 302 : Steel Stringer/Girder
22-OWNER: State Highway Agency
21-MAINTAINER: State Highway Agency
TEAM LEADER: R. C. Angell
107-DECK TYPE: 1 : Concrete Cast-in-Place
WEATHER: Cloudy
TEMP. (air): 19°C
TEAM MEMBERS: R. ORLANDO RO

WEIGHT POSTING — Not Applicable ☐

	H	3	3S2	Single
Actual Posting	20	25	40	N
Recommended Posting	20	25	40	N

Waived Date: 00/00/00 EJDMT Date: 00/00/00

	At bridge E	At bridge W	Advance E	Advance W
Signs In Place (Y=Yes,N=No, NR=NotRequired)	Y	N	N	N
Legibility/ Visibility	7 / 7			

PLANS (Y/N): Y
(V.C.R.) (Y/N): N
TAPE#: ____

RATING

Rating Report (Y/N): Y Date: 02/01/1997
Request for Rating or Rerating (Y/N): N
If YES please give priority: HIGH ( ) MEDIUM ( ) LOW ( )
Inspection data at time of existing rating
I58: 7 I59: 4 I60: 6 I62: - Date : 09/27/1995
REASON:

SPECIAL MEMBER(S):

	MEMBER	CRACK (Y/N)	WELD'S CONDITION (0-9)	LOCATION OF CORROSION, SECTION LOSS (%), CRACKS, COLLISION DAMAGE, STRESS CONCENTRATION, ETC.	CONDITION PREVIOUS (0-9)	CONDITION PRESENT (0-9)	INV. RATING OF MEMBER H-20	3	3S2	Deficiencies
A	Item 58.13 - Deck Joints	N		See remarks in comments section.	4	4	Not Rated			S-A
B	Item 59.1 - Stringers	Y	5	See remarks in comments section.	4	4	18	20	26	S-P
C	Item 59.7 - Conn Plt's, Gussets & Angles	N		See remarks in comments section.	4	4	Not Rated			S-P
D	Item 59.10 - Diaphragms/Cross Frames	N		See remarks in comments section.	4	4	Not Rated			S-P
E										

List of field tests performed:

	I-58	I-59	I-60	I-62
(Overall Previous Condition)	4	4	5	-
(Overall Current Condition)	5	4	5	-

DEFICIENCY: A defect in a structure that requires corrective action.

CATEGORIES OF DEFICIENCIES:

M= Minor Deficiency- Deficiencies which are minor in nature, generally do not impact the structural integrity of the bridge and could easily be repaired. Examples include but are not limited to: Spalled concrete, Minor pot holes, Minor corrosion of steel, Minor scouring, Clogged drainage, etc.

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X=UNKNOWN N=NOT APPLICABLE H=HIDDEN/INACCESSIBLE R=REMOVED

F.C.(1)7-96

MASSACHUSETTS HIGHWAY DEPARTMENT
STRUCTURES INSPECTION FIELD REPORT
ROUTINE & SPECIAL MEMBER INSPECTION

2-DIST: 03 | B.I.N.: 1L2 | BR. DEPT. NO.: W-44-094

CITY/TOWN: WORCESTER	8.-STRUCTURE NO.: W44094-1L2-MHD-NBI	11-Kilo. POINT: 156.701	90-ROUTINE INSP. DATE: Jun 26, 2008	93*-SPEC. MEMB. INSP. D: Jun 26, 2008
07-FACILITY CARRIED: ST 9 BELMONT ST	MEMORIAL NAME/LOCAL NAME	27-YR BUILT: 1958	106-YR REBUILT: 0000	*YR REHAB'D (NON 106): 0000
06-FEATURES INTERSECTED: I 290	26-FUNCTIONAL CLASS: Urban Arterial	DIST. BRIDGE INSPECTION ENGINEER: L. A. Gauthier		
43-STRUCTURE TYPE: 302 : Steel Stringer/Girder	22-OWNER: State Highway Agency; 21-MAINTAINER: State Highway Agency	TEAM LEADER: R. C. Angell		
107-DECK TYPE: 1 : Concrete Cast-in-Place	WEATHER: Cloudy; TEMP. (air): 19°C	TEAM MEMBERS: R. ORLANDO		

WEIGHT POSTING — Not Applicable [ ]

	H	3	3S2	Single
Actual Posting	20	25	40	N
Recommended Posting	20	25	40	N

Waived Date: 00/00/00 EJDMT Date: 00/00/00

	At bridge E	At bridge W	Advance E	Advance W
Signs In Place (Y=Yes,N=No, NR=NotRequired)	Y	N	N	N
Legibility/ Visibility	7 / 7			

PLANS (Y/N): Y
(V.C.R.) (Y/N): N
TAPE#:

RATING

Rating Report (Y/N): Y Date: 02/01/1997

Request for Rating or Rerating (Y/N): N

If YES please give priority: HIGH ( ) MEDIUM ( ) LOW ( )

REASON:

Inspection data at time of existing rating
I58: 7 I59: 4 I60: 6 I62: - Date : 09/27/1995

SPECIAL MEMBER(S):

	MEMBER	CRACK (Y/N)	WELD'S CONDITION (0-9)	LOCATION OF CORROSION, SECTION LOSS (%), CRACKS, COLLISION DAMAGE, STRESS CONCENTRATION, ETC.	CONDITION PREVIOUS (0-9)	CONDITION PRESENT (0-9)	INV. RATING OF MEMBER H-20	3	3S2	Deficiencies
A	Item 58.13 - Deck Joints	N		See remarks in comments section.	4	4	Not Rated			S-A
B	Item 59.1 - Stringers	Y	5	See remarks in comments section.	4	4	18	20	26	S-P
C	Item 59.7 - Conn Plt's, Gussets & Angles	N		See remarks in comments section.	4	4	Not Rated			S-P
D	Item 59.10 - Diaphragms/Cross Frames	N		See remarks in comments section.	4	4	Not Rated			S-P
E										

List of field tests performed:

	I-58	I-59	I-60	I-62
(Overall Previous Condition)	4	4	5	-
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F.C.(1)7-96

CITY/TOWN	B.I.N.	BR. DEPT. NO.	8.-STRUCTURE NO.	INSPECTION DATE
WORCESTER	1L2	W-44-094	W44094-1L2-MHD-NBI	JUN 26, 2008

REMARKS

BRIDGE ORIENTATION

The approaches are West to East and the elevations are South to North. This is a two span steel stringer bridge with eight stringers and seven bays in each span numbered from South to North. There is one pier with three columns numbered from South to North.

GENERAL REMARKS

The deck rating was raised from a 4 to a 5 due to the previously mentioned full depth repair.

The East "at bridge" weight posting sign post is tilted out of alignment.

ITEM 58 - DECK

Item 58.1 - Wearing Surface

There is a 24 foot long x 8 foot wide x full depth repair in the left Westbound travel lane, near the East end of bay #5. The bituminous concrete wearing surface also has minor longitudinal cracking in several areas throughout, and minor transverse cracking, mostly over the pier. The wearing surface has heavy wheel wear throughout.

Item 58.2 - Deck Condition

Span #1: Steel shielding has been placed in all the bays to protect motorists from deck spalling. There is full width hairline cracking with efflorescence and rust staining mostly to the West end of bay #1. There are two areas of delamination cracking and minor spalling with exposed rusted rebar at the West end of bay #3. There is a 2 foot diameter spall in bay #6 with exposed rusted rebar.

Span #2: There is a 1 1/2 foot diameter x 2 inch deep spall in bay #4 with exposed rusted rebar near midspan. Bay #5 has a full width x 4 foot long area of minor delamination cracking near the East abutment. Bay #6 has a 2 foot diameter x 3 inch deep spall near midspan with exposed rusted rebar, a 3 foot x 1 1/2 foot wide spall over the high speed lane, and a 3 foot wide x 8 foot long area of delamination cracking over the 2nd diaphragm from the East. Bay #7 has a few full width transverse hairline cracks at the East end with rust staining. The remainder of the concrete deck has several previously repaired areas, in good condition.

Item 58.4 - Curbs

The granite curbs have scraped and chipped edges with rust staining in several areas. The curb joints have several areas of missing mortar. The North curb stones are rotated outward up to 2 inches at the top.

Item 58.6 - Sidewalks

Both sidewalks have minor transverse, longitudinal, and map cracking in isolated areas, with minor spalling and delamination along the interface of the granite curb, which is filled with dirt. There is a triangular shaped cracked and spalled area at the Southeast corner with a hole down to the utility bank, causing erosion and debris on the backwall in this area. See Photo 1. The North sidewalk has a 2 foot long x 7 inch wide x 3 inch deep spall below the bridge rail, above the pier. See Photo 2.

Item 58.7 - Parapets

Both parapets have many vertical hairline cracks throughout, some with light efflorescence and rust staining, mostly over the pier. The underside of both parapets have minor spalling above the pier, up to 2 feet long x 1 foot wide x 3 inches deep.

REM.(2)7-96

CITY/TOWN	B.I.N.	BR. DEPT. NO.	8.-STRUCTURE NO.	INSPECTION DATE
WORCESTER	1L2	W-44-094	W44094-1L2-MHD-NBI	JUN 26, 2008

REMARKS

Item 58.8 - Railing

The East post on the South rail is missing one anchor bolt and nut. The 6th post from the East on the North rail has a 2 inch long crack to the base plate. See Photo 3. The 3rd post from the West on the North rail has a bolt and nut sheared off at the base plate.

Item 58.12 - Utilities

There is some moderate settlement and heaving to the utility pipes in bay #1, span #2, where the damaged diaphragms were removed. The abandonded steel utility attached along the top of both abutments are 100% surface rusted with minor section loss.

Item 58.13 - Deck Joints

The West compression seal deck joint in the Eastbound lane has been removed and patched with bituminous concrete that has heavy cracking and is starting to break up. Some of these cracks have been sealed. The West compression seal deck joint in the Westbound lane has small areas of missing filler and the concrete headers on both sides have minor spalling and a few pot holes. There is a 10 foot long x 1 foot wide bituminous patch along the West side of the joint that is starting to break up. See Photo 4.

The compression filler is completely missing throughout the East deck joint. The concrete header is missing on the West side of the East joint throughout the Westbound lane. This half of the joint is patched with bituminous concrete that has minor cracking and breakup throughout. The remainder of concrete header in the Westbound lane and on both sides in the Eastbound lane have minor to moderate spalling. See Photo 5.

APPROACHES

Approaches a - Appr. Pavement Condition

The East bituminous concrete approach pavement has moderate transverse and longitudinal cracking, with heavy wheel wear. The West approach has severe cracking and break up, mostly to the North half.

Approaches c - Appr. Sidewalk Settlement

There is up to 1 inch of settlement at the both ends of The North sidewalk.

ITEM 59 - SUPERSTRUCTURE

Item 59.1 - Stringers

There is minor to some severe collision damage to stringers #1 ,2, 3 and 8 in span 2. Stringers #1, #3, and #8 have bottom flanges and webs that are bent and rotated out of plane. There are two impact points to the bottom flange and cover plate of stringer #1. See Photo 6. These impact points are approximately 10 feet apart and are over the 1st and middle travel lanes. The impact point closest to the East abutment has a deep gouge to the bottom flange and the cover plate, and has severe inward bending of the web. There is a crack to the bottom flange, that extends into the web in this area. See Photo 7. This crack is 5/16 inch wide at the South edge of the bottom flange. This crack has an arresting hole drilled in the web. This crack has not propagated in the web or the bottom flange since the drill hole was installed. See Photo 8. This structure was hit several times. One hit took place on 8/18/1994 and the last collision hit occured on 10/28/04. A damage inspection was done on this date. The above mentioned crack occured several days after the 10/28/04 impact. The impact point closest to the pier has a deep gouge to the bottom flange and the cover plate, and has severe inward and upward bending of the bottom flange and web. The hit took place at a utility support, so energy was transferred to stringer #2. This caused only a minor dent and some paint popping off to the opposite side of web. Stringer #3 has a gouge to the cover plate over the 1st travel lane. Stringer #8 has a gouge in bottom flange and cover plate with minor outward bending. See Photo 9. The remainder of the

REM.(2)7-96

CITY/TOWN	B.I.N.	BR. DEPT. NO.	8.-STRUCTURE NO.	INSPECTION DATE
WORCESTER	1L2	W-44-094	W44094-1L2-MHD-NBI	JUN 26, 2008

REMARKS

Item 59.1 - Stringers (Cont'd)
stringers have moderate to heavy paint peeling, isolated rust flaking and surface rusting in many areas throughout, heaviest at the ends of the stringers at both sides of the pier, at both abutments and on underside of bottom flanges.

Item 59.7 - Conn Plt's, Gussets & Angles
The connection plates for the utility diaphragms, between stringers #1 and #2, in span #2 are bent and the diaphragms are detached from the connection plates at six locations near the point of impact.

Item 59.8 - Cover Plates
Re: Item #59.1.

Item 59.9 - Bearing Devices
All bearings show heavy rusting with some rust flaking. The anchor nuts and bolts on most bearings show heavy rusting and corrosion with up to 20% section loss. There is heavy debris around most bearings on the East bridge seat.

