# Bridge Life Cycle Cost Optimization

## Analysis, Evaluation, & Implementation

MOHAMMED ABED EL-FATAH SAFI

Master of Science Thesis

Stockholm, Sweden 2009

KTH Architecture and
the Built Environment

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TRITA-BKN. Master Thesis 278
Structural Design and Bridge, 2009
ISSN 1103-4297
ISRN KTH/BKN/EX-278-SE

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Stockholm, Sweden, 2009

Cover photo: Svinesund bridge between Sweden and Norway - right is Sweden, left is Norway.

# PREFACE

This master thesis is devoted as a research study within ETSI project. ETSI project is contributed between three Nordic countries, Sweden, Norway, and Finland. The main goals of the ETSI project are to develop a Nordic unified methodology and computer program for bridge LCC evaluation.

After thanking God for granting me the strength and the will to fulfill the targets of this research study, I would like to express my sincere thanks and hopes to my darling home country (The occupied Palestine/Gaza), my parents, and my family who have instilled in me the drive and encouragement to complete this work.

I would like to express my sincere appreciation and gratitude to my supervisors, Prof. Håkan Sundquist & Dr. Hans Åke Mattsson, for their invaluable guidance, patience, kindness, and encouragement throughout the work of my master thesis. It has been great honor to work with them and to learn from their experience.

I want here to greatly appreciate my previous degree supervisors in Egypt, Prof. Baher Abou Stait & Dr. Ahmed Al-Laithy, for their invaluable guidance and assistants to join KTH.

Finally, I would also like to acknowledge and thank everybody that has contributed to my pleasant time at KTH during my master studies.

Stockholm, Sweden, Jun 2009

*Mohammed Safi*

## ABSTRACT

Decisions related to implementation of a bridge design proposal generally require that several alternatives be considered. Many factors contribute to an agency's decision to select a particular proposal. Although the initial project costs may dominate this decision, initial agency costs, however, tell only a part of the story.

Currently, almost only functional performance and conventional financial costing guides the design of a new bridge. A new life cycle framework to integrate all bridge life cycle considerations like the aesthetical and cultural value, and the environmental impact with the economic issues become very essential for achieving sustainable infrastructure.

This research study demonstrates a unique methodology and present a new systematic way for analysis, evaluation, and optimization of the bridge life cycle indicators. This study is presenting a unique flexible system, integrating all of bridge life cycle issues, and making them measurable and comparable like the bridge initial cost.

One of the main aims of bridge projects is to preserve the harmony of the scenery and the surrounding context. Aesthetics is not something that can be added on at the end. For aesthetics to be successful, it must first be considered as an integral part of the design. Basic bridge aesthetics design guidelines were proposed, which intended to set down considerations and principles, which help in eliminating the worst aspects of bridge design and encourage the best.

Based on this unique evaluation system, two computer programs were developed to facilitate the usage, one for calculating the bridge user cost and one to evaluate the bridge aesthetical and cultural value. The application of this integrated model to bridge design highlighted a critical importance of using the life cycle modeling in order to enhance the sustainability of bridge infrastructure systems.


**Keywords:** life cycle cost analysis, aesthetical and cultural value, user cost, life cycle assessment

# DENOMINATIONS AND ABBREVIATIONS

| | |
|---|---|
| $LCC$ | Life cycle cost |
| LCCA | Life cycle cost analysis |
| LCA | Life cycle assessment |
| SRA | Swedish Road Administration |
| Finnra | Finnish Road Administration |
| BMS | Bridge Management System |
| BaTMan | Bridge and Tunnel Management System (SRA's BMS since 2004) |
| $C_{AG}$ | Corresponding Agency cost |
| $C_{USER}$ | Corresponding User cost |
| $C_{RACV}$ | Corresponding Relative Aesthetical and Cultural Value cost |
| $C_{REI}$ | Corresponding Relative Environmental Impact cost |
| $k_{AES}$ | Aesthetical and cultural coefficient |
| $k_{EI}$ | Environmental impact coefficient |
| $C_{REI}$ | Corresponding Relative Environmental Impact cost |
| $T$ | Travel time delay for one vehicle in case of work zone |
| $ADT_t$ | Average daily traffic at time t |
| $N_t$ | Number of days needed to perform the work at time t |
| $C_F$ | Average cost per fatal deaths accident for the society |
| $C_I$ | Average cost per serious injury accident for the society |
| $w_T$ | Hourly time value for one truck |
| $w_p$ | Hourly time value for one passenger care |
| $O_T$ | Average hourly operating cost for one truck including its goods operation |
| $O_P$ | Average hourly operating cost for one passenger care |
| $A_n$ | Bridge accident rates during the normal condition |
| $A_a$ | Bridge accident rates during the work activities |

# CONTENTS

# 1. INTRODUCTION

## 1.1 General Background

Decisions related to implementation of a transportation improvement generally require that several alternatives be considered. Many factors contribute to an agency's decision to select a particular option, although initial project costs may dominate this decision. Initial agency costs, however, tell only part of the story.

The idea behind this study is that, bridges investment decisions should consider all of the costs and considerations incurred during the period over which the alternatives are being compared. Bridges are required to provide service for many years. The ability of a bridge to provide service over time is predicated on its being maintained appropriately by the agency. Thus the investment decision should consider not only the initial activity that creates a public good, but also all future activities that will be required to keep that investment available to the public. It is important to note that the lowest agency cost option may not necessarily be implemented when other considerations such as aesthetical and cultural value, user cost, and environmental concerns are taken into account.

## 1.2 Objective

This study was designed firstly to expose the principles of bridge life cycle cost (BLCC) and identify all of relevant affected parameters, secondly to separately focus on each life cycle consideration and deeply illustrate the methodology of assessing its impacts on the whole BLCC.

The most important part of this study is the unique systematic way of converting all of the theoretical data and parameters to a simple numerical calculations system which is relating the aesthetical and cultural values, and the environmental impact with the other important aspects of bridge like functionality, economics and techniques. When doing so, facilitate the implementation of the optimization process.

The final goal is to create a simple compromise computer program, which is based on these data and parameters and providing a simple optimization process to help the design makers to chose the optimum alternative.

## 1.3 Definitions

Life Cycle Cost (LCC):
Technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value. Where the term uses initial capital letters it can be defined as the present value of the total cost of an asset over the period of analysis.

Life-Cycle Cost Analysis (LCCA):
LCCA is a cost-centric approach used to select the most cost-effective alternative that accomplishes a preselected project at a specific level of benefits that is assumed to be equal among project alternatives being considered. All of the relevant costs that occur throughout the life of an alternative, not simply the original expenditures, are included.

Benefit-Cost Analysis (BCA):
BCA is the appropriate tool to use when design alternatives will not yield equal benefits, such as when unlike projects are being compared or when a decision-maker is considering whether or not to undertake a project. The elements typically included in LCCA and BCA are listed below.

Differences between (LCCA) and (BCA):
The agency that uses LCCA has already decided to undertake a project or improvement and is seeking to determine the most cost-effective means to accomplish the project's objectives.
LCCA is appropriately applied only to compare project implementation alternatives that would yield the same level of service and benefits to the project user at any specific volume of traffic.

Unlike LCCA, BCA considers the benefits of an improvement as well as its costs and therefore can be used to compare design alternatives that do not yield identical benefits (e.g., bridge replacement alternatives that vary in the level of traffic they can accommodate), as well as to compare projects that accomplish different objectives (a road realignment versus a widening project). Moreover, BCA can be used to determine whether or not a project should be undertaken at all (i.e., whether the project's life-cycle benefits will exceed its life-cycle costs).

Life Cycle Assessment (LCA):
Tool for identifying and evaluating the environmental aspects of products and services from the "cradle to the grave": from the extraction of resource inputs to the eventual disposal of the product or its waste. Life Cycle Assessment LCA is for assessing the total environmental impact associated with a product's manufacture, use and disposal and with all actions in relation to the construction and use of a building or other constructed facilities. LCA does not address economic or societal aspects!

## 1.4 Terminology

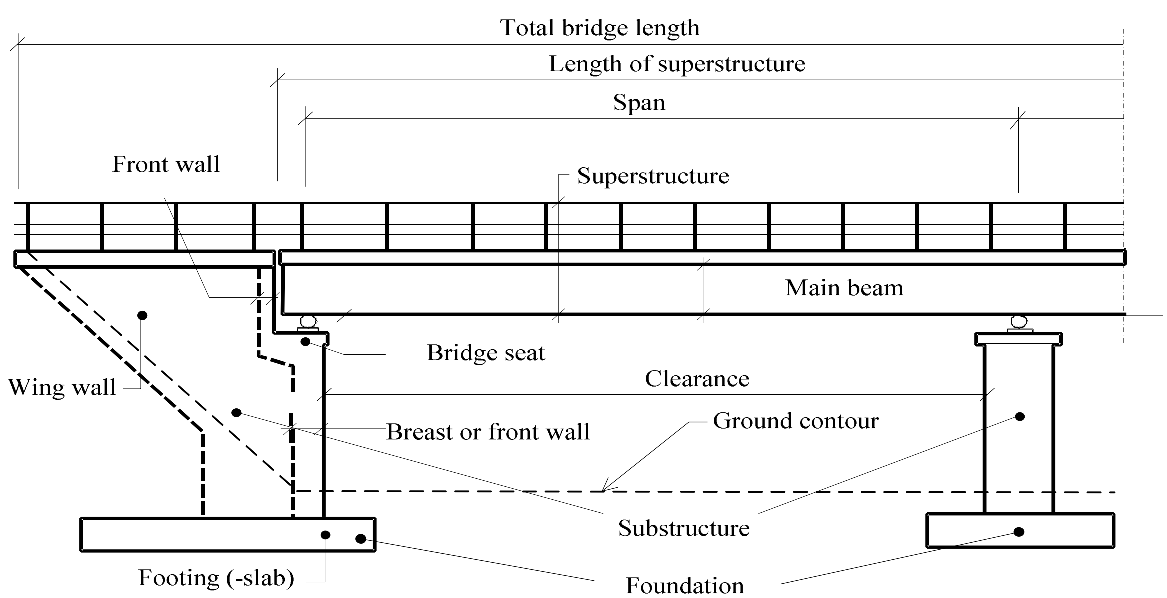



**Figure 1:1** *Bridge breakdown components titles*

**Table 1:1** *Bridge breakdown components name*

Superstructure :
The part of structure which supports traffic (include deck , slab, and girders)

Deck :
bridge floor directly carrying traffic loads

Hunching :
Increase in the depth of a continuous beam at the point of support to withstand the increased moment of bending on the beam.

Transition pier
Pier separating different superstructure types

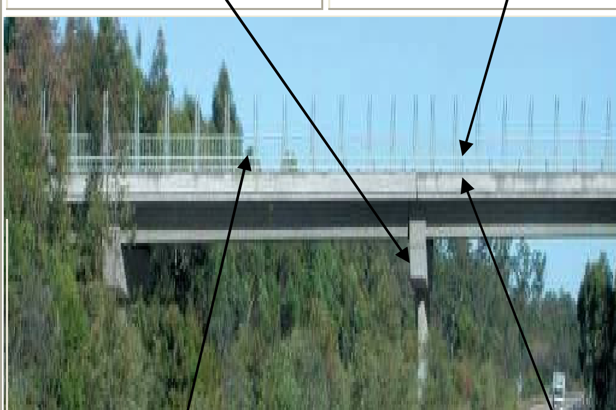
Substructure
That part of the structure, i.e. piers and abutments, which supports the superstructure and transfers load to the foundations

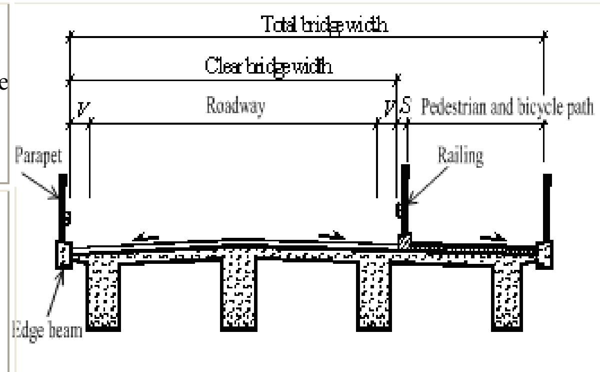
Bearing
A component which transmits forces from that par t to another part

Abutment
The part of the structure which supports the superstructure at its extremities and retains earth works.