Item 59.10 - Diaphragms/Cross Frames
The steel diaphragms have moderate paint peeling and minor to moderate surface rusting in many areas throughout. The 2nd diaphragm from the pier in span #2 between stringers #2 and #3 is bent at the bottom of the connection plate. The concrete end diaphragms at both abutments and over the pier have minor to some severe cracking and spalled areas up to full width x full length x up to 7 inches high with exposed rusting rebar. See Photo 10. The utility supports between stringers #1 and #2 in span #2 are bent at their ends due to collision damage. Some of these supports have been removed and replaced with timber. The support near the impact point has longitudinal bending. Six of the utility supports have missing connection bolts along stringers #2, and ten of the utility supports have missing connection bolts along stringer #1. These supports have dropped up to 2 inches.

Item 59.11 - Rivets & Bolts
Re: Items #59.1 & #59. 9.

Item 59.12 - Welds
Re: Items #59.1 & #59.10.

Item 59.13 - Member Alignment
Stringers #1, #2, #3, & #8 are moderately to severely bent out of alignment in span #2 due to previous collision damage.

Item 59.14 - Paint/Coating
The paint system shows moderate to heavy paint peeling exposing surface rusting in many areas throughout.

SuperStructure Collision Notes
This structure was hit by an over height load on 8/18/1994. There was a damage inspection performed on that same day. The bridge was hit again on 10/28/04 and another damage inspection was done on this date. Re: Item 59.1 for collision remarks.

SuperStructure Load Deflection Notes
Minor under heavy live loads.

REM.(2)7-96

CITY/TOWN	B.I.N.	BR. DEPT. NO.	8.-STRUCTURE NO.	INSPECTION DATE
WORCESTER	1L2	W-44-094	W44094-1L2-MHD-NBI	JUN 26, 2008

REMARKS

SuperStructure Load Vibration Notes
Minor under heavy live loads.

ITEM 60 - SUBSTRUCTURE

Item 60.1 - Abutments
Item 60.1.b - Bridge Seats
Both bridge seats have a heavy build up of debris, mostly along the East seat, due to the missing deck joint seal and severe deterioration to the bricked in backwall utility bays. See Photo 11. There is a 3 foot long x 3 foot high x 1 foot deep spall to the South end of the East breastwall in the seat area. See Photo 12.

Item 60.1.c - Backwalls
There is a 18 inch x 18 inch x 4 inch deep spall to the West backwall, just North of stringer #8. There is also severe deterioration to the utility bricking in bays #1 and #7 of the East backwall. There is severe spalling to the backwall throughout bay #7, up to full depth. See Photo 13.

Item 60.1.d - Breastwalls
Both breastwalls have several large patched areas. All patched areas have hairline map cracking and some minor delamination throughout. Both breastwalls also have several vertical hairline cracks throughout, some almost full height. There is a 3 foot x 3 foot x 1 foot deep spall to top of the East breastwall at the South end. See Photo 12.

Item 60.1.e - Wingwalls
All four wingwalls have some minor outward rotation. The Southwest wingwall has 1 inch of rotatation at the top, and two 6 inch high exposed rusted rebars.

The Northwest wingwall has 1/16 inch of rotation at the top, minor collision scrapes, and two 1/16 inch wide x up to 10 foot high vertical cracks.

The Southeast wingwall has 3/4 inch of rotation at the top, minor collision scrapes with rust staining, and several almost full height hairline cracks.

The Northeast wingwall has up to 2 1/4 inches of rotatation at the top, several exposed rusted rebars, up to 4 feet high, and missing joint filler.

Item 60.1.k - Settlement
Re: Item #60.1e.

Item 60.2 - Piers or Bents
Item 60.2.b - Caps
The pier cap has several large patched areas, that have shrinkage cracking with rust staining, and delamination throughout. There are spalled areas up to 5 feet long x 1 foot high x 2 1/2 inches deep with exposed rusted rebar to the bottom corners of the cap. See Photo 14. There are several areas of map cracking and horizontal cracking to the (original) unpatched area of pier cap.

REM.(2)7-96

CITY/TOWN	B.I.N.	BR. DEPT. NO.	8.-STRUCTURE NO.	INSPECTION DATE
WORCESTER	1L2	W-44-094	W44094-1L2-MHD-NBI	JUN 26, 2008

REMARKS

Item 60.2.c - Columns

The columns have spalls up to 4 feet high x 3 feet wide x 2 inches deep, some with exposed rusted rebar. All columns have several areas of minor vertical and map cracking, and delamination with rust staining. See Photo 15.

TRAFFIC SAFETY

Item 36a - Bridge Railing

Both bridgerails consist of AL-3 rails with aluminum posts. Re: Item #58.8 for condition remarks.

Item 36b - Transitions

There are no traffic safety features in place at all four corners of the bridge. There are only limited access chain link fences in place at all four corners of the bridge. See Photo 16.

Item 36c - Approach Guardrail

Re: Item #36b.

Item 36d - Approach Guardrail Ends

Re: Item #36b.

Photo Log

Photo 1 : Spall to the East end of the South sidewalk.
Photo 2 : Spall to the North sidewalk above the pier.
Photo 3 : Crack to the 6th base plate from the East on the North rail.
Photo 4 : West deck joint.
Photo 5 : East deck joint.
Photo 6 : Stringer #1, Span #2.
Photo 7 : Crack to bottom flange of Stringer #1, Span #2.
Photo 8 : Crack to the bottom flange and web of Stringer #1, Span #2.
Photo 9 : Bottom flange of Stringer #8, Span #2.
Photo 10 : Typical concrete end diaphragm.
Photo 11 : Typical debris along the East bridge seat.
Photo 12 : Spalling and debris in bay #1 on the East backwall/bridge seat.
Photo 13 : Spalling to the East backwall in bay #7 .
Photo 14 : Typical spalling to the underside of the pier cap.
Photo 15 : Typical spalling to the columns.
Photo 16 : Northeast transition area.

REM.(2)7-98

Appendix C: Concrete Deck Hand Calculations

Compute Dead Loads:

Slab and Parapet Load Factors

maximum = 1.25 $\gamma_{pDC\ max}$

minimum = 0.90 $\gamma_{pDC\ min}$ — STable 3.4.1-2

Wearing Surface Load Factors

maximum = 1.5 $\gamma_{pDW\ max}$

Minimum = 0.65 $\gamma_{pDW\ min}$ — STable 3.4.1-2

$M = \frac{wL^2}{10}$

Weight of Deck $= \left(\frac{8in}{12in}\right)(150pcf) = 100psf$

Unfactored Weight for positive or negative moment $= \frac{\frac{100psf}{1000lbs}(8ft)^2}{10} = 0.64\ \frac{K\text{-}ft}{ft}$

Bituminous Wearing Surface $= \frac{2.5in}{12in}(145pcf) = 30psf$

Unfactored Weight for positive or negative moment $= \frac{\frac{30psf}{1000lbs}(8ft)^2}{10} = 0.19\ \frac{K\cdot ft}{ft}$

Compute Live Loads:

The minimum distance from the center of vehicle wheel to inside face of parapet — S.3.6.1.3.1

The minimum distance between the vehicle wheels of two adjacent design vehicles = 4ft — S.3.6.1.3.1

Dynamic Load Allowance (IM) = .33 or 33% — STable 3.6.2.1-1

Load Factor for Live Load (strength 1) $\gamma_{LL} = 1.75$ — STable 3.4.1-1

multiple presence factors m:

with > three lanes loaded, m = 0.65 — S3.6.1.1.2-1

Fatigue does not need to be investigated for concrete deck design — S9.5.3/S5.5.3.1

Resistance Factors for Flexure:

Strength Limit State $\phi_{stre} = 0.90$ — S5.5.4.2

Service Limit State $\phi_{serv} = 1.00$ — S1.3.2.1

Extreme Event Limit State $\phi_{ext} = 1.00$ — S1.3.2.1

1

Design for Positive Moment (method B, preferred for design)

Factored Positive Live Load Moment: STable A4.1-1: tabulated value includes impact

For a girder with 8ft spacing, the maximum unfactored live load moment is 5.69 K.ft/ft

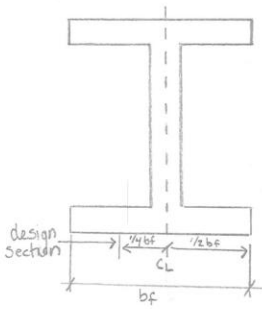
$M_{u\,pos\,live\,B} = \gamma_{LL}\,5.69$ K.ft/ft
$M_{u\,pos\,live\,B} = 1.75(5.69$ K.ft/ft)
$M_{u\,pos\,live\,B} = 9.96$ K.ft/ft

Factored Positive Dead Load moment:

$M_{u\,pos\,dead\,B} = 1.25(0.64$ K.ft/ft$) + 1.5(0.19$ K.ft/ft$) = 1.09$ K.ft/ft
(0.64: Deck; 0.19: Wearing Surface)

$M_{u\,pos\,total\,B} = 9.96$ K.ft/ft $+ 1.09$ K.ft/ft $= 11.05$ K.ft/ft → **$M_{u\,pos\,total\,B} = 11.05$ K.ft/ft**

Design for Negative moment



Factored Negative Live Load moment: STable A4.1-1

For a girder with 8ft spacing and a distance of 0" from the centerline of girder to the design section, the maximum unfactored live load moment is −6.58 K.ft/ft.

$M_{u\,neg\,live\,B} = \gamma_{LL}(-6.58$ K.ft/ft)
$M_{u\,neg\,live\,B} = 1.75(-6.58$ K.ft/ft)
$M_{u\,neg\,live\,B} = -11.515$ K.ft/ft

Factored Negative Dead Load Moment:

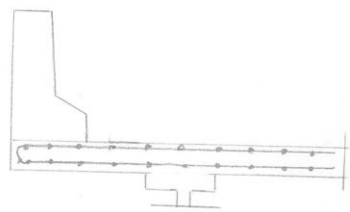
$M_{u\,neg\,dead\,B} = 1.25(.64$ K.ft/ft$) + 1.5(.19$ K.ft/ft$) = 1.09$ K.ft/ft
(.64: Deck; .19: wearing surface)

DL+LL Design Factored Positive moment (Strength 1 Limit State)

$M_{u\,neg\,total\,B} = 11.52 + 1.09 = 12.605$ K.ft/ft → **$M_{u\,neg\,total\,B} = 12.605$ K.ft/ft**

2

Design for Positive Flexure in Deck



Assume #5 bars:

Bar Diameter = 0.625 in

Bar Area = 0.31 in²

Effective Depth de = total slab thickness - bottom cover - ½ diameter - top integral wearing surface

$d_e = t_s - Cover_b - \frac{\text{bar diameter}}{2} - 2.5\text{in}$

$d_e = 8" - 0.5" - 0.625"/2 - 2.5\text{ in} = 4.69\text{ in}$

Solve for required amount of reinforcing steel, as follows:

$\phi_f = 0.90$

$b = 12\text{in}$

$R_n = \frac{M_{upos total B}(12\text{in})}{\phi_f\, b\, d_e^2} = \frac{11.05\text{K}\cdot\text{ft/ft}\,(12\text{in})}{0.9\,(12\text{in})(4.69\text{in})^2} = 0.56\text{ K/in}^2$

$\rho = 0.85\left(\frac{f'c}{f'y}\right)\left[1.0 - \sqrt{1.0 - \left(\frac{2R_n}{.85f'c}\right)}\right] = .85\left(\frac{4\text{KSI}}{60\text{KSI}}\right)\left[1.0 - \sqrt{1.0 - \left(\frac{2(0.56\text{KSI})}{.85(4\text{KSI})}\right)}\right] = 0.0102$

$A_s = \rho \frac{b}{ft} d_e = 0.0102\left(\frac{12\text{in}}{ft}\right)(4.69\text{ in}) = 0.58\text{ in}^2/\text{ft}$

Required Bar Spacing

$= \frac{\text{bar Area}}{A_s} = \frac{0.31\text{ in}^2}{0.58\text{ in}^2/\text{ft}} = 6.69\text{ in}$

Use #5 bars @ 6.0 in Spacing

$T = (\text{bar Area}) f_y$

$= 0.31\text{ in}^2(60\text{KSI}) = 18.4\text{ K}$

$a = \frac{T}{.85f'c\,(\text{bar space})} = \frac{18.4\text{ K}}{.85(4\text{KSI})(6\text{in})} = 0.90\text{ in}$

$\beta_1 = 0.85$

$C = \frac{a}{\beta_1} = \frac{0.90}{0.85} = 1.06\text{ in}$

$\frac{C}{d_e} = \frac{1.06\text{ in}}{4.69\text{ in}} = 0.23$ where $\frac{c}{d_e} \le 0.76$ ∴ $0.23 \le 0.76$ ✓ OK

3

Design for Negative Flexure in Deck

Assume #5 bars:

Bar Diameter = 0.625 in

Bar Area = $0.31 in^2$

(min. value AASHTO spec.)

Effective Depth de = total slab thickness − top cover − ½ bar diameter

$d_e = 8'' - 2.5'' - \frac{1}{2}(.625) = 5.19$ in

$d_e = 5.19$ in

Solve for required amount of Reinforcing steel:

$\phi_f = 0.90$

$b = 12in$

$$R_n = \frac{M_{u\,neg\,total\,B}(12in)}{\phi_f\, b\, d_e^2} = \frac{12.605(12in)}{.9(12)(5.19)^2} = 0.52\ K/in^2$$

$$\rho = .85\left(\frac{f'c}{f'y}\right)\left[1.0 - \sqrt{1.0 - \left(\frac{2R_n}{.85 f'c}\right)}\right] = .85\left(\frac{4ksi}{50ksi}\right)\left[1 - \sqrt{1 - \frac{2(0.52)}{0.85(4)}}\right] = 0.0095$$

$$A_s = \rho \frac{b}{ft} d_e = 0.0095\left(\frac{12in}{ft}\right)(5.19\ in) = 0.59\ in^2/ft$$

$$\text{Required Bar Spacing} = \frac{\text{bar Area}}{A_s} = \frac{0.31\ in^2}{0.59\ in^2/ft} = 6.25\ in$$

Use #5 bars @ 6.0 in Spacing

$T = (\text{bar Area}) f'y$

$= .31 in^2 (50 Ksi) = 18.4\ K$

$$a = \frac{T}{.85 f'c(\text{bar space})} = \frac{18.4\ K}{.85(4Ksi)(6in)} = 0.90\ in$$

$\beta_1 = 0.85$

$$c = \frac{a}{\beta_1} = \frac{0.90}{.85} = 1.06\ in$$

$$\frac{c}{d_e} = \frac{1.06in}{5.19in} = 0.20 \quad \text{where } \frac{c}{d_e} \le 1.07 \qquad \therefore 0.20 \le 1.07\ \checkmark\ OK$$

For overall concrete deck design, use #6 reinforcement bars @ 6.0 in spacing for both positive and negative flexure.

4

Appendix D: Rolled Steel Girder Hand Calculations

$M_u = 2075.7$ ft·k from RISA See Appendix

$Z_x \geq \frac{M_u}{\phi F_y} = \frac{2076 \text{ ft·k} (12 \text{in/ft})}{0.9(50\text{ksi})} = 553.6 \text{ in}^3$

Table 3-2 AISC Manual

W40 X 167 $Z_x = 693 \text{ in}^3$

Update Mu to reflect member weight

$M_u = 2189$ ft·k from RISA

$\phi M_p = \phi Z_x F_y$

$\phi M_p = 0.9(693 \text{in}^3)(50\text{ksi})\left(\frac{\text{ft}}{12\text{in}}\right)$

$\phi M_p = 2599$ ft·k

$\phi M_p > M_u$ 2599 ft·k > 2189 ft·k ✓ ok

Conditions for plastic capacity

① No local buckling of flange (FLB)

$\frac{b_f}{2t_f} \leq 0.38\sqrt{\frac{E}{f_y}}$

$\frac{11.8}{2(1.03)} \leq 0.38\sqrt{\frac{29{,}000\text{ksi}}{50\text{ksi}}}$

$5.73 \leq 9.2$ ✓ ok

② No local buckling of web (WLB)

$\frac{h}{t_w} \leq 3.76\sqrt{\frac{E}{F_y}}$

$\frac{38.6}{1.03} \leq 3.76\sqrt{\frac{29{,}000\text{ksi}}{50\text{ksi}}}$

$37.5 \leq 90.6$ ✓ ok

③ No lateral buckling of the beam along its length (LTB)

Deck slab ✓ ok

Unshored Construction:

Construction Loads

Wet concrete weight: $145pcf\left(\frac{8in}{12in}\right)(8ft)(1.10)=957 lb/ft$ (ponding ↓ 1.10)

Construction LL: $20psf(8ft)=180 lb/ft$

Steel girder: $167 lb/ft(8)(8ft)/66ft = 182 lb/ft$

$Wu = 1.2(182 lb/ft)+1.6(957 lb/ft + 180 lb/ft) = 2037.6 lb/ft$

$Mu = \frac{WuL^2}{8} = \frac{2037.6 lb/ft(66ft)^2}{8} = 1109 ft \cdot k$

Table 3-19 AISC Manual

Try W30x99 $\phi_b M_p = 1170 ft \cdot k$

Check Construction Deflection:

Table 1-1 AISC Manual $I_x = 3990 in^4$

Fig. 3-2 AISC Manual $C_1 = 161$

$\Delta = \frac{ML^2}{C_1 I_x} = \frac{1061 ft \cdot k(66ft)^2}{161(3990 in^4)} = 7.20$

$7.20 \geq 2.5 in$ X NOT OK

Try W36x194 $\phi_b M_p = 2880 ft \cdot k$

Construction Load Adjustment:

Steel Girder: $194 lb/ft(8)(9ft)/66ft = 211 lb/ft$

$Wu = 1.2(211 lb/ft)+1.6(957 lb/ft + 180 lb/ft) = 2073 lb/ft$

$Mu = \frac{2073 lb/ft(66ft)^2}{8} = 1129 ft \cdot k \leq \phi_b M_p = 2880 ft \cdot k$

Check Construction Deflection:

Table 1-1 AISC Manual $I_x = 12,100 in^4$

$\Delta = \frac{1129 ft \cdot k(66ft)^2}{161(12,100 in^4)} = 2.5 in$

$2.5 in \leq 2.5 in$ ✓ OK

Composite Capacity:

Table 3-19 AISC Manual $\Sigma Q_n = 2850 K$

$T = A_s F_y = \Sigma Q_n = 2850k$

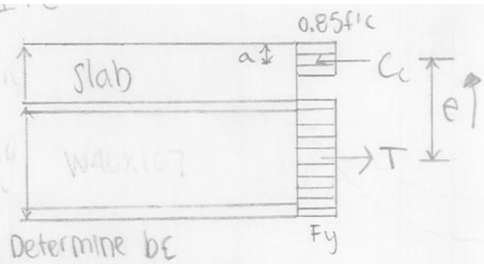
$a = \frac{\Sigma Q_n}{0.85 f'_c b_e} = \frac{2850k}{0.85(4ksi)(9ft)(12in)} = 7.76 in$

$a \leq t_s$ $7.76 in \leq 8 in$ ✓ OK

$Y_{con} = 8 in$

$Y_1 = 0 in$

$Y_2 = Y_{con} - \frac{a}{2} = 8in - \left(\frac{7.76 in}{2}\right) = 4.12 in$



Determine b_E

① $b_E \leq \frac{1}{4}L = \frac{1}{4}(66ft)$

$b_E \leq 16.5 ft$

② $b_E \leq s$

$b_E \leq 9ft$ ✓ OK Governs

$M_u = 2075.7$ ft·k from RISA see Appendix

Table 3-19 AISC Manual

$\phi_b M_p = 4760 + \left(\frac{0.12in}{0.5in}\right)(4860 - 4760) = 4784$ ft·k

4784 ft·k ≥ 2075.7 ✓ OK

Shear Studs:

Nominal Strength:

$Q_n = 0.5 A_{sc}\sqrt{f'c E_c} \leq A_{sc} F_u$

$F_u = 65ksi$

$E_c = w_c^{1.5}\sqrt{f'c} = 145pcf^{1.5}\sqrt{4ksi} = 3492ksi$

$A_{sc} = \frac{\pi d_{sc}^2}{4} = \frac{\pi(3/4in)^2}{4} = 0.4418in^2$

$A_{sc}F_u = (0.4418in^2)(65ksi) = 28.7k$

$Q_n = 0.5(0.4418in^2)\sqrt{4ksi(3492ksi)} = 26.1$ ft·k ✓ GOVERNS

Table 3-21 AISC Manual

$n = \frac{2\sum Q_n}{Q_n} = \frac{2850k}{26.1k} = 218$ studs

Spacing:

minimum: $6d_v = (6)(3/4in) = 4.5in$

maximum: $8t_s = 8(8in) = 64in \leq 36in$ 36in GOVERNS

Actual: $\frac{131ft(12in/ft)}{218+1} = 7.18in$

$4.5in \leq 7.18in \leq 36in$ ✓ OK

Compute LL Deflection:

Table 3-20 AISC Manual

$I_{LB} = 26200 + \left(\frac{0.12in}{.5in}\right)(26800 - 26200) = 26344in^4$

$\Delta_L = \frac{ML^2}{C_1 I_{LB}} = \frac{734ft\cdot k(66ft)^2}{161(26344in^4)} = 0.75in$

$0.75in \leq 2.2in$ ✓ OK

3

W36x194

Table 3-19 AISC Manual

$Y_{con} = 8in$

$Y_1 = 0.945in$ (PNA is 4)

$\Sigma Q_n = 1710K$

$a = \frac{\Sigma Q_n}{0.85 f'_c b_e} = \frac{1710K}{0.85(4ksi)(9ft)(12in)} = 4.66in$

$Y_2 = Y_{con} - \frac{a}{2} = 8in - \frac{4.66in}{2} = 5.67in$

Composite capacity:

Table 3-19 AISC Manual

$\phi_b M_p = 4560 + \left(\frac{0.17in}{0.51in}\right)(4630-4560) = 4583.8\ ft \cdot k$

$\phi_b M_p \geq M_u$ $4583.8 ft \cdot k > 2075.7$ ✓ ok

Shear Studs:

Nominal Strength:

Table 3-21 AISC Manual

$Q_n = 26.1K$

$n = \frac{2\Sigma Q_n}{Q_n} = \frac{1710K(2)}{26.1K} = 131$ studs

Spacing:

minimum = 4.5in

maximum = 36in

Actual $= \frac{131ft(12in/ft)}{131+1} = 11.91in$

$4.5in \leq 11.91in \leq 36in$

Compute LL Deflection:

$w_u = 211 lb/ft + 180 lb/ft + 957 lb/ft = 1348 lb/ft$

$M_L = \frac{1.348 k/ft (66ft)^2}{8} = 733.99 ft \cdot k$

Table 3-20 AISC Manual

$I_{LB} = 24200 + \left(\frac{0.17}{0.5}\right)(24700-24200) = 24370\ in^4$

$\Delta_L = \frac{M L^2}{C_1 I_{LB}} = \frac{734 ft \cdot k (66ft)^2}{161(24370 in^4)} = 0.81\ in$

$\frac{1}{360}$ span $= \frac{12in \times 66ft}{360} = 2.2in$

$0.81in \leq 2.2in$

4

Appendix E: Concrete Column Hand Calculations

$P_u = 2V_n = 2(213k) = 426k$ from RISA column spacing: 34ft

$f'c = 4ksi$

$f_y = 60ksi$

Slenderness Ratio

Limit slenderness: $KL/r \leq 22$ for $K=1.2$ and $L=$ clear span of column

$KL/r \leq 22$

$KL/22 \leq r$ $\quad r = 0.3b$ for rectangle section

$KL/22 \leq 0.3b$

$KL/22(0.3) \leq b$

$$\frac{(1.2)((15ft)(12in)+9.5in)}{22(0.3)} \leq b$$

$34 \leq b$ say $b = 36in$

Reinforcement:

$\rho_{min} = 0.01 \quad \rho_{max} = 0.08$

$$\rho = \frac{A_s}{A_g}$$

$$0.01 = \frac{A_s}{(36in)(36in)} = 12.96in^2$$

Try 6#14 bars $A_g = 13.5\ in^2$

$\phi P_{n(max)} = 0.80\phi[0.85f'c(A_g - A_{st}) + f_y A_{st}]$

$\phi P_{n(max)} = 0.80(0.65)[0.85(4ksi)((36in)(36in) - 13.5\ in^2) + 60ksi(13.5in^2))$

$\phi P_{n(max)} = 2689k$

$\phi P_n > P_u \quad 2689k > 426k$

Ties:

Try #4 ties + 6 #14 bars

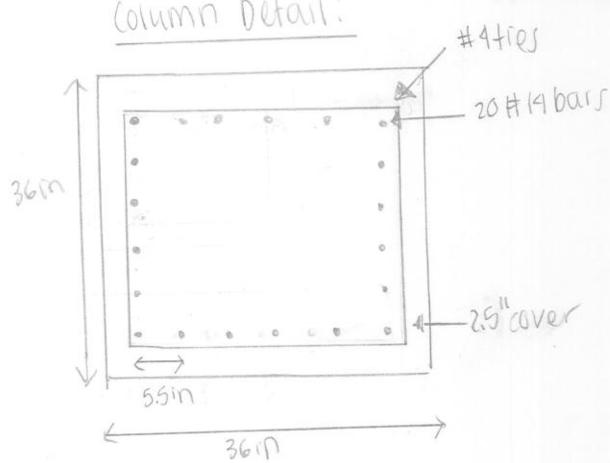
Spacing: Ties
16dbars = 16(1.693in) = 27in
48 dties = 48(4in/8) = 24in
smallest dim = 36in