Pier Cap / Headstock :
A component which transfers loads from the multiple girders to the pier.

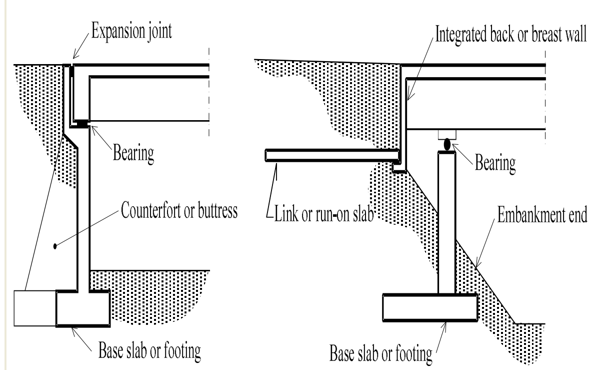
Safety / throw screen :
protective fence to deter the launching of objects from the bridge onto the highway below






Pedestrian barrier

Traffic barrier :
Parapet – low protective concrete wall at edge of bridge deck.



# 2. AGENCY COST

## 2.1 Bridge LCC Classification Scheme

There are two primary reasons for establishing a life-cycle cost classification or taxonomy when evaluating bridges. First, the classification insures that all costs associated with the project are taken into account. Second, the classification scheme allows for a detailed, consistent breakdown of the life-cycle cost and net savings estimates at several levels so that a clear picture can be had of the respective cost differences between material/design alternatives.

The third benefit of this life-cycle cost classification is that, actual construction costs classified by the same structural elements can be used to compile historical unit cost data on bridge element costs to be used in future life-cycle cost analyses.

## 2.2 Costs by the Entity that Bears the Cost (Level 1)

In this level, the costs can be divided as shown in Figure 2:1 below, and will discuss in he following subsections.

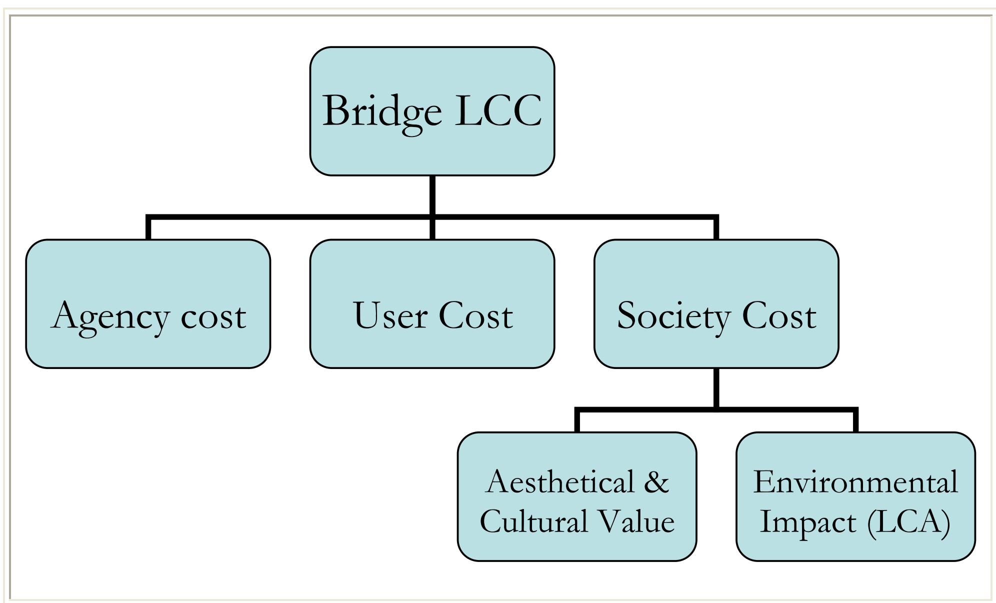



**Figure 2:1** *Cost by the Entity that Bears the Cost (Level 1)*

### 2.2.1 Agency Costs

Agency costs are all costs incurred by the project's owner or agent over the study period. These include but are not limited to design costs, capital costs, insurance, utilities, and servicing and repair of the facility. Agency costs are relatively easy to estimate for conventional material/designs since historical data on similar projects reveal these costs, will discuss it later in this chapter.

### 2.2.2 User Costs

User costs accrue to the direct users of the project. For example, bridge construction often causes congestion and long delays for private and commercial traffic. New bridge construction impacts traffic on the highway over which it passes. Maintenance and repair of an existing bridge, along with the rerouting of traffic, can impact drivers' personal time, as well as the operating cost of vehicles sitting in traffic. Accidents, involving harm to both vehicles and human life, tend to increase in road work areas; will deeply discuss it later in this chapter (3).

### 2.2.3 Society Costs or Third-Party Costs

Third-party or spillover costs are all costs incurred by entities who are neither the agency/owners themselves nor direct users of the project. One example is the lost sales for a business establishment whose customer access has been impeded by construction of the project, or whose business property has been lost through the exercise of eminent domain. A second example is cost to humans and the environment from a construction process that pollutes the water, land, or atmosphere. These costs can be subdivided into two main categories:

***Bridge Aesthetical & Cultural Value (ACV)***

Some projects have exceeded all cost estimates but still it has been possible to fulfill them with success. One of the main aims of bridge projects is to preserve the harmony of the scenery. Location of a bridge, cultural values of the surroundings, landscape and the viewpoints of local people have influence on the goals that are set to a bridge in the beginning of a project. Bridges are often seen more or less as sculptures and icons which the citizens may relate with the soul of the city. This atmosphere and the will to identify the town and its values with an icon may motivate for bold and spectacular solutions.

So, absolutely there is a hidden value for the external appearance and the beauty of the bridge, it should be considered during the design and in the LCCA process. This value is called the ACV.

It is not the intention to provide a formula for good design. Rather it is the intention to set down considerations and principles, which will help, eliminate the worst aspects of bridge design and encourage the best, will deeply discuss it later in this chapter (4).

***Bridge Environmental Impact (LCA)***

Environmental impact categories evaluated include energy and material resource consumption, air and water pollutant emissions, solid waste generation, energy use, fuel consumption, and emissions for the traffic. Life cycle assessment is an analytical technique for evaluating the full environmental burdens and impacts associated with a product system, will deeply discuss it later in this chapter (5).

## 2.3 Costs by LCC Category (Level 2)

Level 2 groups the costs according to the life-cycle categories which, in KTH we agreed to classify them ascending by there occurrence during the bridge life cycle, with these proposed titles as follow:

- Investment Cost (Purchasing, Construction, & Installation)
- Operation & Maintenance Cost

- Inspection Cost
- Repair/Rehabilitation & Replacement Cost
- End of life Management Cost (Demolition and Landscaping)

Historical agency data are only one mechanism that may be used to feed LCCA input needs. The expert opinion of senior agency staff members can also provide a wealth of information for investment analyses, as can research conducted by industry and government. Still, the agency will have to devote resources toward the development and validation of data sources for LCCA inputs, as well as toward learning how to use those sources.

### 2.3.1 Investment Cost (Purchasing, Construction, & Installation)

An example of historical agency data for bridge investment costs can be as shown in following table:

**Table 2:1** *Investment Feedbacks and Recommendation*

| Investment (Purchasing, Construction,& Installation) | | | | | |
|---|---|---|---|---|---|
| The Action Name | Service Life (*Year*) | Average Required Unit Duration | | | Average Cost |
| | | Value | Unit | From | |
| Prefabricated Prestressed concrete bridges | 100 | 0.12 | day/m$^2$ | The Bridge Area | ?! |
| Convential reinforced concrete bridges | 80 | 0.15 | day/m$^2$ | The Bridge Area | |
| Steel Structures | 70 | 0.1 | day/m$^2$ | The Bridge Area | |
| Timber Bridges | 50 | 0.12 | day/m$^2$ | The Bridge Area | |

### 2.3.2 Operation & Maintenance

<u>**Operation**</u>**: -** The preservation and upkeep of a structure, including all its appurtenances, in its original condition (or as subsequently improved). Maintenance includes any activity intended to "maintain" an existing condition or to prevent deterioration. Examples include: cleaning, lubricating, painting, and application of protective systems.

<u>**Maintenance**</u>**: -** The minor repair and preventative maintenance activities necessary to maintain a satisfactory and efficient structure, usually prescheduled maintenance and repair activities.

An example of historical agency data for bridge operation and maintenance costs can be as shown in following table:

**Table 2:2** *Operation & Maintenance Feedbacks and Recommendation*

| Operation & Maintenance activities | | | | | |
|---|---|---|---|---|---|
| The Action Name | Recommended Intervals(*Year*) | Average Required Unit Duration | | | Average Cost % From The Agency Cost |
| | | Value | Unit | From | |
| Cleaning the bridge of salt | 1 | 0.05 | hr/m$^2$ | Bridge Area | ,05 |
| Cleaning & rodding of the drainage system | 1 | 0.2 | hr/m | Bridge Length | |
| Maintenance of parapets,gardrail& railings | 1 | 0.5 | hr/m | Bridge Length | |
| Maintenance of surface finish and laning | 1 | 0.5 | hr/m$^2$ | Bridge Area | |
| Dehumidification, electricity and maintenance | 1 | 0.5 | hr/m$^2$ | Bridge Area | |
| Protection against scour | 1 | 0.2 | hr/m$^2$ | Bridge Area | |
| Improvement of painting | 10 | 2 | hr/m$^2$ | Bridge Area | |

### 2.3.3 Inspection

The main purpose of the inspections is to ensure that the safety and traffic ability of the bridges meet the requirements; the inspections reveal the physical and functional condition thus providing the basis for an efficient and economical bridge management. The bridge inspections in Sweden are since 1987 divided into three types, according to the nature of their aim, scope and frequency. They are:

- General inspection
- Major inspection
- Special inspection

**General inspection: -** The aim of is to follow up the assessed damage during earlier inspections, detect and assess new damage, and detect if the contracted maintenance work has been properly performed. Every structural part of the bridge together and their included elements have to be visually inspected. Structural parts under water are excluded. There is no demand on hand-close investigation unless new damage is detected. General inspection is a simpler inspection compared to the major inspection. The scope of the general inspection is to check the recorded damage from previous major inspections and check if the assessed development of these was correct. If new damages are detected, they will be recorded and assessed according to current rules. General inspection has to be performed on bridges with a theoretical span larger than 2,0 meters. Smaller bridges are normally exempted from this inspection type. The time interval between two general inspections is maximum three years. The personnel performing this inspection type have to posses the same competence as the inspectors performing major inspections.

**Major inspection: -** The most important inspection type performed on the Swedish road bridges. The scope of this inspection type is to detect and asses damages and defects which can affect the designed function or the traffic safety, both in the short and the long run (within 10 years). Another aim is to detect even minor damage or defects that, if not attended to, can cause increased maintenance or repair costs within a 10-year period. Every structural part and their in-going elements, which are within hand reach, have to be investigated.
During this inspection, even the structural parts located under the water surface have to be closely inspected by qualified divers. Even adjoining parts of the bridge such as road embankments, slopes, abutment ends, fill revetment and fenders have to be inspected. If the inspected bridge contains mechanical or electrical equipment, such as movable bridges, these parts will also be subject to close inspection. The inspection has to be done hand-close. Special inspection equipment, such as a bridge-lift, will allow a close look under the bridge deck, a structural part difficult to inspect otherwise.
This inspection type requires that a series of physical measurements have to be performed. Such measurements are made to determine for example the real bottom profile (erosion risk), chloride content and carbonization of concrete, measurements of the level of corrosion of the reinforcement bars and cracking. The major inspection has to be carried out at least every sixth year. The demands on the bridge inspectors performing these are high.