Use 36 in ties spacing and #4 ties

Spacing: Bars = $\frac{h - 2cover - 2ties - 2(db/2)}{5}$ = 5.66in < 6in OK

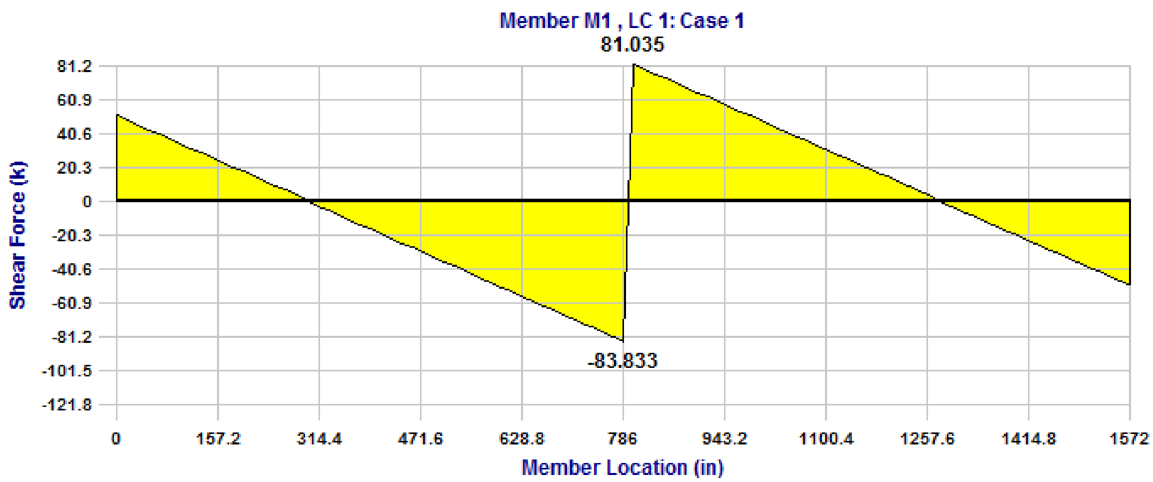
Use 5.5in spacing for center to center spacing of bars

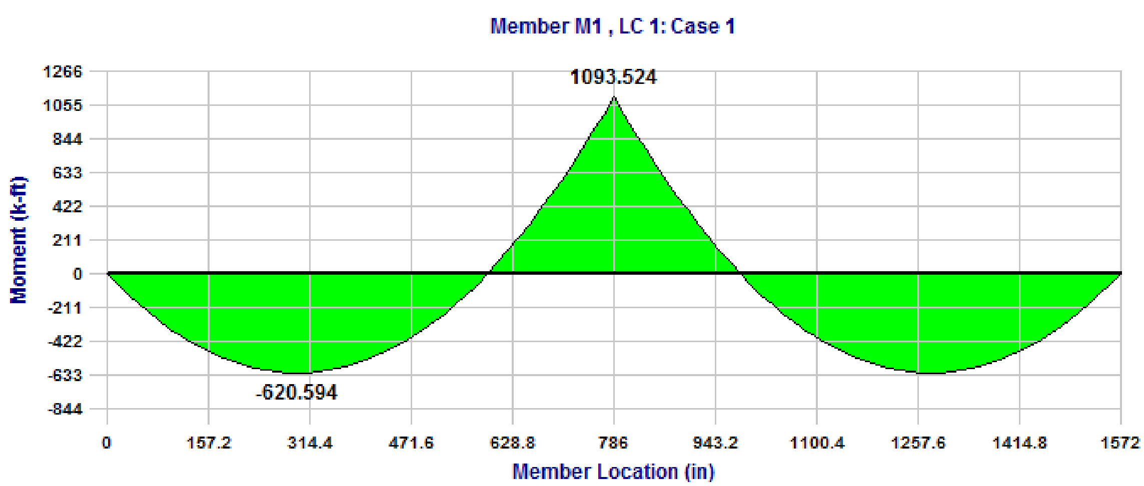
Column Detail:



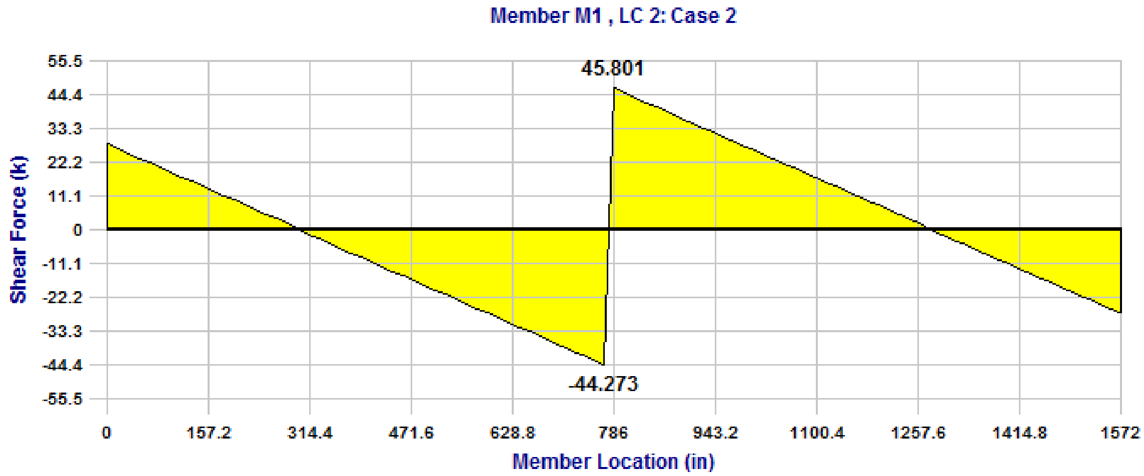
Appendix F: RISA 2-D Outputs

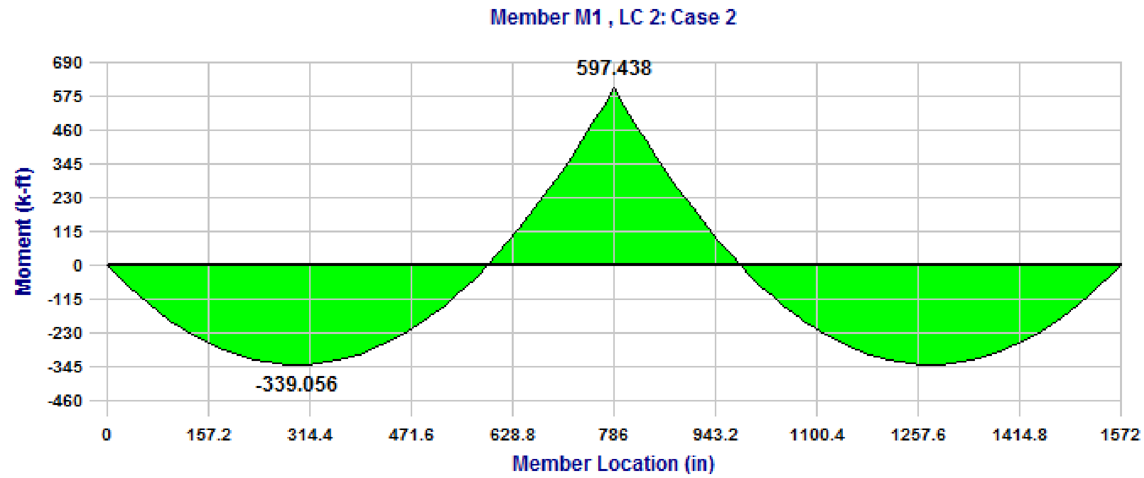
Case 1 – Uniform Dead Load



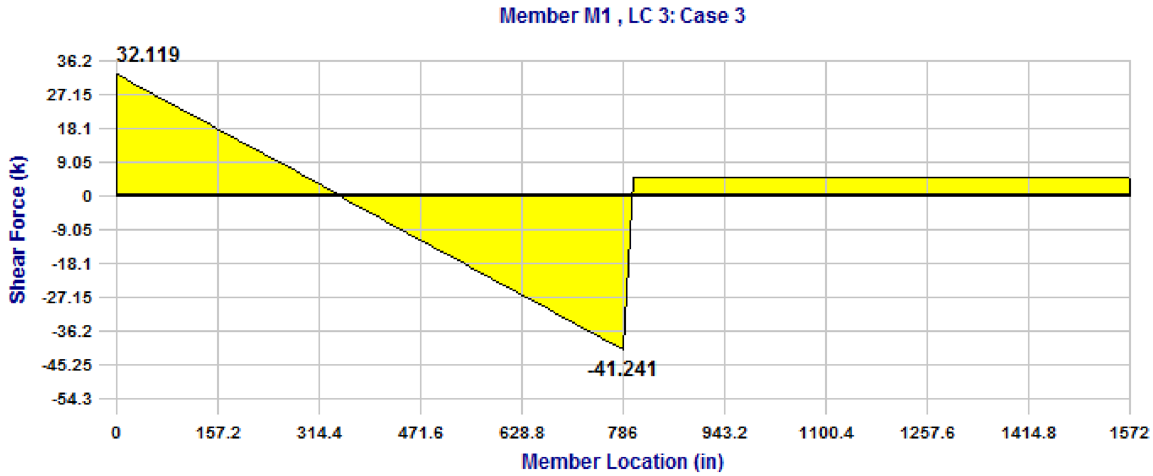


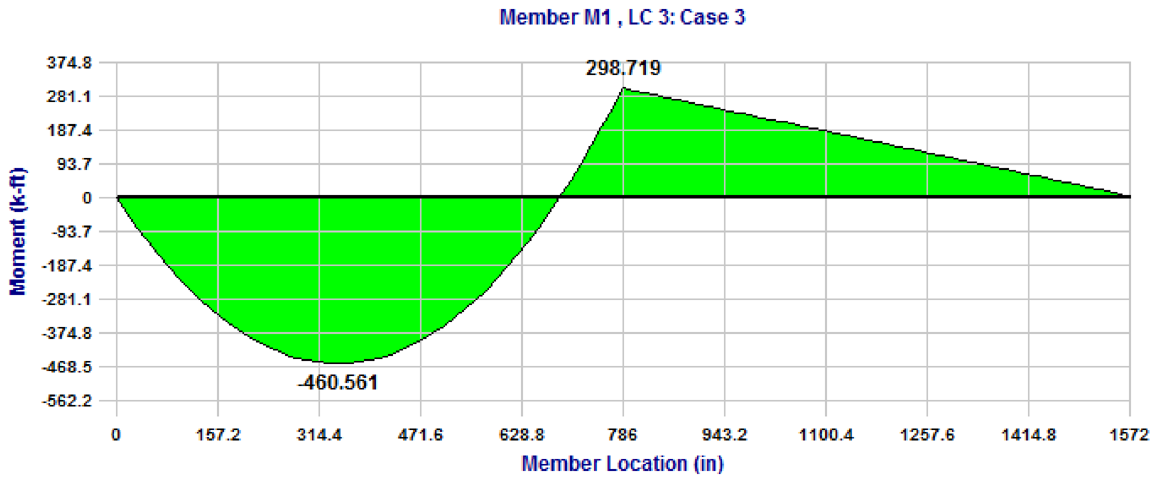
Case 2 – Uniform Live Load for 2 Spans



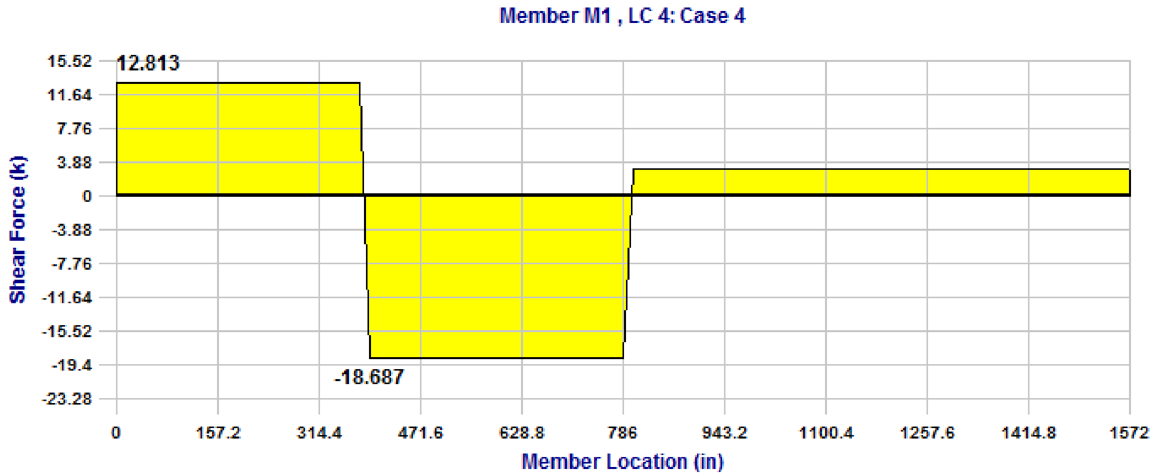


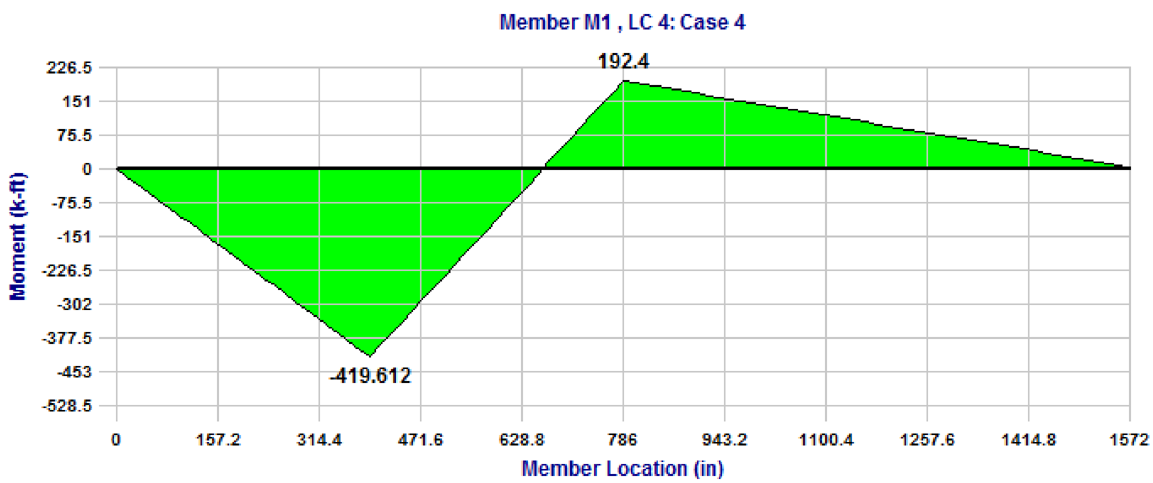
Case 3 – Uniform Live Load on 1 Span



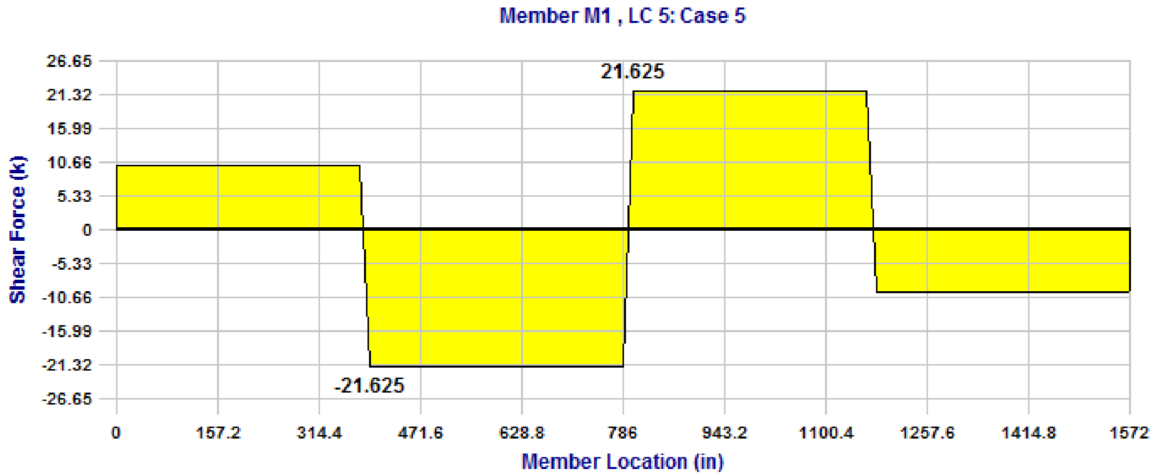


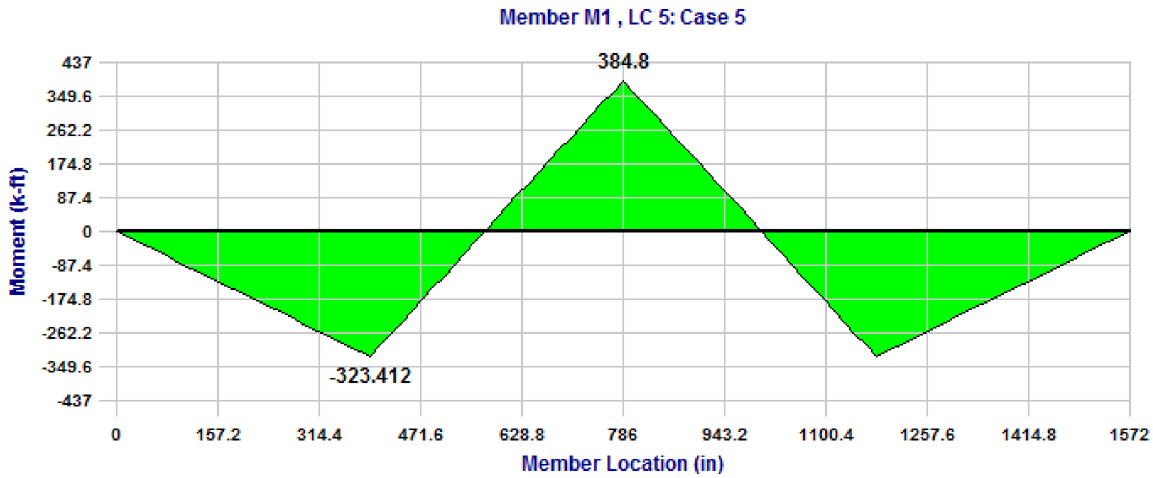
Case 4 – Concentrated Live Load at Center of First Span



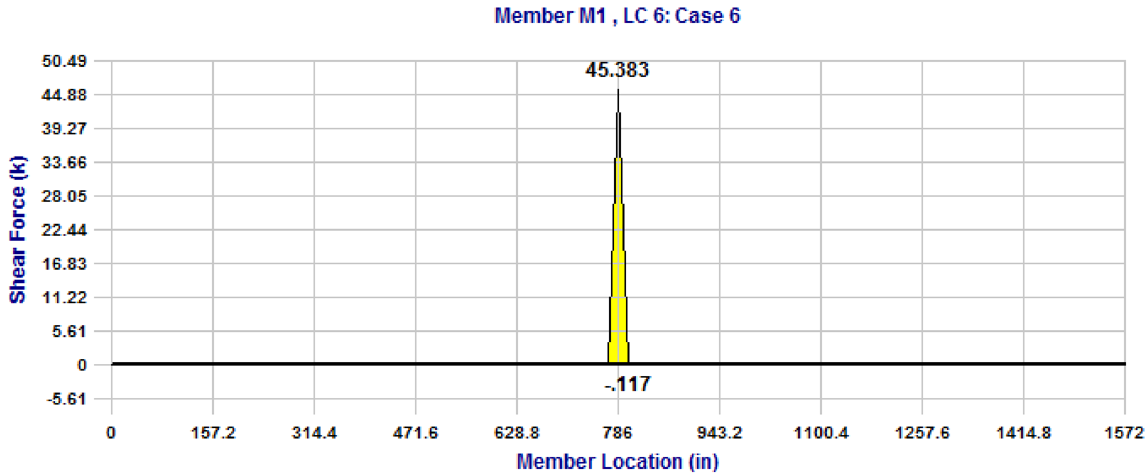


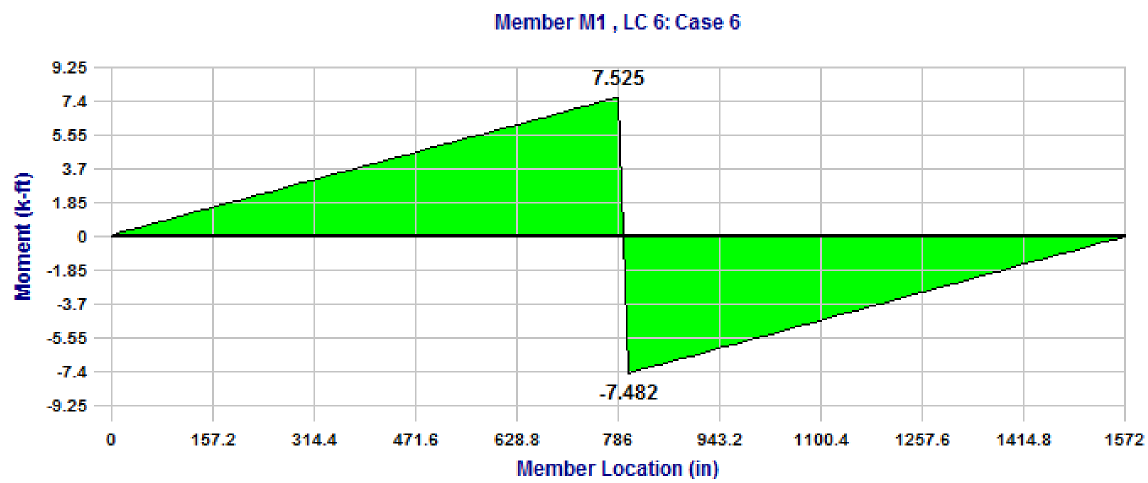
Case 5 – Concentrated Live Loads at Center of Both Spans



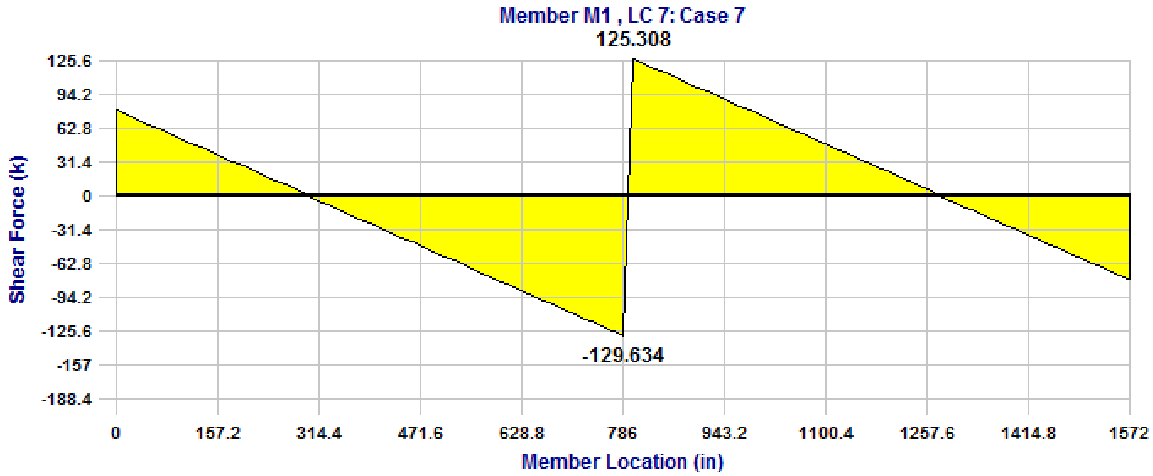


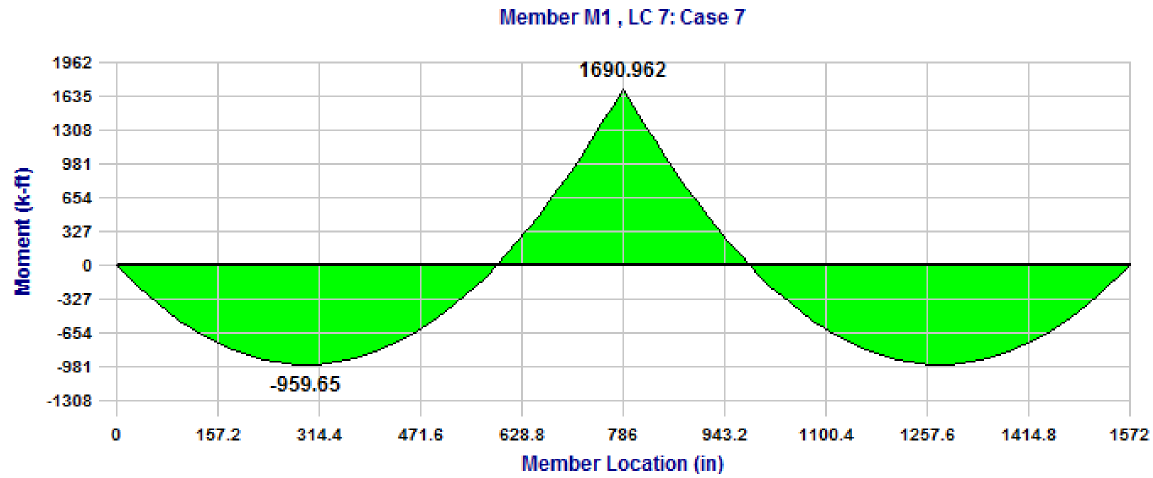
Case 6 – Concentrated Live Load at Center Support