**Special inspection: -**For more information see BaTMan (2000) or the Swedish Bridge inspection

An example of historical agency data for bridge inspection costs can be as shown in following table:

**Table 2:3** *Inspection Feedbacks and Recommendation*

| Inspections activities | | | | | |
|---|---|---|---|---|---|
| The Action Name | Recommended Intervals(*Year*) | Average Required Unit Duration | | | Average Cost % From The Agency Cost |
| | | Value | Unit | From | |
| General inspection | 1 | 0.05 | hr/m$^2$ | Bridge Area | 0,15 (*Concrete Structures*) 0,20 (*Steel Structures*) |
| Major inspection | 6 | 0.1 | hr/m$^2$ | Bridge Area | |
| Special inspection | when needed | 0.2 | hr/m$^2$ | Bridge Area | |

### 2.3.4 Repair/Rehabilitation & Replacement

**Repair: -** The restoration of a structure, including all its appurtenances, to its original condition (or as subsequently improved) insofar as practicable. Repair includes any activity intended to correct the affects of material deterioration by restoring or replacing in-kind any damaged member.

**Rehabilitation:** - The improvement or betterment of a structure, including all its appurtenances, to a condition which meets or exceeds current design standards.

Examples of rehabilitation include, widening a bridge to meet lane/shoulder width requirements, raising a bridge to meet clearance requirements, replacement of substandard bridge rails, strengthening a bridge to increase load carrying capacity to accepted limits, replacement of deck, rehabilitation of deck, and rehabilitation of superstructure**.**

**Replacement:** - The erection of a new structure at or near an existing structure, with the new structure(s) intended to receive the service loads from the existing structure which is eventually abandoned, relocated, or demolished.

An example of historical agency data for bridge repair/rehabilitation & replacement costs can be as shown in following table:

**Table 2:4** *Repair/Rehabilitation & Replacement Feedbacks and Recommendation*

| Repair, Rehabilitations & Replacement activities | | | | | |
|---|---|---|---|---|---|
| The Action Name | Recommended Intervals(*Year*) | Average Required Unit Duration | | | Average Cost % From The Agency Cost |
| | | Value | Unit | From | |
| Deck repair & maintenance | 12 | 0.2 | hr/m$^2$ | Bridge Area | 20 (*Concrete Structures*) 22 (*Steel Structures*) |
| Deck overlay & resurfacing | 26 | 0.4 | hr/m | Bridge Length | |
| Deck replacement | 44 | 1 | hr/m$^2$ | Bridge Area | |
| Expansion joints repair | 4 | 2 | hr/m | Bridge Width | |
| Expansion joints replacement | 12 | 3 | hr/m | Bridge Width | |
| Bridge seat & bearings repair | 4 | 0.02 | hr/m$^2$ | Bridge Area | |
| Bridge seat & bearings replacement | 40 | 0.04 | hr/m$^2$ | Bridge Area | |
| Gradrail,railings, parapets & fittings replacement | 20 | 2 | hr/m | Bridge Length | |
| Edge beam impregnation & repair | 25 | 0.5 | hr/m | Bridge Length | |
| Edge beam replacements | 50 | 1.5 | hr/m | Bridge Length | |
| Superstructure strengthening & rehabilitation | 30 | 4 | hr/m$^2$ | Bridge Area | |
| Superstructure replacements | 50 | 8 | hr/m$^2$ | Bridge Area | |
| Substructure strengthening & rehabilitation | 30 | 1 | hr/m$^2$ | Bridge Area | |
| Substructure replacement | 50 | 2 | hr/m$^2$ | Bridge Area | |
| Painting of steel structure, whole bridge | 25 | 0.2 | hr/m$^2$ | Bridge Area | |

### 2.3.5 End of life Management (Demolition and Landscaping)

An example of historical agency data for bridge demolition and landscaping costs can be as shown in following table:

**Table 2:5** *Ends of Life Management Feedbacks and Recommendation*

| End of life Management ( Demolition and Landscaping) activities | | | | | |
|---|---|---|---|---|---|
| The Action Name | Recommended Intervals(*Year*) | Average Required Unit Duration | | | Average Cost % From The Agency Cost |
| | | Value | Unit | From | |
| Prestressed concrete bridges | 100 | 0.025 | day/m$^2$ | Bridge Area | 9 |
| Convential reinforced concrete bridges | 80 | 0.04 | day/m$^2$ | Bridge Area | 10 |
| Steel Structures | 70 | 0.02 | day/m$^2$ | Bridge Area | 8 |
| Timber Bridges | 50 | 0.015 | day/m$^2$ | Bridge Area | 6 |

## 2.4 Costs by Elemental Breakdown (Level 3)

The third level of classification organizes costs (1) by specific functional element of the structure or facility, (2) by activities not assignable to functional elements (e.g., overhead). Parts (2) is the traditional "elements" cost. We add new-technology introduction costs to measure the unique costs of using a new material. Schematically Figure 2:2 below will introduce this level.

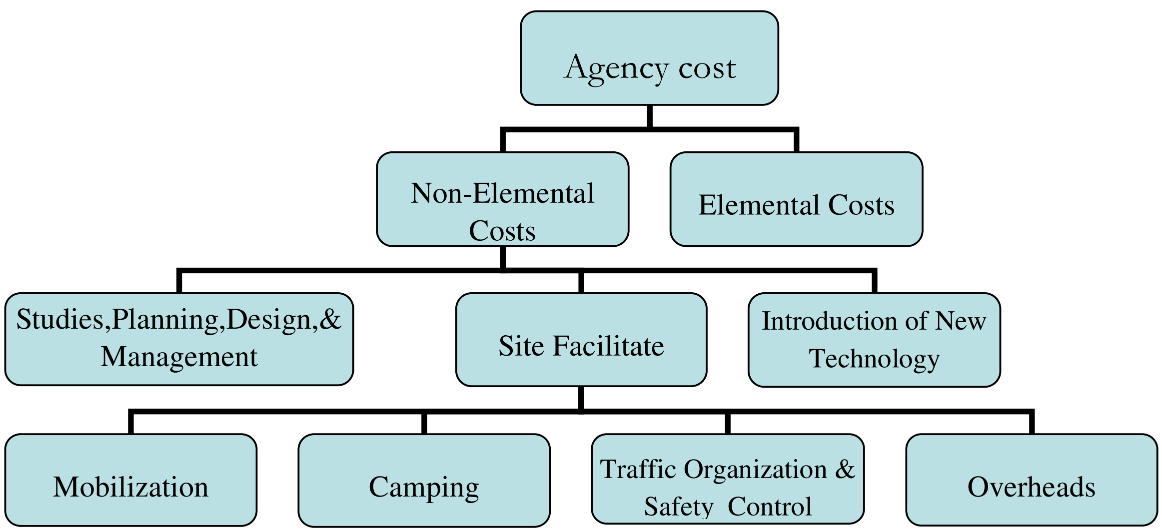



**Figure 2:2** *Costs by Elemental Breakdown (Level 3)*

### 2.4.1 Elemental Costs

Elements are major components of the project's structure, and are sometimes referred to as component systems or assemblies. Elements common to bridges are superstructure, substructure, and approach. Each element performs a given function regardless of the materials used, design specified, or method of construction employed.

Individual cost estimates at the elemental level (e.g., $/square meter to furnish and install a concrete deck) are most useful in the pre-design stage when a variety of material/design combinations are being considered. This is the stage at which large net savings can be achieved by making economically optimal material/design choices as shown in Figure 2:3.

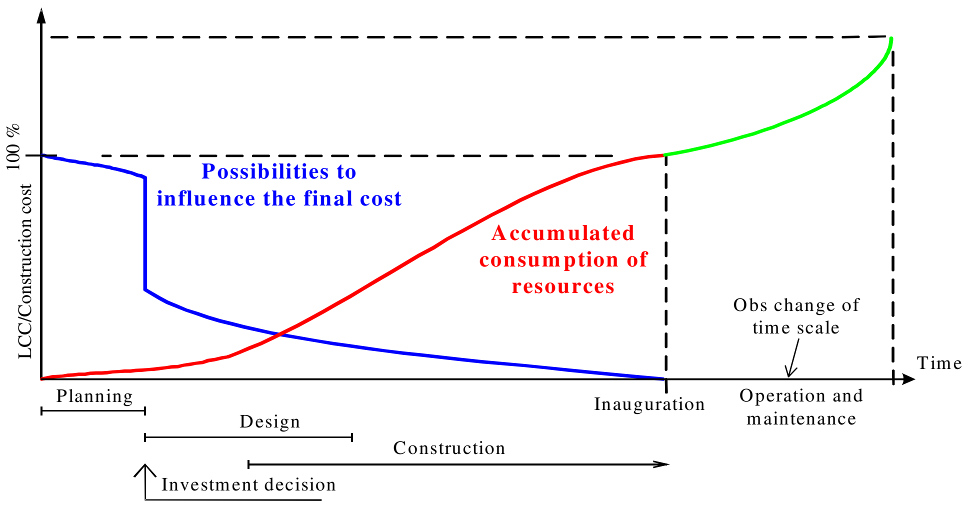



**Figure 2:3** *Bridge Stages and the possibilities to influence the LCC*

### 2.4.2 Non-Elemental Costs

Non-elemental costs are all costs that cannot be attributed to specific functional elements of the project. A common example of a non-elemental agency cost is overhead expenses; a non-elemental third-party cost could be spillover costs. Because elemental cost categories are useful for generating and updating historical unit cost measures, all project costs that are not truly elemental must be excluded from these historical statistics and put in the non-elemental group. Schematically graph compose these three levels can be as shown in Figure 2:4 below

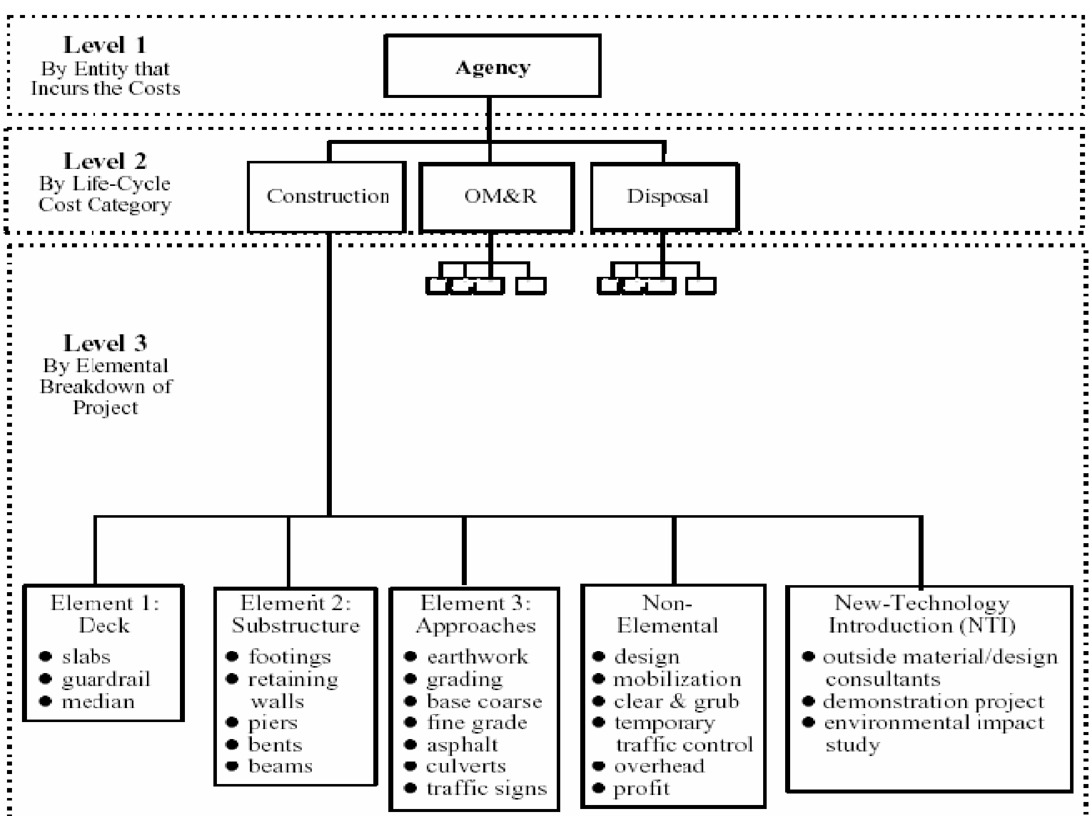


**Figure 2:4** Bridge LCC Classification Levels

Notation for bridge main structures and its elements are presented in Table 2:6; see also Figure 1:1, and Table 1:1.