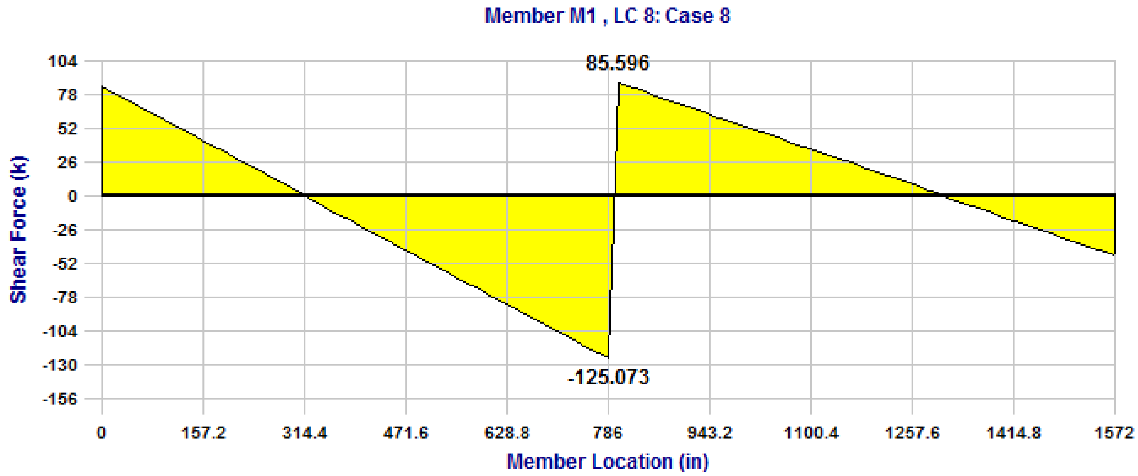


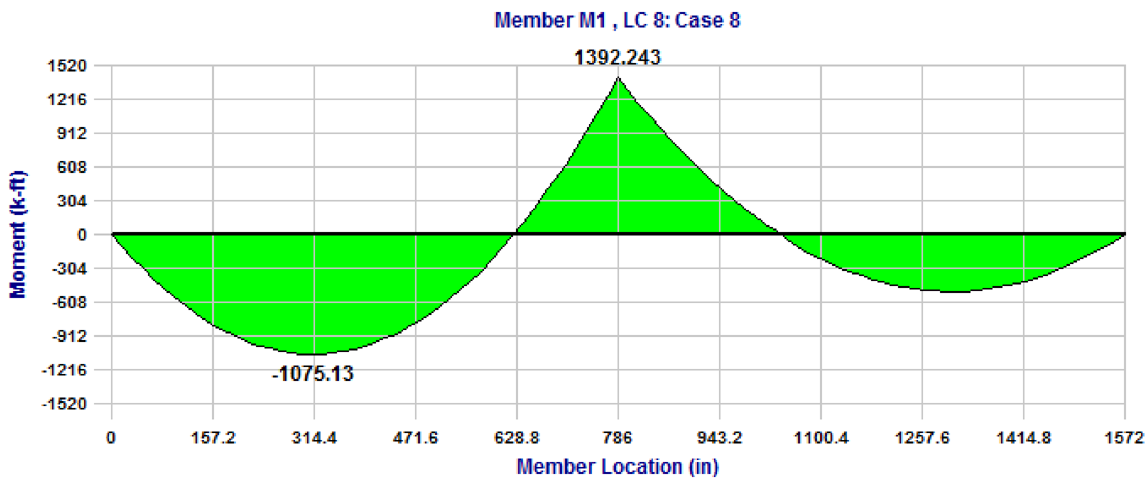
Case 7 – Combined Case 1 & Case 2



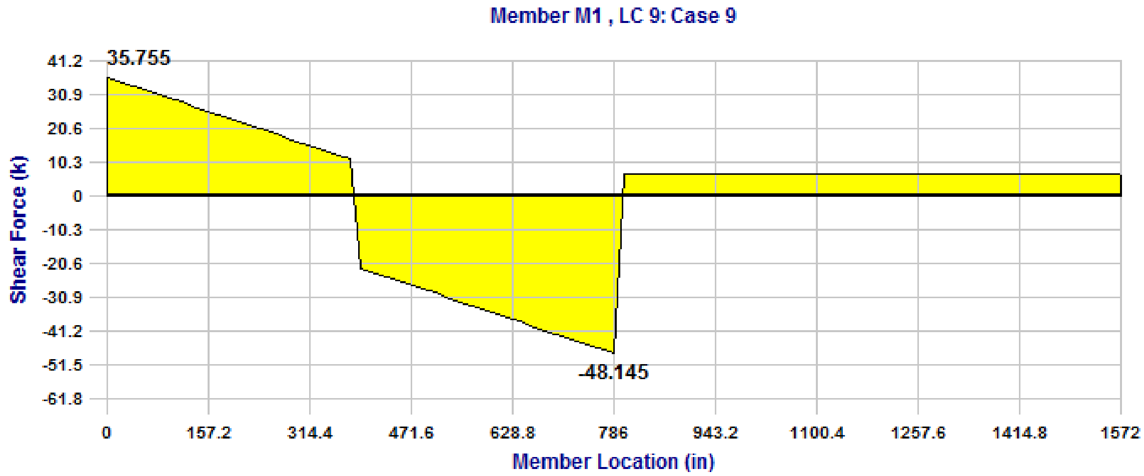


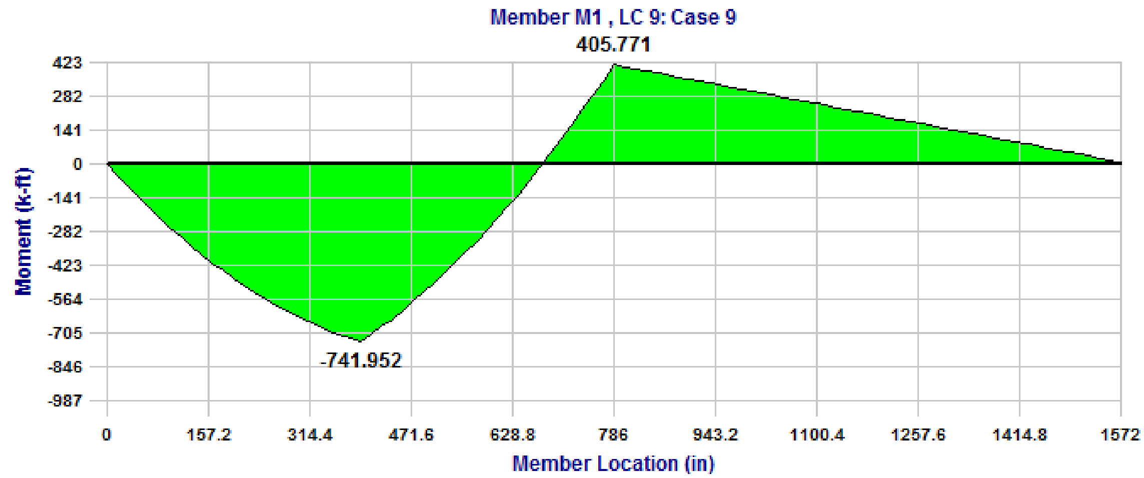
Case 8 – Combined Case 1 & Case 3



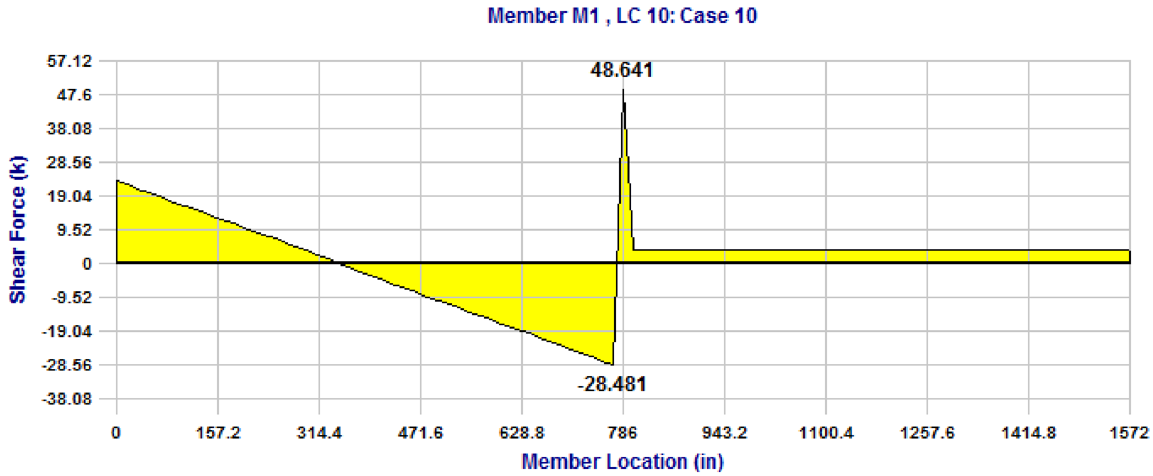


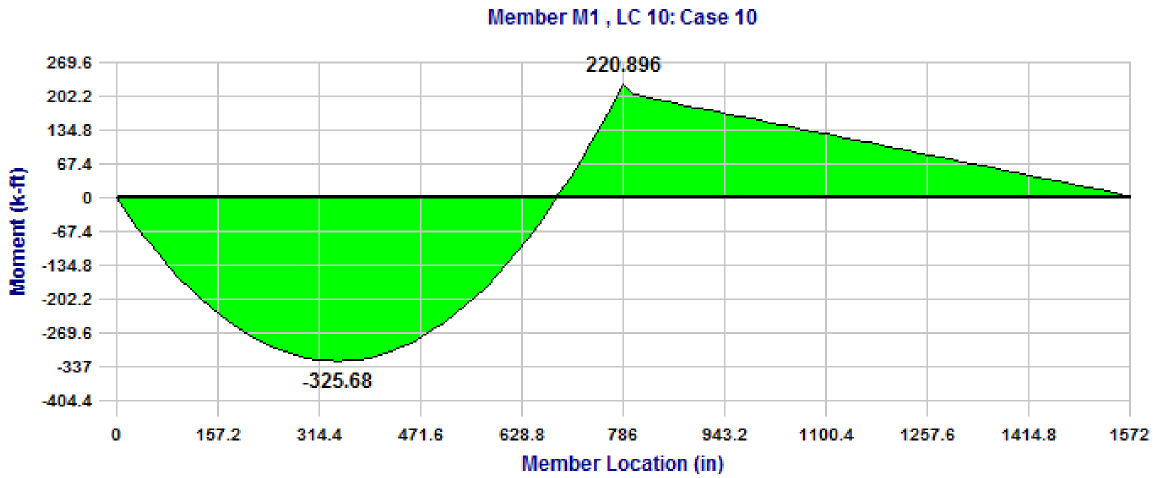
Case 9 – Combined Case 3 & Case 4



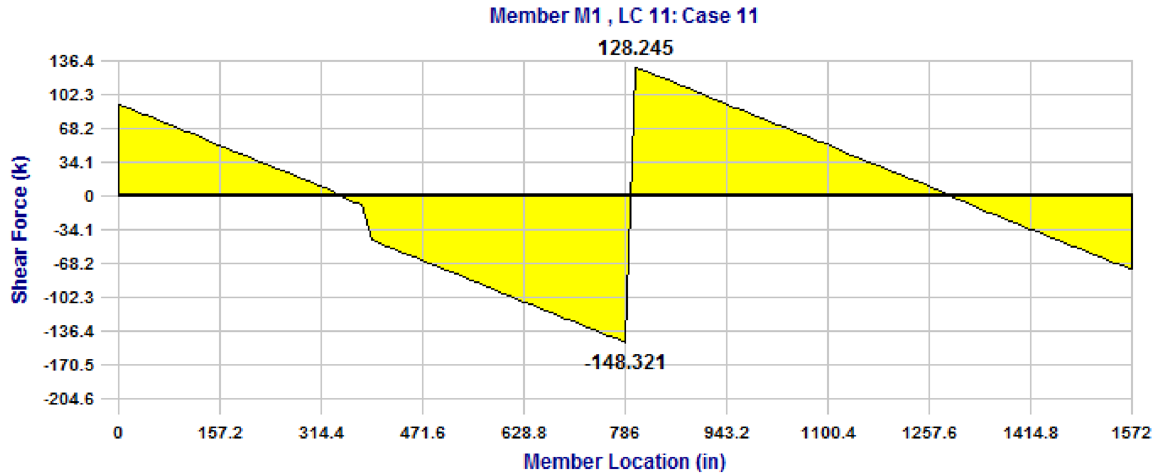


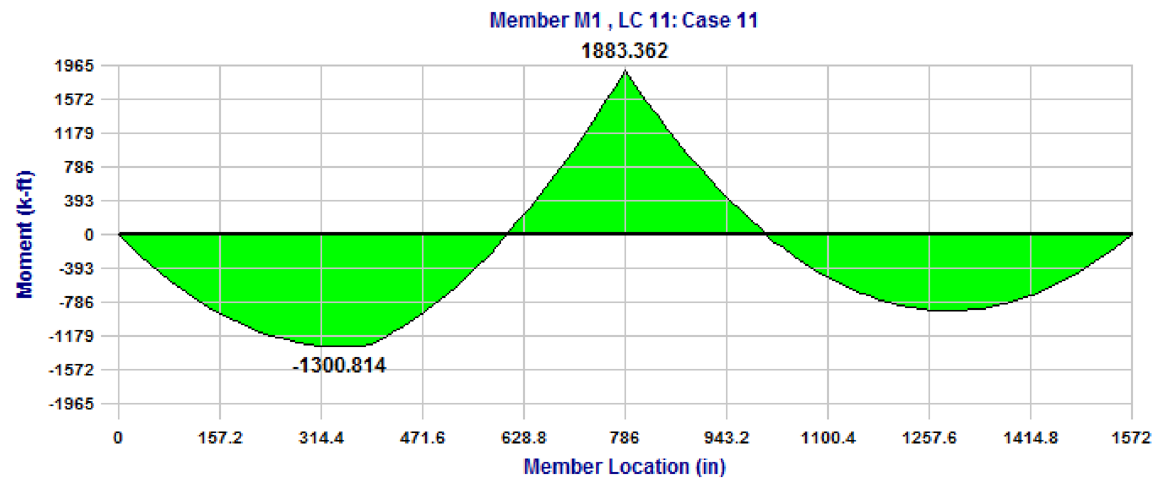
Case 10 - Combined Case 3 & Case 6



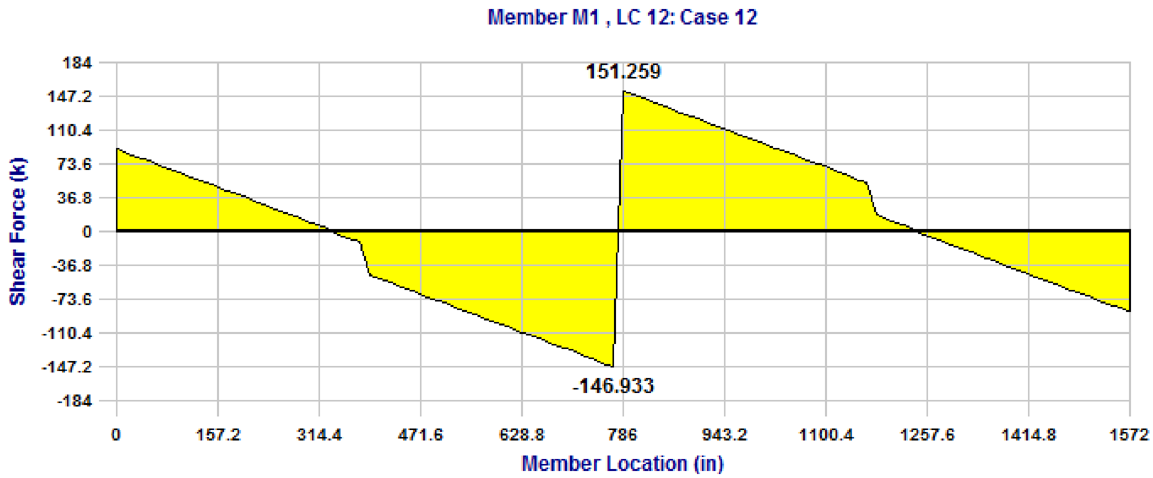


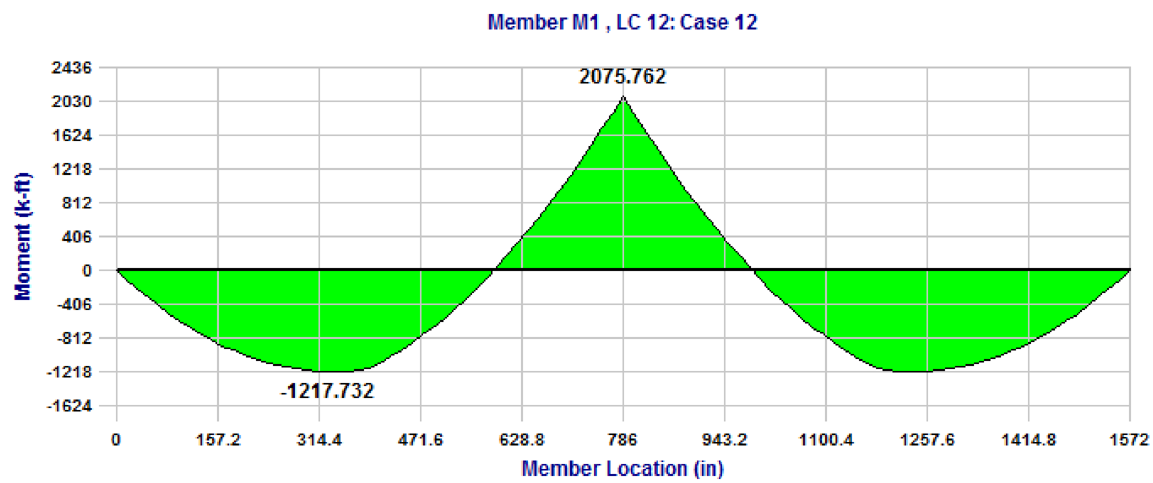
Case 11 – Combined Case 1, Case 2, & Case 4



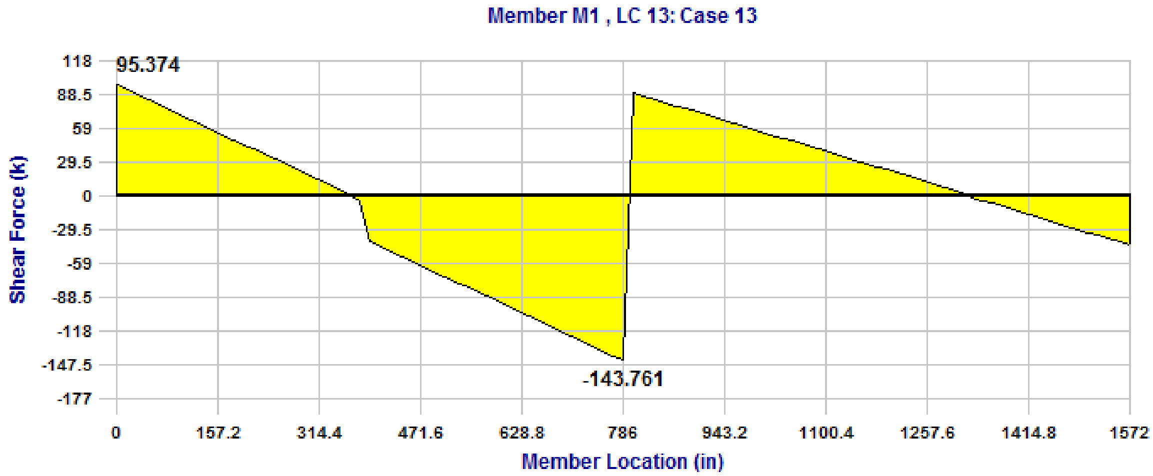


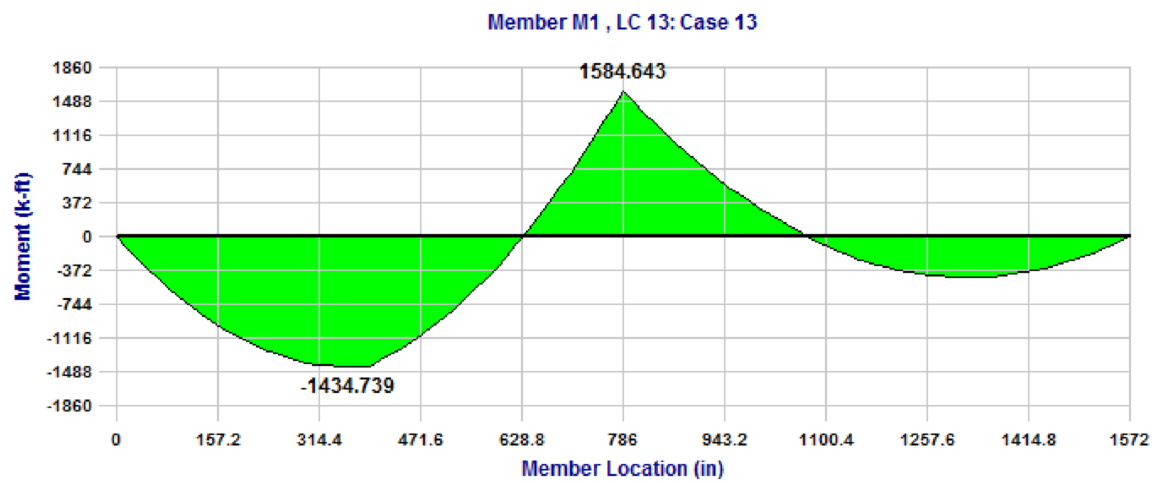
Case 12 – Combined Case 1, Case 2, & Case 5



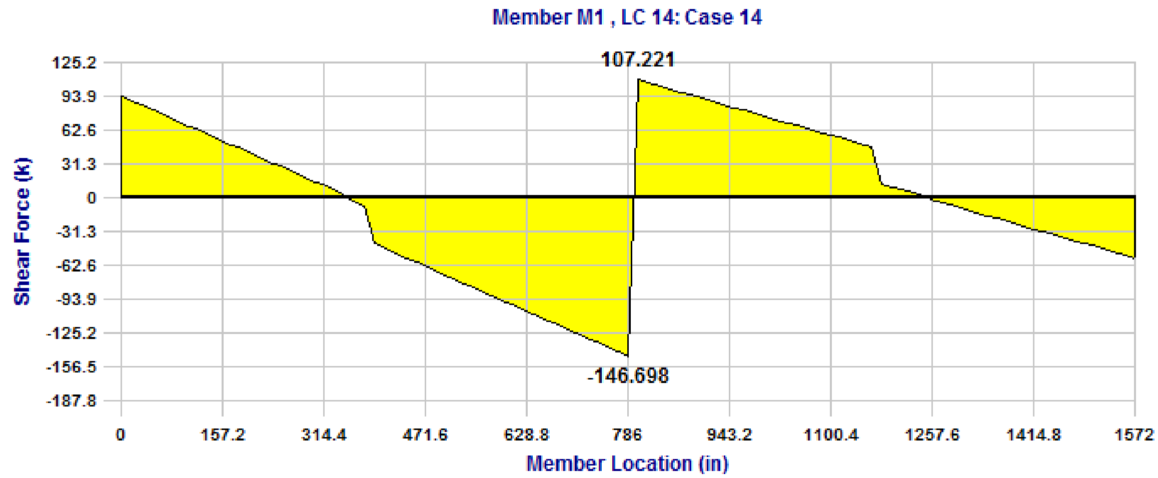


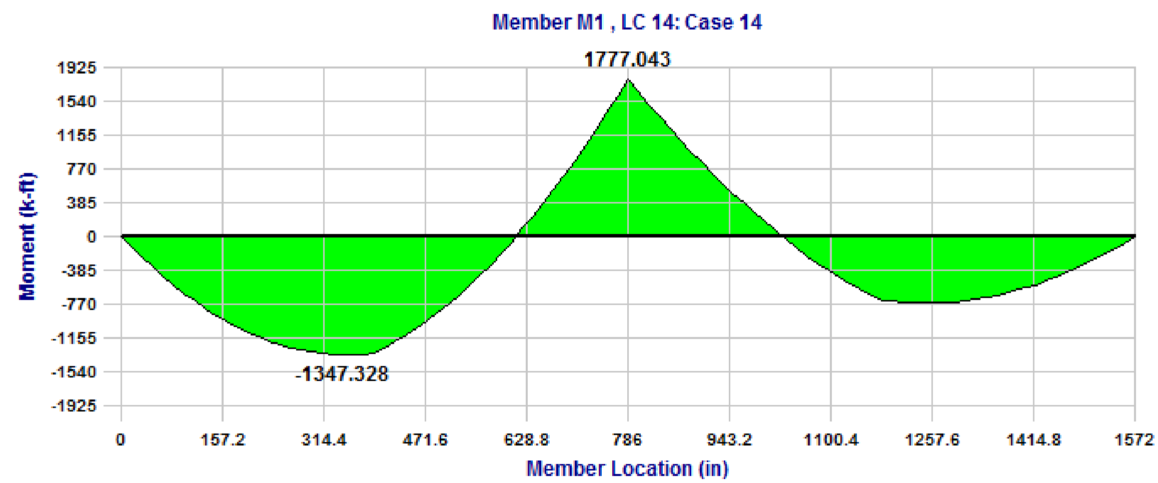
Case 13 – Combined Case 1, Case 3, & Case 4





Case 14 – Combined Case 1, Case 3, & Case 5





Appendix G: Microsoft Excel Deck Design Template

	(AASHTO STable 3.4.1-1)	
load factor for live load	1.75	
	(AASHTO STable A4.1-1)	
maximum unfactored live load moment		k-ft/ft
$M_{u\text{-}pos\text{-}live}$ =	0	k-ft/ft
$M_{u\text{-}pos\text{-}dead}$ =	0	k-ft/ft
$M_{u\text{-}pos\text{-}total}$ =	0	k-ft/ft

DESIGN FOR NEGATIVE MOMENT

(AASHTO STable A4.1-1)

* use distance of 0" from centerline

maximum unfactored live load moment		k-ft/ft
$M_{u\text{-}neg\text{-}live}$ =	0	k-ft/ft
$M_{u\text{-}neg\text{-}dead}$ =	0	k-ft/ft
$M_{u\text{-}neg\text{-}total}$ =	0	k-ft/ft

DESIGN FOR POSITIVE FLEXURE IN DECK

bar size		
bar diameter		in
bar area	0	in^2
bottom cover		in
top cover		in
Φ_f =		
b =		in
d_e =	0	in
Rn =	0	k/in^2
ρ =	0	
A_s =	0	in^2/ft
β_1 =		
required bar spacing		in
use		in
T =	0	k
a =	0	in

C =	0	in
C/d_e =	0	in

ok if ≤ 0.76

DESIGN FOR NEGATIVE FLEXURE IN DECK

d_e =	0	in
Rn =	0	k/in^2
ρ =	0	
A_s =	0	in^2/ft

required bar spacing		in
use		in

T =	0	k
a =	0	in
C =	0	in
C/d_e =	0	in

ok if ≤ 0.76

Appendix H: Microsoft Excel Non-Composite Girder Design Template

ϕ_b =	0.90	
F_y =		ksi
E =	29000	ksi
dead load factor	1.2	
live load factor	1.6	
M_u (from RISA 2-D) =		ft-k

DETERMINE MEMBER SIZE

(AISC Steel Manual Table 3-2)