**Table 2:6** *Bridge Component Breakdown*

| Component / Activities | | Type / Include | Component / Activities | | Type / Include |
|---|---|---|---|---|---|
| 1 | **Foundation** | Foundation slab | 6 | **Bridge equipment** | Bearing and Hinge |
| | | Foundation plinth | | | Expansion joint |
| | | Rock filled box timber caisson | | | Parapet |
| | | Caisson | | | Railing |
| | | Timber grillage | | | Guardrail |
| | | Pile | | | Insulation, water proofing |
| | | Backfill | | | Drainage system |
| | | Erosion protection | | | Lightening, Electrical work and Accessories |
| | | Sheet pile wall | | | |
| | | Rock anchor bolt | | | |
| 2 | **Slope and Embankment** | Embankment, embankment end, backfill | 7 | **Surface layers** | Pavement (asphalt etc.) |
| | | | | | Insulation, water proofing |
| | | Soil reinforcement and slope protection | | | Epoxy sealing |
| | | | | | Others |
| 3 | **Substructure** | Lower front wall | 8 | **Earthworks** | Excavation soil |
| | | Bridge seat | | | Excavation rock |
| | | Upper front wall | | | Soil filling |
| | | Pier | | | Others |
| | | Footing slab for pier | | | |
| | | Counterfort | | | |
| | | Wing wall | | | |
| | | Supporting wall | | | |
| 4 | **Superstructure** | Slab and deck | 9 | **Construction** | Scaffolding |
| | | Beam | | | Temporary constructions |
| | | Truss | | | Bridge construction |
| | | Arch, Vault | | | Transportation of workers |
| | | Arch spandrel wall | | | Other activities |
| | | Cable system | | | |
| | | Pipe, Culvert | | | |
| 5 | **Secondary load-bearing structure** | Secondary load-bearing beam, cross beam | 10 | **End of Life Management** | Demolition |
| | | Secondary load-bearing truss, Wind bracing | | | Landscaping |
| | | Edge beam | | | Waste management (incl. recycling and recovery) |

## 2.5 Life-Cycle Cost Analysis Approach

### 2.5.1 Integrated Life-Cycle Cost Analysis Approach

The term life cycle cost (LCC) is not used consistently. The more traditional view of LCC evaluates costs incurred by government agencies all through the value chain (from raw material acquisition to end of life). Such costs are termed “agency costs.” Recently, efforts have been made to broaden this definition to be more inclusive of other costs associated with construction projects. In particular, several studies, using a more holistic LCC approach, have been conducted with the goal of determining agency costs as well as user costs

An integrated life cycle assessment, aesthetical and cultural value, and cost model was developed in this master thesis to evaluate the bridge sustainability, and compare alternative materials and designs using environmental, economic and social indicators where, the bridge LCC is equal to:

$$LCC = C_{AG} + C_{USER} + C_{RACV} + C_{REI}$$

Where:

- $C_{AG}$ Is the corresponding ***Ag****ency cost*.
- $C_{USER}$ Is the corresponding ***User*** *cost*.
- $C_{RACV}$ Is the corresponding ***R****elative* ***A****esthetical and* ***C****ultural* ***V****alue cost*.
- $C_{REI}$ Is the corresponding ***R****elative* ***E****nvironmental* ***I****mpact cost*.

Where:

Here $C_{AG}$ is the *Agency cost* obtained by cost calculation considering the construction, repair, maintenance and demolishing costs of the bridge from its whole lifetime.

The ***R****elative* ***A****esthetical and* ***C****ultural* ***V****alue cost* $\boldsymbol{C_{RACV}}$ of a bridge, is then obtained by equation:

$$C_{RACV} = k_{AES} C_{AG}$$

- $k_{AES}$ Is the aesthetical and cultural coefficient. Range from +0,30 To -0,30

Finally, the ***R****elative* ***E****nvironmental* ***I****mpact cost* $\boldsymbol{C_{REI}}$ of a bridge, is then obtained by equation:

$$C_{REI} = k_{EI} C_{AG}$$

- $k_{EI}$ Is the environmental impact coefficient. Range from 0,0 To +0,20

Consequently, the system described above enables comparison between different design proposals, existing bridges and bridge types as well as evaluation of even different construction methods.

### 2.5.2 Steps in Life-Cycle Cost Analysis

- Define the project objective and minimum performance requirements.
- Identify the alternatives for achieving the objective.
- Establish the basic assumptions for the analysis.
- Identify, estimate, and determine the timing of all relevant costs.
- Compute the life-cycle cost of each alternative
- Perform sensitivity analysis by reusing different assumptions
- Compare the alternatives' life-cycle costs
- Consider other project effects
- Select the best alternative.

For LCCA to yield valid results, each project alternative considered must provide the same level of service or utility for a specific, given volume of traffic. In the event that the alternatives yield different levels of service or utility, then benefit-cost analysis (BCA), not LCCA, would be the appropriate decision tool. LCCA provides a comprehensive means to select among two or more alternatives to accomplish the project.

### 2.5.3 Economic Analysis Technique

The time value of money is germane to LCCA because costs included in the analysis are incurred at varying points in time. Figure 2:5 show an example of the bridge LCC cash flow. For LCCA, costs occasioned at different times must be converted to their value at a common point in time. It's recommended to use the present value (PV) approach (also known as “present worth”), the formula to discount future constant value costs to present value is:

$$\text{Present Value} = \text{Future Value} \times \frac{1}{(1+r)^n}$$

Where:

- r Is the real discount rate
- n Is the number of years in the future when the cost will be incurred.

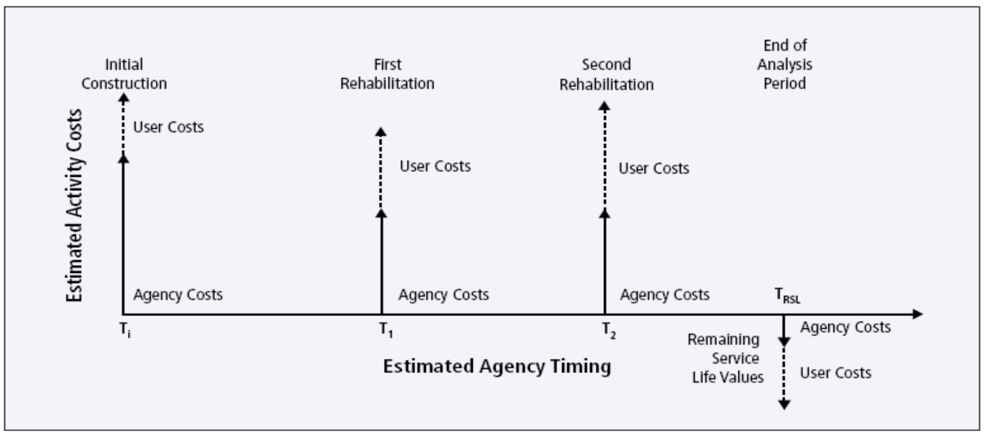



**Figure 2:5** *LCC Cash Flow Example*

For LCCA to be performed in a right way, the proposals on, how to design the bridge should contain a lot of documents describing the bridge from a lot of different aspects, Table 2:7 present these documents as follow.

**Table 2:7** *Documents to be submit with the bridge design proposal*

| **A) Descriptions** | **B) Design calculations** |
|---|---|
| • General description of the proposal and design concept<br>• Technical description.<br>• Description of the construction process.<br>• Description on how to inspect and maintain the bridge | • Rough statical and dynamical analyses of the bridge<br>• A lot of other important factors that affect the bridge, as for instance wind, stability, vibration, stiffness, etc<br>• Rough estimated cost calculations<br>• LCC-calculation. |
| **C) Drawings** | **D) Perspective/Photomontage/Model** |
| • Plan.<br>• Elevation.<br>• Special elevations in a smaller scale 1:100.<br>• Type sections.<br>• Important details. | • Photomontage of the bridge on four delivered pictures.<br>• Model in scale 1:500. |

# 3. BRIDGE USER COST

## 3.1 Introduction

### 3.1.1 Definition

Bridge user costs are costs incurred by users of the bridge as a result of deteriorated conditions on the bridge, such as a narrow width, low load capacity, or low vertical clearance which are resulting from construction, maintenance, inspection, rehabilitation, and demolition activities, leading to an increase in the vehicles trip time which is translated into user delay costs, additional vehicle operating costs and increase risk and accident costs.

### 3.1.2 Background

The bridges are aging, and the agencies are focusing on maintenance and rehabilitation of existing bridges infrastructure to a greater extent than ever before. Work on existing bridges, whether its purpose is to rehabilitate or to add capacity, requires the use of work zones to protect bridge users and construction workers. By reducing capacity, work zones often cause user costs to rise due to increases in travel time, vehicle operating costs, and possibly the number and severity of crashes.

User costs contribute significantly to the total life cycle cost and should be considered in the analysis of bridge networks, designers should consider road user costs when determining the most appropriate construction staging and final design. A study by the Florida Department of Transportation (Thompson et al., 1999) estimated that user costs may exceed the repair costs by a factor of 5 or more.

Bridge user costs are not direct costs, but they do directly affect the public it serves. For example, the construction of a $1 million full width shoulder to reduce bridge user costs by $2 million increases agency costs to reduce road user costs.

### 3.1.3 Objective

This chapter will familiarize the analyst with work zone and traffic characteristics, explain the possible related bridge user cost components, and provide a step by step procedure for computations considering all traffic condition related aspects.

Based on this procedures and information, develop a systematic computer program to simplify and facilitate the quantification and then, enable to determine the cost effectiveness of various alternatives and optimize the work-zone strategies in order to minimize user costs.

## 3.2 Bridge User Cost Components

Before addressing bridge user cost calculation procedures, it is helpful to understand the bridge user cost components. Figure 3:1 illustrate the user cost components and their appearance events.

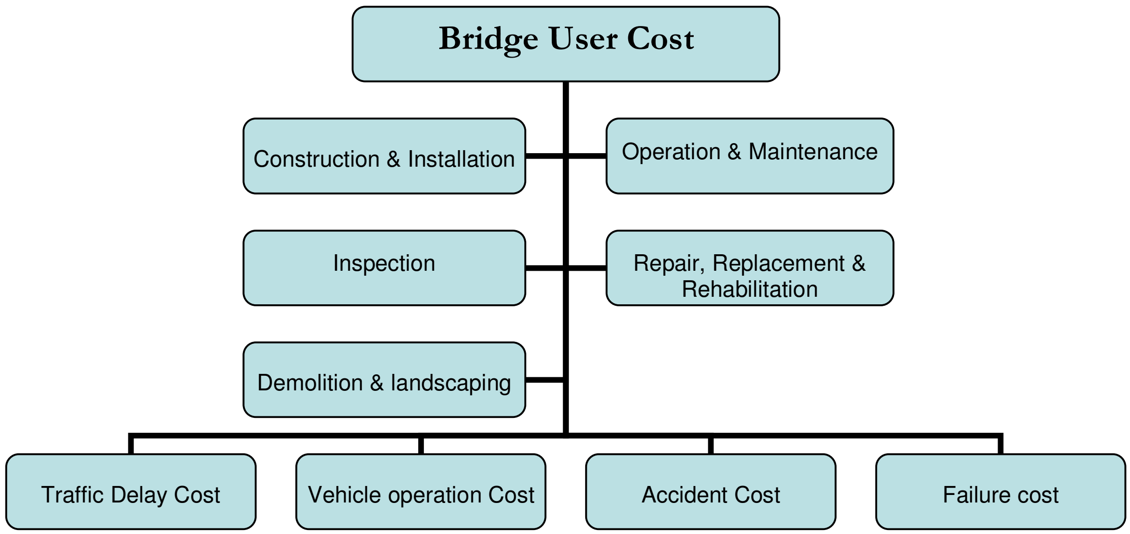



**Figure 3:1** *Bridge user cost components and appearance events*

Bridge user cost during a work zone are usually evaluated with respect to the traffic delay costs (TDC), the additional vehicle operating costs (VOC) to cross the work zone, the related-accident-costs (AC), and the risk of failure cost (FC). The following equation is used to determine bridge user cost during a work zone.

$$Bridge\ User\ Cost = TDC + VOC + AC + FC$$

The costs should be calculated to present value and added up for all foreseen maintenance and repair works for the studied time interval $T_E$.

### 3.2.1 Traffic Delay Cost (TDC)

The traffic delay cost (TDC) results from the increase in travel time through the work zone due to speed reductions, congestion delays, or increased distance as a result of a detour. Therefore, the TDC is calculated based on the difference between the time taken to cross the bridge and the time taken to finish the detour or the work zone.

$$TDC = \sum_{t=0}^{T_E} T \times ADT_t \times N_t \times (r_T w_T + (1 - r_T) w_P) \frac{1}{(1+r)^t}$$

Where:-

$$T = T_{WZ} - T_o \quad , \quad T_o = \frac{L}{v_o} \quad , \quad T_{WZ} = ???$$

- $T$ is the travel time delay for one vehicle in case of work zone, *(hour)*,
- $ADT_t$ is the average daily traffic at time t, measured in number of, *(vehicle/day)*,

- $N_t$ is the number of days needed to perform the work at time t, *(Day)*,
- $r_T$ is the percentage of trucks from all AVD,
- $w_T$ is the hourly time value for one truck,
- $w_p$ is the hourly time value for one passenger care,
- $T_{wz}$ is the time taken to finish the detour or to cross the work zone, *(hour)*,
- $T_o$ is the taken to cross the bridge during the normal flow conditions, *(hour)*,
- $L$ is the affected bridge length, *(km)*,
- $v_o$ is the traffic speed in the normal traffic flow condition, *(km/hr)*,
- $v_{WZ}$ is the work zone speed, *(km/hr)*,
- $T_E$ is the bridge expected life span.

The duration travel delay time in case of work zone *(T)* is strongly associated with the traffic flow condition, the hourly traffic distribution, and work zone construction window; we will do deeply in this matter in the work zone and traffic characteristics subsection in this chapter.

***The value of w***

The value of one hour of travel time per vehicle is assumed to be equal to:

- $8/hr/veh regardless of vehicle type; *The Federal Highway Administration (1989)*
- $25/hr/veh. regardless of vehicle type; *He et al. (1997)*
- $12/hr/veh. regardless of vehicle type; *Schonfeld (2003)*
- *Thoft-Christensen (2006)*
  - $ 11,38 - 11,58 for passenger cars.
  - $ 22,31 - 27,23 for trucks

<u>Recommended value of *w*:</u>

It should be equal to the average hourly wage for average employee in the considered country. The argument for that is, because *W* is representing the value of delaying the vehicle driver one hour instead of reaching his work at time. For example, in *Sweden 2009* the average hourly wage is equal to 120 SEK which is approximately equal to $14, this will be suitable for passenger cars, and for other vehicles is equal to this value multiply by 2, regardless the number of persons inside the vehicle, so the recommended value according to <u>*Sweden 2009*</u>:

- $ 14,0 /hr for passenger cars.
- $ 28,0/hr for other vehicles.

### 3.2.2 Vehicle Operation Cost (VOC)

VOC is an additional cost incurred by the bridge user, expressed as extra costs to operate the vehicle additional time due to the traffic disturbances because of the work zone or detour. The operating costs include fuel, engine oil, lubrication, maintenance, and depreciation.

$$VOC = \sum_{t=0}^{T_E} T \times ADT_t \times N_t \times (r_T O_T + (1 - r_T) O_P) \frac{1}{(1+r)^t}$$

Where:-

Same parameters are used except for:

- $O_T$ is the average hourly operating cost for one truck including its goods operation,
- $O_P$ is the average hourly operating cost for one passenger care.

***The value of O***

The recommended value according to Sweden 2009:

- $ 9,5/hr for passenger cars.
- $ 21,5/hr for other vehicles.

### 3.2.3 Accident Cost (AC)

***Background***

AC is representing the costs of increasing the risk of crushes, health-care, and deaths which resulting from the traffic disturbances due to work zone on the bridge.

Although bridge-related accidents represent only about 1.7% of all traffic accidents, the degree of severity is estimated to be from 2 to 50 times the severity of general roadway traffic accidents. The average number of peoples were killed in bridge related accidents was determined to be equal to 0.009 persons/accident *(Abed-Al-Rahim and Johnston, 1991, 1993).*

***Computation method***

Obviously its consequences appear when comparing two different types bridge structures, where the risks for accidents and the safe maintainability are differs. The bridge accident costs during work zone could be calculated as:

$$AC = \sum_{t=0}^{T_E} ADT_t \times N_t \times (A_n - A_a) \times \left[ (C_F \times P_F) + (C_I \times P_I) \right] \frac{1}{(1+r)^t}$$

Where:-

Same parameters are used except for:

- $A_n$ The bridge accident rates during the normal condition, *(Accident/Vehicle/L/day),*
- $A_a$ The bridge accident rates during the work activities, *(Accident/Vehicle/L/day),*
- $C_F$ The average cost per fatal deaths accident for the society
- $C_I$ The average cost per serious injury accident for the society
- $P_F$ The average number of killed persons in bridge related accidents, which is equal to *0,009 (Persons/Accident)*
- $P_I$ The average number of injured persons (not killed) in bridge related accidents, which is equal to *0,991 (Persons/Accident)*

***Value of average cost per accident***

- Swedish Road Administration 2009
    - $1,500,000 for fatal deaths crush
    - $500,000 for serious injury crush
- United States of America FHWA
    - $1,240,000 for fatal deaths crush
    - $151,000 for serious injury crush
- $68,404 Soares (1999)
- Recommended value in this chapter
    - $1,500,000 for fatal deaths crush
    - $160,000 for serious injury crush

***Bridge- related accident rate***

*Aded-Al-Rahim and Johnston (1991, 1993)* proposed a model for calculating the risk of accidents that considers the average daily traffic (ADT) and the bridge length, as follows:

$$NOACC = \left[0,783 \times (ADT^{0,073}) \times (BL^{0,033}) \times (WZ + 1)^{0,05}\right] - 1,33$$

Where:

- $NOACC$ = The number of accidents per year,
- $LB$ = The bridge length in (Feet)
- $WZ$ = The work zone width, in (Feet), equal to zero during normal conditions

***Comments & Recommendation***

It is difficult to accurately quantify the work zone exposure rate (i.e. the length of the work zone and the hours and days the work zone queues are in place). Further, the crash rate, while generally higher in work zones than non-work zones, is still low enough that there may not be any crashes in a given work zone because the exposure period is just too short to allow for statistically valid results. Finally, the problem is compounded by the fact that work zones differ in the way they treat maintenance of traffic. For example, some work zones use permanent barriers, while others use cones or drums; some narrow the lanes, while others maintain lane width and shoulders, etc.

- *While there is a limited amount of work zone crash data, the validity of the data used to compute the crash rates is sometimes suspected.*

### 3.2.4 Failure cost (FC)

There is a small risk for the total failure of a structure. To get the cost for failure one has to calculate all costs ($K$H,$j$) for the failure, accidents, rebuilding, user delay costs and so on and then multiply these costs with the probability for failure and with the appropriate present value factor according to the formula

$$FC = \sum_{j=1}^{n} K_{H,\,j} R_j \frac{1}{(1+r)^j}$$

*Rj* is the probability for a specified failure coupled to $K$H,$j$. For normal bridges the probability of failure is so small that the failure costs could be omitted in the analysis. The cost for serviceability limit failure is discussed in *Radojičić (1999*), but actually the methods presented in the present paper are a kind of statistically LCC-method given that the parameters for remedial actions are considered random.

- *Due to the limited availability of probability of failure data, the inclusion of the failure costs as part of the Bridge user costs is not recommended.*

## 3.3 Sources of the Traffic Delay on the Bridge

An example of historical agency data and feedbacks including recommended time required to perform work activates are presented in Table 3:1 as follow:

**Table 3:1** *Work activities that affect the traffic*

| Work Activities That affect or disturb the Traffic | | | | | | | |
|---|---|---|---|---|---|---|---|
| The Action Name | Recommended Intervals(*Year*) | Average Required Unit Duration | | | Affected Traffic | | Limitations & Comments |
| | | Value | Unit | From | Over | Under | |
| **Investment (Purchasing, Construction,& Installation)** | | | | | | | |
| Prefabricated Prestressed concrete bridges | 100 | 0.12 | day/m$^2$ | The Bridge Area | Yes | Yes | Traffic must detour (Bridge Full Closer) |
| Convential reinforced concrete bridges | 80 | 0.15 | day/m$^2$ | The Bridge Area | Yes | Yes | |
| Steel Structures | 70 | 0.1 | day/m$^2$ | The Bridge Area | Yes | Yes | |
| Timber Bridges | 50 | 0.12 | day/m$^2$ | The Bridge Area | Yes | Yes | |
| **Operation & Maintenance activities** | | | | | | | |
| Cleaning the bridge of salt | 1 | 0.05 | hr/m$^2$ | Bridge Area | Yes | No | |
| Maintenance of parapets,gardrail& railings | 1 | 0.15 | hr/m | Bridge Length | Yes | No | |
| Maintenance of surface finish and laning | 1 | 0.1 | hr/m$^2$ | Bridge Area | Yes | No | |
| **Repair, Rehabilitations & Replacement activities** | | | | | | | |
| Deck repair & maintenance | 12 | 0.2 | hr/m$^2$ | Bridge Area | Yes | No | |
| Deck overlay & resurfacing | 26 | 0.4 | hr/m | Bridge Length | Yes | No | |
| Deck replacement | 44 | 1 | hr/m$^2$ | Bridge Area | Yes | No | |
| Expansion joints repair | 4 | 2 | hr/m | Bridge Width | Yes | No | |
| Expansion joints replacement | 12 | 3 | hr/m | Bridge Width | Yes | No | |
| Bridge seat & bearings replacement | 40 | 0.04 | hr/m$^2$ | Bridge Area | Yes | No | |
| Gradrail,railings, parapets & fittings replacement | 20 | 2 | hr/m | Bridge Length | Yes | No | |
| Edge beam impregnation & repair | 25 | 0.5 | hr/m | Bridge Length | Yes | No | one closed lane |
| Edge beam replacements | 50 | 1.5 | hr/m | Bridge Length | Yes | No | one closed lane |
| Superstructure replacements | 50 | 2 | hr/m$^2$ | Bridge Area | Yes | No | |
| Substructure replacement | 50 | 0.5 | hr/m$^2$ | Bridge Area | Yes | No | |
| Painting of steel structure, whole bridge | 25 | 0.2 | hr/m$^2$ | Bridge Area | No | Yes | |
| **End of life Management ( Demolition and Landscaping) activities** | | | | | | | |
| Prefabricated Prestressed concrete bridges | 100 | 0.12 | day/m$^2$ | The Bridge Area | Yes | Yes | Traffic must detour (Bridge Full Closer) |
| Convential reinforced concrete bridges | 80 | 0.15 | day/m$^2$ | The Bridge Area | Yes | Yes | |
| Steel Structures | 70 | 0.1 | day/m$^2$ | The Bridge Area | Yes | Yes | |
| Timber Bridges | 50 | 0.12 | day/m$^2$ | The Bridge Area | Yes | Yes | |

## 3.4 Work Zone and Traffic Flow Condition Relationship

### 3.4.1 Work Zone Definition

Work zone is defined as an area of a highway in which maintenance and construction operations are taking place that impinge on the number of lanes available to traffic or affect the operation of the traffic flowing. Work zones restrict traffic flow either by restraining the capacity of the bridge or, by posting lower speed limits.

In order to calculate bridge work zone related user costs the characteristics of the work zone must be defined. Work zone characteristics include such factors as work zone length, number and capacity of lanes open, duration of lane closures, timing (hours of the day and days of the week) of lane closures, posted speed, and the availability and traffic characteristics of alternative routes.

### 3.4.2 Causes of the Traffic Delay at the Work Zone

There are three sources of traffic delay at work zone:

- Speed reduction delay (moving delay),
- Congestion delay (stopping delay).
- Circuity delay (extra distance moving delay),

<u>Speed-reduction delay</u>: result from vehicles moving more slowly than the normal bridge speed.

<u>Congestion delay</u>: occurs when the hourly traffic volume is greater than the capacity of a work zone for a significant period of time. In this case a queue forms, the queue decreases only during time periods when the demand is less than the capacity.

<u>Circuity delay</u>: is a term used to describe the additional mileage that users travel, either voluntarily or involuntarily, on a detour to avoid a bridge work zone or queue situation. Its usually take place in the construction and in the major replacement activities when the bridge have to be closed.