Z_x =	#DIV/0!	in^3

shape		
weight		k
Z_x		in^3
$b_f/2t_f$		
h/t_w		

CALCULATE CAPACITY INCLUDING GIRDER WEIGHT

M_u (from RISA 2-D) =		ft-k
ΦM_p =	0	ft-k

ok if $\Phi M_p > M_u$

CHECK PLASTIC CAPACITY CONDITIONS

FLB	ok if FLB ≤ 9.2
WLB	ok if WLB ≤ 90.6

Appendix I: Microsoft Excel Composite Girder Design Template

smaller value governs		ft
Span		
weight of wet concrete	145	pcf
construction live load	20	psf
weight of girder		lb/ft
thickness of slab		in
tributary width	0	ft
factor for ponding	1.1	
dead load factor	1.2	
live load factor	1.6	
number of girders		
f'c		ksi
M_u (from RISA 2-D)		ft-k
F_u =		ksi
length of girder		ft

CALCULATE FACTORED LOAD

w_u = #DIV/0! lb/ft

CALCULATE FACTORED MOMENT

M_u = #DIV/0! ft-k

SELECT TRIAL BEAM SIZE

(AISC Steel Manual Table 3-19)

Size		
Weight		lb/ft
$\Phi_b M_p$ =		ft-k

CHECK CONSTRUCTION STRENGTH

RE-CALCULATE FACTORED LOAD

w_u = #DIV/0! lb/ft

RE-CALCULATE FACTORED MOMENT

M_u = #DIV/0! ft-k

ok if $\Phi_b M_p \geq M_u$

CHECK CONSTRUCTION DEFLECTION

(AISC Steel Manual Table 1-1)

I_x = [ ] in^4

(AISC Steel Manual Figure 3-2)

C_1 = [ ]

Δ_{con} = #DIV/0! in

ok if $\Delta \leq 2.2$

COMPOSITE CAPACITY

(AISC Steel Manual Table 3-19)

PNA [ ]

$\sum Q_n$ = [ ] k

a = #DIV/0! in

ok if $a \leq t_s$

$Y_{con} = t_s$ 0

Y_1 [ ] in

Y_2 #DIV/0! in

INTERPOLATE TO FIND $\Phi_b M_p$

		ft-k
		ft-k

$\Phi_b M_p$ = #DIV/0! ft-k

ok if $\Phi_b M_p \geq M_u$

AMOUNT OF SHEAR STUDS REQUIRED

d_s = [ ] in

Q_n = 0.0 ft-k

(AISC Steel Manual Table 3-21)

n = #DIV/0! studs

[ ] studs

STUD SPACING

minimum 0 in

*maximum 0 in or 36 in

*smaller value governs

spacing	#DIV/0!	in
4.5 in ≤ in ≤ 36 in		

COMPUTE LIVE LOAD DEFLECTION

INTERPOLATE TO FIND I_{LB}

(AISC Steel Manual Table 3-20)

0		in^4
0		in^4

I_{LB} = #DIV/0! in^4

CALCULATE UNFACTORED LOAD

w_u = #DIV/0! lb/ft

CALCULATE UNFACTORED MOMENT

M_u = #DIV/0! ft-k

Δ_{LL} = #DIV/0! in

ok if $\Delta_{LL} \leq 2.2$ in

Appendix J: Microsoft Excel Concrete Column Design Template

Column Design: Square Tied

DETERMINE AXIAL LOAD			
V		k	
Pu=2V		k	
f'c		ksi	
Fy		ksi	
S (spacing of columns)		ft	
SLENDERNESS RATIO			
K			
L		ft	
KL/22*0.3	0		
Select Colum Size (nearest foot)		inches	
REINFORCEMENT			
Pmin			
Pmax			
As=ρminAg	0	in2	
Select Reinforcement Bar Size		in 2	**6#14 Bars**
CHECK LOAD CAPACITY			
ϕPn=0.8(0.85f'c(Agc-Ag)+FyAg)	0		
ϕPn>Pu	0	0	
TIES			
Trial Dtie		in	
Dbars		in	
SPACING OF TIES			
Dcolumn		in	
16Dbars	0	in	
48Dties	0	in	
Select Smallest Value		in	
SPACING OF BARS			
H		in	
Cover		in	
Number of Spaces			
S=(h-2cover-2Dties-2(Dbars/2))/spaces	0	in	
Select Reinforcement Spacing		in	

Appendix K: Consigli Construction Waste Management Plan Template

Waste Management Plan

General Contractor: **Project:**

Designated Waste Management Coordinator:

WASTE MANAGEMENT GOALS:

- This project will recycle, reuse, or salvage at least XX% of the waste generated on-site.

COMMUNICATION PLAN:

- Waste prevention and recycling activities will be discussed at each job site meeting with *GENERAL CONSTRACTOR* employees and subcontractors.
- All *GENERAL CONTRACTOR* employees have been notified of *GENERAL CONTRACTOR'S* Source Separation & Recycling Plan on all *GENERAL CONTRACTOR'S* projects and are obligated to comply with the plan.
- All *GENERAL CONTRACTOR* employees and subcontractors will receive a copy of this Waste Management Plan (WMP) for *PROJECT NAME*.
- The subcontract used for this project clearly requires all subcontractors to comply with *GENERAL CONTRACTOR'S* Source Separation and Recycling Plan.
- Any incidence of contamination of source separated waste materials by a subcontractor will result in a $XXX fine (per the subcontract.)
- All recycling containers will be clearly labeled.
- GENERAL CONTRACTOR will submit detailed monthly reports documenting types and quantities (tons) of materials recycled, reused, salvaged, and disposed.

Appendix L: Construction Cost Estimate

Determine Quantity of Items

DECK

Deck Slab- 8"

Length (ft)	Width (ft)	Unit (SF)
131	48	6288.00

Bituminous Concrete Wearing Surface

Length (ft)	Width (ft)	Depth (ft)	Unit (CY)
131	48	0.21	48.52

Granite Curbing

Length (ft)	Quantity	Unit (LF)
131	2	262

Sidewalk

Length (ft)	Width (ft)	Quantity	Unit (SF)
131	4	2	1048

Railings

Length (ft)	Quantity	Unit (LF)
131	2	262

Guard Rail

Length (ft)	Quantity	Unit (LF)
131	2	262

Asphalt Pavement

Length (ft)	Width (ft)	Unit (SF)
131	48	6288

SUPERSTRUCTURE

Girders

Size	Length (ft)	Quantity	Spans	Unit (LF)
W40x199	131.00	8	2	2096
W40x211	131.00	8	2	2096
W40x215	131.00	8	2	2096
W40x235	131.00	8	2	2096
W36x247	131.00	8	2	2096
W36x231	131.00	8	2	2096
W36x232	131.00	8	2	2096

Bearings

Unit (EA)
32

SUBSTRUCTURE

Abutment

Length (ft)	Width (ft)	Depth (ft)	Quantity	Unit (CY)
60	14	3.00	2	186.67
60	4.333	16.00	2	308.15
			Total	494.81

Wingwall

Length (ft)	Width (ft)	Depth (ft)	Quantity	Unit (CY)
60	28	3.00	4	746.67
28	2	16	4	132.74
27.5	1.5	5	4	30.56
0.5	1.5	5	4	0.56
			Total	910.52

Column

D (ft)	Depth (ft)	Quantity	Unit (Tons)
3	16.00	2	16.40

Girder Cost Estimate

COST OF SHEAR CONNECTORS							
GIRDER SIZE	PNA	NO. STUDS	NO. GIRDERS	NO. SPANS	UNIT	COST/UNIT ($)	TOTAL
W40x199	0	224	8	2	EA	$ 1.29	$ 4,623.36
	2	193	8	2	EA	$ 1.29	$ 3,983.52
	3	161	8	2	EA	$ 1.29	$ 3,323.04
	4	128	8	2	EA	$ 1.29	$ 2,641.92
W40x211	0	238	8	2	EA	$ 1.29	$ 4,912.32
	2	206	8	2	EA	$ 1.29	$ 4,251.84
	3	174	8	2	EA	$ 1.29	$ 3,591.36
	4	142	8	2	EA	$ 1.29	$ 2,930.88
W40x215	0	243	8	2	EA	$ 1.29	$ 5,015.52
	2	207	8	2	EA	$ 1.29	$ 4,272.48
	3	170	8	2	EA	$ 1.29	$ 3,508.80
	4	133	8	2	EA	$ 1.29	$ 2,745.12
W40x235	0	265	8	2	EA	$ 1.29	$ 5,469.60
	2	229	8	2	EA	$ 1.29	$ 4,726.56
	3	193	8	2	EA	$ 1.29	$ 3,983.52
	4	157	8	2	EA	$ 1.29	$ 3,240.48
W36x247	0	279	8	2	EA	$ 1.29	$ 5,758.56
	2	236	8	2	EA	$ 1.29	$ 4,871.04
	3	193	8	2	EA	$ 1.29	$ 3,983.52
	4	150	8	2	EA	$ 1.29	$ 3,096.00
W36x231	0	261	8	2	EA	$ 1.29	$ 5,387.04
	2	222	8	2	EA	$ 1.29	$ 4,582.08
	3	182	8	2	EA	$ 1.29	$ 3,756.48
	4	142	8	2	EA	$ 1.29	$ 2,930.88
W36x232	0	262	8	2	EA	$ 1.29	$ 5,407.68
	2	225	8	2	EA	$ 1.29	$ 4,644.00
	3	188	8	2	EA	$ 1.29	$ 3,880.32
	4	152	8	2	EA	$ 1.29	$ 3,137.28

COST OF GIRDERS AND SHEAR CONNECTORS			
GIRDER SIZE	PNA	NO. STUDS	TOTAL
	0	224	$ 418,000.00
	2	193	$ 417,000.00
	3	161	$ 416,000.00
W40x199	4	128	$ 416,000.00
	0	238	$ 440,880.32
	2	206	$ 440,219.84
	3	174	$ 439,559.36
W40x211	4	142	$ 438,898.88
	0	243	$ 449,367.52
	2	207	$ 448,624.48
	3	170	$ 447,860.80
W40x215	4	133	$ 447,097.12
	0	265	$ 487,549.60
	2	229	$ 486,806.56
	3	193	$ 486,063.52
W40x235	4	157	$ 485,320.48
	0	279	$ 506,702.56
	2	236	$ 505,815.04
	3	193	$ 504,927.52
W36x247	4	150	$ 504,040.00
	0	261	$ 476,987.04
	2	222	$ 476,182.08
	3	182	$ 475,356.48
W36x231	4	142	$ 474,530.88
	0	262	$ 478,055.68
	2	225	$ 477,292.00
	3	188	$ 476,528.32
W36x232	4	152	$ 475,785.28

GIRDER COST ESTIMATE				
GIRDER SIZE	COST/UNIT	UNIT	QUANTITY	TOTAL
W40x199	$ 197.00	LF	2096	$ 412,912.00
W40x211	$ 208.00	LF	2096	$ 435,968.00
W40x215	$ 212.00	LF	2096	$ 444,352.00
W40x235	$ 230.00	LF	2096	$ 482,080.00
W36x247	$ 239.00	LF	2096	$ 500,944.00
W36x231	$ 225.00	LF	2096	$ 471,600.00
W36x232	$ 225.50	LF	2096	$ 472,648.00

Final Construction Cost Estimate

ITEM	UNIT	QUANT	COST/UNIT ($)	TOTAL	DIVISON	SOURCE
DECK						
CONCRETE IN PLACE-REGULAR CONCRETE 8" SLAB	SF	6288.00	$ 3.00	$ 19,000.00	03310-240-3200*	RS MEANS pg. 159
GRANITE CURBING 6"x18"	LF	262	$ 17.01	$ 4,000.00	02700-500-1100	RS MEANS pg. 106
BITUMINOUS CONCRETE 2.5" THICK	LF	48.52	$ 5.50	$ 300.00	02710-100-0500*	RS MEANS pg. 102
SIDEWALK 6" THICK	SF	1048	$ 3.57	$ 4,000.00	02775-275-0400	RS MEANS pg 106
FENCE CHAIN LINK INDUSTRIAL 9 GA. ALUMINIZED	LF	262	$ 18.38	$ 5,000.00	02820-130-0300	RS MEANS pg 111
BRIDGE RAILINGS STEEL, GALV PIPE, 3 LINE W/ SCREEN	LF	262	$ 303.76	$ 80,000.00	02850-205-4200	RS MEANS pg. 119
ASPHALTIC CONCRETE PAVEMENT, HIGHWYS 4"	SY	698.67	$ 8.06	$ 6,000.00	02740-310-0200	RS MEANS pg. 103
SUPERSTRUCTURE						
ROLLED STEEL BEAM GIRDER	LF			$ 416,000.00	05120-640-*	RS MEANS pg. 194
BEARING WITH ELASTOMERIC PADS	EA	32	$ 3,000.00	$ 96,000.00		CTDOT
SUBSTRUCTURE						
PREFABRICATED ABUTMENT	CY	494.81	$ 263.10	$ 130,000.00	02850-205-1050	RS MEANS pg. 118
PREFABRICATED WINGWALL	CY	910.52	$ 327.75	$ 298,000.00	02850-205-1100	RS MEANS pg. 118
COLUMNS REINFORCING IN PLACE 24"-36" DIAMETER	TONS	16.40	$ 1,555.00	$ 26,000.00	03210-600-0330	RS MEANS pg. 154
			TOTAL COST:	$ 1,058,300.00		