### 3.4.3 Work Zone Construction Window

Bridge repair and rehabilitation window (time of day to do the work) traditionally occur at nighttime because daytime closures cause unacceptable delays to weekday peak travel. However, the disadvantage of having nighttime closures is that they may lead to lower work quality, longer closure time and higher construction and traffic control plan costs. Four construction window strategies are recommended:

- Nighttime shifts closure, from 7:00PM To 5:00AM,
- Fulltime closure, 24 Hour/Day.
- Weekend closure,
- Weekday closure.

Alternatively, combinations of the four construction windows are used some times.

***Hourly traffic distribution***

The effective procedure for quantifying speed reduction delay and is to convert the ADT into an hourly volume, estimate the delay on an hourly basis, and cumulate the hourly delay into a daily delay. Data related to the ADT and the hourly traffic distribution is often available from the municipalities. As an illustration, Table 3.2 shows an example of hourly traffic distribution

(USDOT/FHWA, 1998) and provides a distribution factor (% ADT) for each hour of the day for different highway types. Based on this distribution factor, the hourly traffic can be calculated as:

$$Hourly\ Traffic = ADT \times Distribution\ Factor$$

**Table 3:2** *Example of Hourly Traffic Distribution (USDOT/FHWA, 1998)*

| Hour | | Distribution Factor(%ADT) | | Hour | | Distribution Factor(%ADT) | |
|---|---|---|---|---|---|---|---|
| From | To | Interstate | Other | From | To | Interstate | Other |
| 0 | 1 | 1.70% | 0.90% | 12 | 13 | 5.70% | 5.70% |
| 1 | 2 | 1.40% | 0.50% | 13 | 14 | 5.90% | 5.90% |
| 2 | 3 | 1.30% | 0.50% | 14 | 15 | 6.30% | 6.60% |
| 3 | 4 | 1.30% | 0.50% | 15 | 16 | 6.90% | 7.70% |
| 4 | 5 | 1.40% | 0.90% | 16 | 17 | 7.20% | 8.00% |
| 5 | 6 | 2.10% | 2.30% | 17 | 18 | 6.60% | 7.40% |
| 6 | 7 | 3.70% | 4.90% | 18 | 19 | 5.30% | 5.50% |
| 7 | 8 | 4.90% | 6.20% | 19 | 20 | 4.40% | 4.30% |
| 8 | 9 | 4.90% | 5.50% | 20 | 21 | 3.80% | 3.60% |
| 9 | 10 | 5.20% | 5.30% | 21 | 22 | 3.40% | 3.00% |
| 10 | 11 | 5.50% | 5.40% | 22 | 23 | 2.90% | 2.30% |
| 11 | 12 | 5.80% | 5.60% | 23 | 24 | 2.40% | 1.50% |

### 3.4.4 Work Zone & Traffic Flow Conditions

The duration of work zone delay time is strongly associated with the traffic flow condition. Three types of the traffic flow condition:

- Unrestricted flow conditions, where the traffic operates under "Base Case" situation
- Forced flow conditions, where traffic operates under "Queue" situation
- Circuity flow condition, where traffic is forced to utilize a detour

***Unrestricted Flow Condition***

Where the traffic volume is below the work zone capacity, all traffic that flows through the work zone, must slow down while traveling through it and then accelerate back to normal operating speed. The delay time components associated with the unrestricted flow condition are described in the below figure.

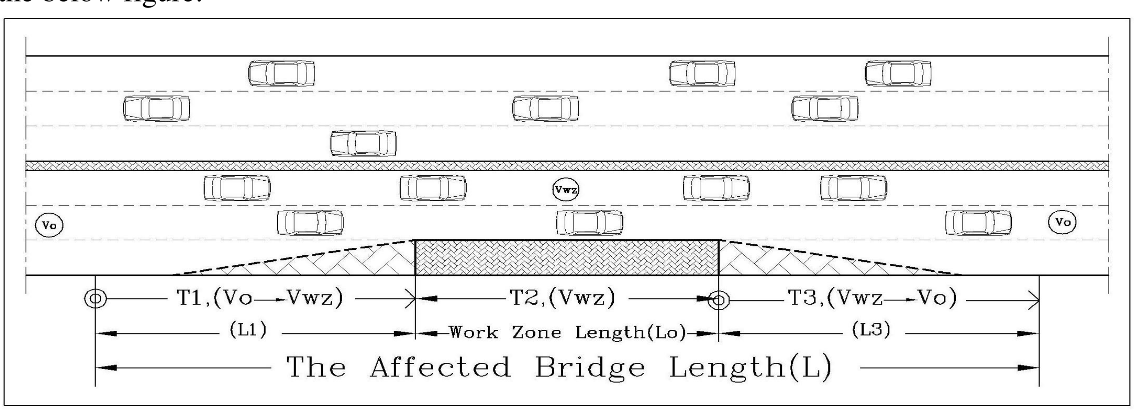



**Figure 3:2** *The Delay Time Duration In Case of Unrestricted Flow Condition*

$$T = T_{WZ} - T_o \quad , \quad T_o = \frac{L}{V_o} \quad , \quad T_{WZ} = T_1 + T_2 + T_3$$

Where:-

- $T$ is the travel time delay, *(hour)*,
- $T_o$ is the required to cross the affected bridge length *(L)* during the normal flow conditions, *(hour)*,
- $T_1$ is the time required to decelerate from the normal speed *($V_0$)* to the work zone speed *($V_{WZ}$), (hour)*,
- $T_2$ is the time required to cross the work zone driving by the posted work zone speed *($V_{WZ}$), (hour)*,
- $T_3$ is the time required to accelerate back from the work zone speed *($V_{WZ}$),* to the normal speed *($V_0$)*, *(hour)*.

<u>Parameters identification and valuation:</u>

❖ $L_1$ Is the minimum distance needed to decelerate from $V_o$ to $V_{wz}$ (*m*)

$$L_1 = d_r + d_{dec.} = 0.278\, t_r V_0 + \frac{V_0^{\,2} - V_{wz}^{\,2}}{245\,(f \pm G)}$$

Where:

- $d_r$ The perception reaction distance (*m*)
- $d_{dec}$ The minimum deceleration distance (*m*)
- $V_0, V_{wz}$ The normal speed and work zone speed (*km/h*)
- $t_r$ The perception/reaction time(*Sec.*), average equal to 2,5 sec.
- $f$ The AASHTO stopping friction coefficient (*dimensionless*), Table 3:3
- $G$ The roadway grade (*dimensionless*), assume it equal to zero(horizontal bridge)

**Table 3.3** *Design speed and the corresponding friction coefficient (USDOT/FHWA, 1998)*

| Design Speed (km/h) | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
|---|---|---|---|---|---|---|---|---|---|---|
| Coefficient of Skidding Friction(f) | 0.4 | 0.38 | 0.35 | 0.33 | 0.31 | 0.3 | 0.3 | 0.29 | 0.28 | 0.28 |

➢ $T_1$ Is the time needed to decelerate from $V_o$ to $V_{wz}$ (*hr*)

$$T_1 = t_r + \frac{2\, d_{dec.}}{(V_0 + V_{wz})}$$

❖ $L_0$ Is the optimum work zone length, which is the suitable length to fit the work equipments, workers, and the working area itself. Of coarse its depend on the type of the working activities, the bridge length, and the technology used in the work. But we can say here, the minimum acceptable safe working length should not be less than 150 m regardless the bridge length, the recommended length can be obtained from the following table:

**Table 3:4** *Bridge length and the recommended work zone length*

| Bridge Length (m) | <150 | 150 - 500 | >500 |
|---|---|---|---|
| Recommended optimum work zone length L0 (m) | 150 | 200 | 300 |

For simplification consider the average length regardless the bridge length is equal to 200 m.

- $T_2$ Is the time required to cross the work zone driving by $V_{WZ}$, *(hour)*,

$$T_2 = \frac{L_0}{V_{wz}}$$

- $L_3$ Is the minimum distance needed to accelerate back from $V_{wz}$ to $V_0$

$$L_3 = V_{wz} T_3 + \frac{a (T_3)^2}{2}$$

Where:

- $a$ is an average vehicle acceleration rate which is equal to 2,28 m/Sec$^2$ (29458,8km/hr)

- $T_3$ Is the time required to accelerate back from $V_{WZ}$ to $V_0$, (*hr*).

$$T_3 = \frac{V_0 - V_{wz}}{a}$$

- As an application for the above mentioned system and formulas, we can relate the travel time delay of the bridge work zone to bridge normal speed as shown in Table 3:5.

**Table 3:5** *Traffic delay time due to unrestricted flow condition*

| Unrestricted Flow Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Design Speed $V_0$(km/h) | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
| $L_1$ (*m*) | 23.66 | 35.32 | 45.25 | 55.31 | 65.77 | 85.19 | 96.22 | 108.56 | 134.76 | 161.75 |
| $L_0$ (*m*) | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| $L_3$(*m*) | 0.43 | 1.04 | 1.37 | 1.71 | 2.05 | 3.35 | 3.86 | 4.37 | 6.18 | 8.17 |
| $T_1$ (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_2$(*hr*) | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_3$(*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Affected Bridge length L(*m*) | 224.08 | 236.35 | 246.62 | 257.02 | 267.82 | 288.54 | 300.08 | 312.92 | 340.94 | 369.92 |
| The Travel during work zone $T_{wz}$(*hr*) | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Normal Travel time $T_0$(*hr*) | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Travel Time Delay T (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Travel Time Delay T (*Sec.*) | 4.84 | 6.12 | 3.71 | 2.49 | 1.80 | 2.25 | 1.75 | 1.41 | 1.69 | 1.91 |

***Forced Flow Condition***

Where the traffic volume exceeds the work zone capacity, traffic flow breaks down and a queue of vehicles develops as shown in Figure 3.4. Once a queue develops, all approaching vehicles must stop at the approach to the work zone and creep through the length of the physical queue under forced flow conditions at significantly reduced speeds, it is common for queues to develop in the morning peak traffic period, dissipate, and then redevelop in the afternoon peak traffic period. The delay time components associated with the forced flow condition are described in the below figure.

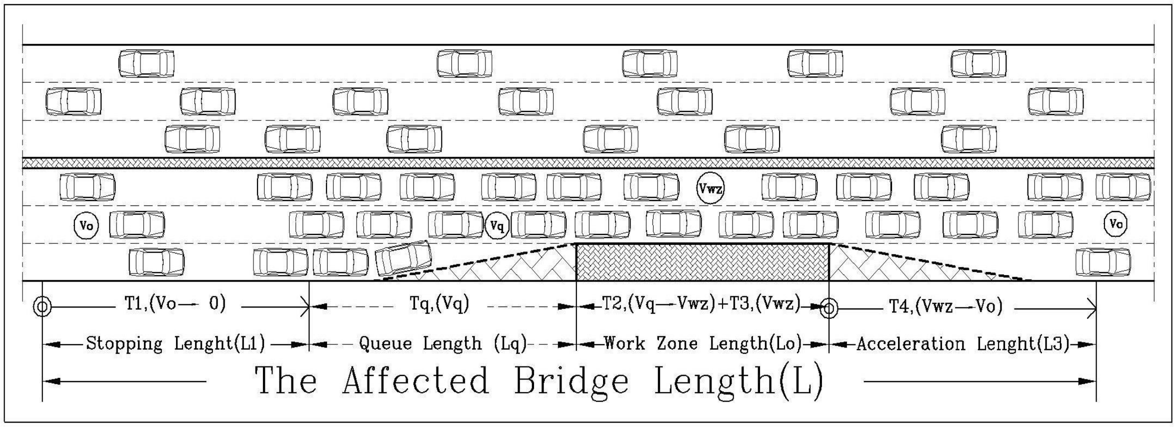



**Figure 3:3** *The Delay Time Duration In Case of Forced Flow Condition*

$$T = T_{WZ} - T_o \quad , \quad T_o = \frac{L}{V_o} \quad , \quad T_{WZ} = T_1 + T_q + T_2 + T_3 + T_4$$

Where:-

- $T$ is the travel time delay, *(hour)*,
- $T_o$ is the required to cross the affected bridge length *(L)* during the normal flow conditions, *(hour)*,
- $T_1$ is the time required to stop the vehicle from the normal speed *($V_0$), (hour)*,
- $T_q$ is the time required to creep through the queue by the queue speed *($V_q$), (hour)*,
- $T_2$ is the time required to creep through the work zone by firs step, accelerating from The queue speed *($V_q$ )* the work zone speed*($V_{WZ}$), (hour)*,
- $T_3$ is the time required to creep through the work zone by second step, driving by work zone speed*($V_{WZ}$), (hour)*,
- $T_4$ is the time required to accelerate back from the work zone speed *($V_{WZ}$),* to the normal speed *($V_0$)*, *(hour)*.

<u>Parameters identification and valuation:</u>

❖ $L_1$ Is the minimum stopping sight distance needed to decelerate from $V_o$ to $0$ , (m)

$$L_1 = d_r + d_b = 0.278\ t_r V_0 + \frac{V_0^{\ 2}}{245\ (f \pm G)}$$

Where:

- $d_r$ The perception reaction distance (*m*)
- $d_b$ The minimum breaking distance (*m*)
- $V_0$ The normal speed, (*km/h*)
- $t_r$ The perception/reaction time (*Sec.*), average equal to 2,5 sec.
- $f$ The AASHTO stopping friction coefficient (*dimensionless*)
- $G$ The roadway grade (*dimensionless*), assume it equal to zero(horizontal bridge)

- $T_1$ Is the time needed to stoop the vehicle (Sec.)

$$T_1 = t_r + \frac{2d_b}{V_0}$$

- $L_q$ Is the average length of the queue , (m)

$$L_q = \text{Average vehicle lenght}(AVL) \times \text{Average queued vehicles/Lan}(AQV)$$

The average vehicle length includes an assumed vehicle length (VL) and the space between vehicles. The mixed flow VL is 7,62 m. The space between vehicles is computed as one VL for every 16 km/h of the average queue velocity ($V_q$). The minimum average vehicle length is 12,2 m.

$$AVL = \text{max. of} \begin{Bmatrix} 7{,}62 + 7{,}62\left(\frac{V_q}{16}\right) \\ 12{,}2\ m \end{Bmatrix}$$

## V/C Ratio

The volume to capacity (V/C) ratio is calculated by dividing capacity of the bridge in case of work zone by the normal capacity of the bridge. The average queue velocity ($V_q$) is determined by using V/C Ratio and the following graph.

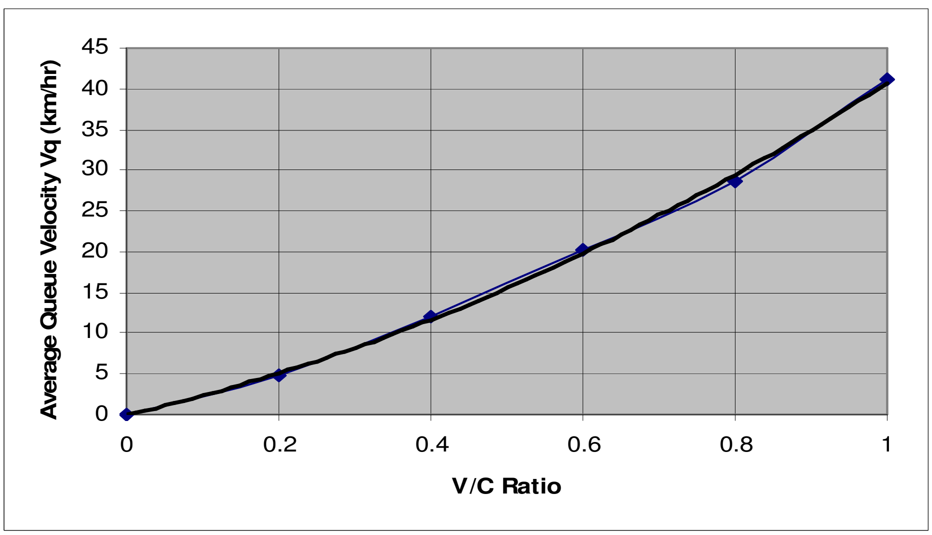



**Figure 3:4** *Average Queue Velocity Vq versus V/C Ratio sourc:(NCHRP133)*

The formula for this graph can be utilities in the following equation.

$$V_q = 19{,}18(V/C)^2 + 21{,}48(V/C) + 0{,}0057$$

According to this, the average vehicle length can be calculated as show in Table 3:6.

**Table 3:6** *Average vehicle length according to bridge configuration*

| Bridge Configuration Type | Normal Capacity (*Veh/lane/hr*) | Up normal Capacity (*Veh/lane/hr*) | Normal Capacity (*Veh/Dir./hr*) | Up normal Capacity (*Veh/Dir./hr*) | Volume To Capacity Ratio *V/C* | Average Queue Speed *Vq* (*km/hr*) | Average Vehicle Length *AVL* (*m*) |
|---|---|---|---|---|---|---|---|
| Two-Lane Undivided / (*TCP1*) | 1,400 | 600 | 1,400 | 600 | 0.43 | 13 | 13.7 |
| Four-Lane Divided / (*TCP3*) | 2,100 | 1,300 | 4,200 | 1,300 | 0.31 | 8 | 12.2 |
| Six-Lane Undivided / (*TCP4*) | 2,200 | 1,400 | 6,600 | 2,800 | 0.42 | 13 | 13.6 |
| Six-Lane Divided / (*TCP4*) | 2,200 | 1,400 | 6,600 | 2,800 | 0.42 | 13 | 13.6 |
| Six-Lane Undivided / (*TCP5*) | 2,200 | 1,200 | 6,600 | 1,200 | 0.18 | 5 | 12.2 |
| Six-Lane Divided / (*TCP5*) | 2,200 | 1,200 | 6,600 | 1,200 | 0.18 | 5 | 12.2 |
| Multilane Bridge / (*TCP6*) | 2,300 | 1,400 | 9,200 | 2,800 | 0.30 | 8 | 12.2 |

➢ $T_q$ Is the time required to creep through the queue (Sec.)

$$T_q = \frac{L_q}{V_q}$$

❖ $L_2$ Is the minimum distance needed to accelerate from speed equal to $V_q$ to $V_{WZ}$

$$L_2 = V_q T_2 + \frac{a(T_2)^2}{2}$$

➢ $T_2$ Is the time required to accelerate from $V_q$ to $V_{WZ}$ through the work zone, *(hour)*,

$$T_2 = \frac{V_{wz} - V_q}{a}$$

Where:

– $a$ is an average vehicle acceleration rate which is equal to 2,28 m/Sec$^2$ (29458,8km/hr)

❖ $L_3$ Is the remaining work zone length which is equal to $L_o$-$L_2$

$$L_3 = L_0 - L_2$$

$T_3$ Is the time required to creep through the work zone by driving with *($V_{WZ}$), (hour)*,

$$T_2 = \frac{L_3}{V_{wz}}$$

❖ $L_4$ Is the minimum distance accelerate back needed to from $V_{wz}$ to $V_0$

$$L_4 = V_{wz} T_4 + \frac{a(T_4)^2}{2}$$

Where:

– $a$ is an average vehicle acceleration rate which is equal to 2,28 m/Sec$^2$ (29458,8km/hr)

- $T_4$ Is the time required to accelerate back from $V_{WZ}$ to $V_0$,

$$T_4 = \frac{V_0 - V_{wz}}{a}$$

***Cricuity Flow Condition***

Circuity is a term used to describe the additional distance that users travel, either voluntarily or involuntarily, on a detour to avoid a highway work zone or because of the bridge closing situations. For non-detour cases, it is assumed the traffic will remain on the bridge and travel the queue and/or work zone situations. If a formal detour is established and traffic is forced to detour, the associated cost components are described below.

$$T = T_{WZ} - T_o \quad , \quad T_o = \frac{L}{V_o} \quad , \quad T_D = \frac{L_D}{V_D}$$

Where:-

- $T$ is the travel time delay, *(hour)*,
- $T_o$ is the time required to cross the affected bridge length *(L)* during the normal flow conditions, *(hour)*,
- $L_D$ is the length of the detour*, (km)*,
- $V_D$ is the posted detour speed, *(km/hr)*.

If the traffic is forced to detour and the length of the detour is not mentioned as in the construction and demolition stages, assume the length of the detour and the detour velocity are equal to:

$$L_D = 3 \times The\ Bridge\ Lenght$$

$$V_D = 0{,}85 \times V_0$$

### 3.4.5 Work Zone Duration (Nt)

The duration of the maintenance/rehabilitation activity is a major factor in determining the number of days a work zone is required. The work zone duration is defined as the length of time a work activity occupies a specific location. *The manual of uniform traffic control devices (MUTCD) (USDOT/FHWA, 1998)* divides work duration into the following five categories:

- Long-term: for several days or more
- Intermediate-term: from a minimum of one day up to several days
- Short-term: for no more than 12 hours
- Short-duration: for up to one hour
- Mobile-work: a work zone that moves continuously

***Work Zone Velocity ($V_{wz}$)***

"The safety of motorists and construction workers is the top priority of the department," said Transportation Secretary Gene Conti. "Speeding is the number one contributing factor in work zone crashes and the results of this partnership should remind motorists that it will not be tolerated."

- Road User Cost Manual (*NJDOT*)
  - Generally a 10 - 15 mph reduction in the normal speed ($V_0$).
- Chen and Schonfeld, *2003,*
  - On average, $V_{wz}$ is equal to 50 km/hr work zones $V_0$ equal to 80 km/hr
- Michigan Vehicle Code, *1974*,
  - Work zone speed is 45 mph maximum unless otherwise posted,
- National Cooperative Research (NCHRP) report 1996, 2006 adopted by AASHTO,
  - Maximum speed reduction should not exceed 10 mph,
  - In case of worker existence on the work zone, $V_{wz}$ should be less than 45 mph,
- North Carolina Department of Transportation 2008,
  - Typical speed limit reductions are 10 mph below the existing posted speed limit a maximum 15 mph speed reduction may be used,
  - It is strongly recommended that no speed limits below 55 mph be posted on fully controlled access facilities,
  - Speed reduction should applies to an area 1/2 mile in length or greater.
- Recommended Values of $V_{wz}$,
  - Generally a 15 - 25 mph reduction in the normal speed ($V_0$).

**Table 3:7** *Average vehicle length according to bridge configuration*

| Normal speed $V_0$ (km/h) | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
|---|---|---|---|---|---|---|---|---|---|---|
| Recommended $V_{wz}$(km/h) | 25 | 30 | 40 | 50 | 60 | 65 | 75 | 85 | 90 | 95 |

## 3.5 Traffic Characteristics

Bridge user costs are directly dependent on the volume and operating characteristics of the traffic on the bridge. Each construction, maintenance, and rehabilitation activity generally involves some temporary impact on traffic using the facility. The impact can vary from insignificant for minor work zone restrictions on low volume facilities to highly significant for major lane closures on high volume facilities.
The major traffic characteristics of interest for each work zone include such factors as the overall projected Average Daily Traffic (ADT) volumes, the associated 24-hour hourly traffic distributions, and the vehicle classification distribution within the traffic stream. Each of the major traffic characteristics is discussed in the sections that follow.

### 3.5.1 Vehicle Classification

Bridges users are not a homogeneous group. They include commercial and non-commercial vehicles ranging from motorcycles and passenger cars through the heaviest trucks. *Appendix of the*

*FHWA Traffic Monitoring Guide, Third Edition (February 1995)* includes 13 different vehicle classifications. These different vehicle types have different operating characteristics and associated operating costs.
For simplification of vehicle classifications and consistency with available traffic data, it is recommended to use **Passenger Car** and **Truck** classifications only.

***The Truck Percent from the ADT ($r_T$)***

Of course the percentage of the truck on bridges is differing from case to case. Many case studies were tock place to compute the average percent of trucks on the roads or bridges. The following information and equation are concluding some.

- Calgary Region External Truck Survey Study 2001:
  - Average for All Locations 15.3%

- FSOT Florida Traffic Information 2002 :
  - Average for All Locations range from 7,36% to 11,74%

- Based on analysis of intensive traffic surveying data, the recommended value

$$r_T = 0{,}0001\ ADT\ + 8{,}40$$

Where:

- $r_T$ is the percentage of trucks from the AVD,

### 3.5.2 Traffic Growth Rate

Due to factors such as population growth and economic prosperity, the volume of traffic on bridges increases each year. *Johnston et al. (1994)* estimated that the traffic growth on interstate highways is 4.06% and on other highways is 1.94%.

*Calvano (2003)* stated that in Canada the traffic growth between 2006 and 2011 is estimated to be 1.1%. Based on these values, the current ADT estimate in the present user cost model is given in the following equation,

$$ADT_t = ADT \times (1 + 1.1\%)^{Year_t - Year_m}$$

Where:-

- $ADT_t$ is the ADT to be used in the analysis at year t, *(Vehicle/Day),*
- $ADT$ is the measured average daily traffic, *(Vehicle/Day),*
- $Year_t$ is the current year,
- Year $_m$ is the last year in which the ADT is measured.

### 3.5.3 Traffic Control Plan (TCP)

The basic concept of a traffic control plan is to permit the contractor to work on a bridge while maintaining a safe and uniform flow of traffic. TCP are chosen based on the number of bridge lanes and the type of repair. Table 3:8 and Figure 3:5 illustrate some available bridge TCP.

**Table 3:8** *Suggested Traffic Control Plans for Bridge Configurations*

| Bridge Configuration Type | Direction Lanes | | TCP | Notes |
|---|---|---|---|---|
| | Normal | Open | | |
| Two-Lane Undivided | 1 | 1 | Plan 1 | One lane open for traffic in two directions |
| Two-Lane Divided | 1 | 1 | Plan 2 | Shoulder used as a lane in the work zone (*) |
| Four-Lane Undivided | 2 | 1 | Plan 3 | One lane closed in one direction |
| Four-Lane Divided | 2 | 1 | Plan 3 | One lane closed in one direction |
| Six-Lane Undivided | 3 | 2 | Plan 4 | One lanes closed in one direction |
| Six-Lane Divided | 3 | 2 | Plan 4 | One lanes closed in one direction |
| Six-Lane Undivided | 3 | 1 | Plan 5 | Two lanes closed in one direction |
| Six-Lane Divided | 3 | 1 | Plan 5 | Two lanes closed in one direction |
| Multilane | >3 | ≥2 | Plan 6 | Two lanes closed in each direction |
| Special Traffic control Planes | | | | |
| Six-Lane Undivided | 3 | 1,5 | Plan 7 | Two lanes closed in one direction and one lane in the other direction |
| Deck full replacement | | 0 | Plan 8 | Full bridge closure and complete detour |

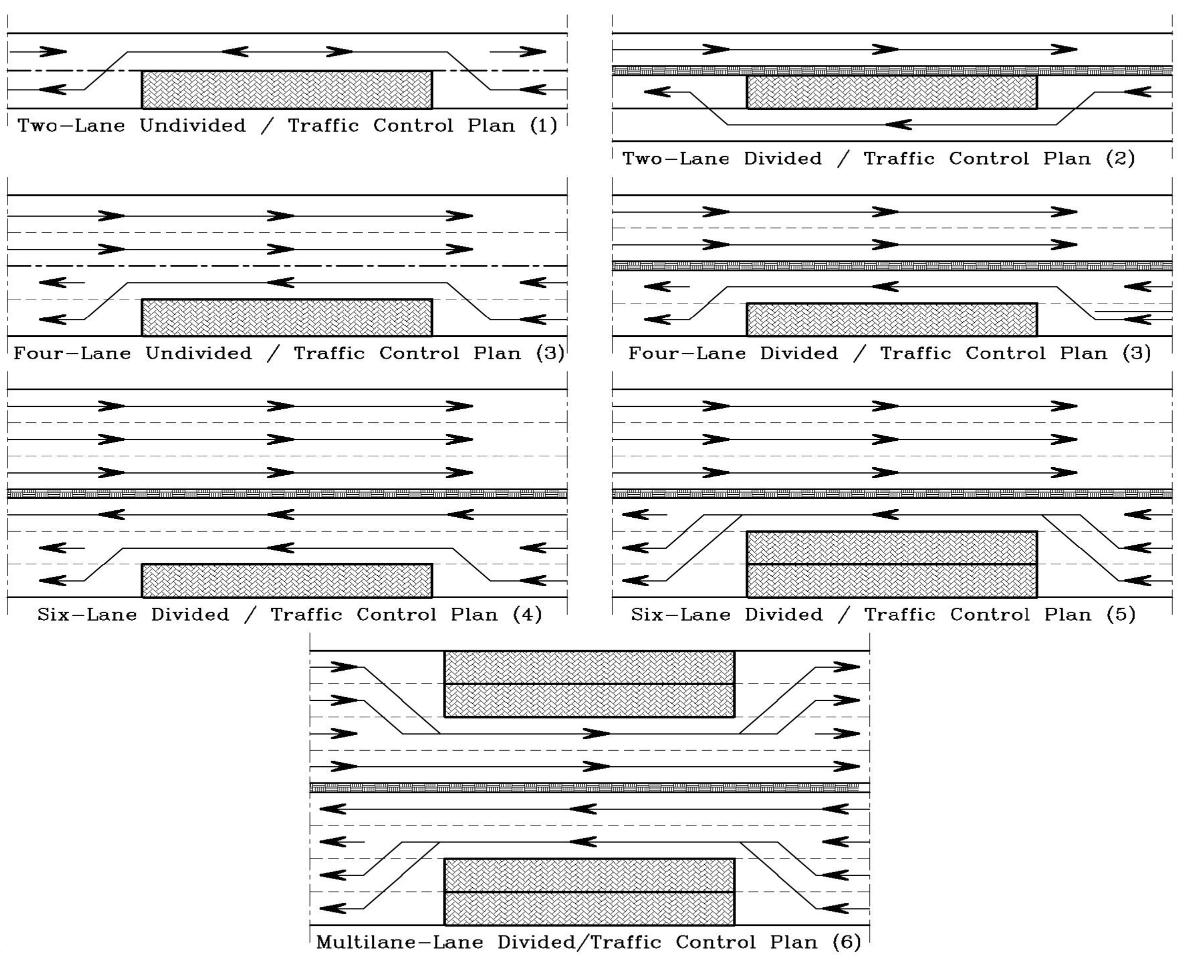



**Figure 3:5** *Suggested Bridge Traffic Control Plans (TCP)*

(*) in this case, the cost of the temporally shoulder must be added as extra cost

### 3.5.4 Bridge Traffic Capacity

Bridge traffic capacity is the maximum number of vehicles passing a point on the bridge at established bridge conditions. In analyzing bridge work zone related user costs, there are two possible capacities:

- o The capacity of the bridge under normal operating conditions,
- o The capacity of the bridge when the work zone is in place,

***Normal Bridge Traffic Capacity***

Normal Capacity is the maximum traffic volume a bridge can handle under normal bridge conditions. Table 3.9 provides the ideal capacity a facility type can handle. The normal capacity of the bridge is used during the non-work zone hours when all traffic lanes are open.

**Table 3:9** *Normal Bridge Traffic Capacity*

| Bridge Configuration Type | Ideal Capacity Veh/lane/hour |
|---|---|
| Two-Lane Undivided | 1,400 |
| Two-Lane Divided | 1,400 |
| Four-Lane Undivided | 2,100 |
| Four-Lane Divided | 2,100 |
| Six-Lane Undivided | 2,200 |
| Six-Lane Divided | 2,200 |
| Multilane Highway bridge | 2,300 |

***Work Zone / Detour Capacity***

Bridge capacity in the work zone is estimated from research studies according to intensive traffic data, and adopted in this chapter according to the traffic control planes Table 3.10 reflects average vehicle flow capacities at several real world work zones under several lane closure scenarios.

**Table 3:10** *Bridge Traffic Capacity in Case of Work Zone*

| Bridge Configuration Type | Traffic Control Plan (TCP) | Recommended Average Capacity Veh/lane/hour |
|---|---|---|
| Two-Lane Undivided | Plan 1 | 600 |
| Two-Lane Divided | Plan 2 | 900 |
| Four-Lane Undivided | Plan 3 | 1,300 |
| Four-Lane Divided | Plan 3 | 1,300 |
| Six-Lane Undivided | Plan 4 | 1,400 |
| Six-Lane Divided | Plan 4 | 1,400 |
| Six-Lane Undivided | Plan 5 | 1,200 |
| Six-Lane Divided | Plan 5 | 1,200 |
| Multilane | Plan 6 | 1,400 |

## 3.6 Developed (BUC) Computer program & Practical Example

As culmination of the progress in this chapter, a simple Excel based computer program was developed; to illustrate this model let us take a real example during a bridge design competition.

### 3.6.1 Practical Example

***Overview***

The project objective is to build, maintain, and eventually dispose of a new interstate bridge. The engineer first makes a general description of the size of the bridge and the environment in which it will exist. The structure is 115 meters long, 14.5 meters wide. The bridge is part of an interstate highway that has a currently traffic volume of 35,000 Vehicle per day. The unrestricted design speed is 90 km/hr. The engineer next lists the minimum performance requirements of the structure that all design proposals must satisfy. The structure must be able to carry the loads prescribed in Bro 2004 specification. The spans between piers must not deflect more that L/800 meters.

A four lanes conventional reinforced concrete bridge is on of the proposed design alternatives which satisfied these performance-based requirements during design competition.

The target now is to calculate the total bridge user cost that will incurred by this design proposal during its whole life cycle.

### 3.6.2 Application using the developed computer program

The developed bridge user cost model is available and can be order from KTH or from the author, the model has four windows, the input window, assumption window, work activation and deactivation window, and the output window. Consequently, using the above mentioned example, the input data window is shown in Figure 3:6 below.

***Input Data Window***

| Input Data | | |
|---|---|---|
| Bridge Type | Conventional Reinforced Concrete Bridge | |
| Bridge Parameters (*m*) | Total Length | Total Width |
| | 115 | 12 |
| Current Average Daily Traffic ADT (*Vehicle/Day*) | Over the Bridge | Under the Bridge |
| | 35000 | 0 |
| Bridge Configuration & Traffic Control Plan | Four-Lane Divided / (TCP3) | |
| Bridge Normal Driving Speed (*km/hr*) | 90 | |
| Bridge Place Type | Interstate Bridge | |
| Work Zone Construction Window | Nighttime Shifts Closure | |

**Figure 3:6** *BUC computer model window No. 1 (Input Data)*

### 3.6.3 Assumptions Window

All of the assumptions are according to the above mentioned system and formulas, but the user can change them according to the bridge situation. Accordingly, the assumption window is shown in the following figure.

| Assumptions | | | |
|---|---|---|---|
| Symbol | Description | Value | Unit |
| $w_p$ | The hourly time value for one passenger care | 14 | $/hr |
| $w_T$ | The hourly time value for one truck | 28 | $/hr |
| $O_T$ | The average hourly operating cost for one truck | 21.5 | $/hr |
| $O_P$ | The average hourly operating cost for one passenger care | 9.5 | $/hr |
| $C_F$ | The average cost per fatal deaths accident for the society | 1500000 | $/crush |
| $C_I$ | The average cost per serious injury accident for the society | 160000 | $/crush |
| $L_0$ | The optimum work zone length | 200 | m |
| $L_D$ | The length of the detour, during construction and demolition stages | 345 | m |
| $V_D$ | The detour Speed | 76.5 | km/hr |
| $r_T$ | The percentage of trucks from the AVD | 11.90% | % |
| $TE$ | The Bidge Expected Life Span | 80 | Year |
| $ADT_m$ | The ADT to be used in the last year of the bridge service life | 83977 | Vehicle/Day |
| $ADT_a$ | The average ADT within the whole bridge service life | 59489 | Vehicle/Day |
| $A_n$ | The bridge accident rates during the normal condition | 5.58995E-08 | accident/veh/L/day |
| $A_a$ | The bridge accident rates during work activities | 7.7659E-08 | accident/veh/L/day |
| $r$ | The real interest rate | 4% | % |
| $P_F$ | The average number of killed persons in bridge related accidents | 0.009 | Persons/Accident |
| $P_I$ | The average number of injured persons in bridge related accidents | 0.991 | Persons/Accident |

**Figure 3:7** *BUC computer model window No. 2 (Assumptions)*

### 3.6.4 Working Tasks Activation Window

According to the bridge type, the user can activate or deactivate of the proposed actions and can also change the intervals or add other working activities. Consequently, using the above mentioned example, work activities window is shown in Figure 3:8 below.

| Work and Activities That Affect and Disturb Traffic | | | | |
|---|---|---|---|---|
| Activation | Action Name | Recommended Intervals(*Year*) | Frequency | Time Required For the whole Bridge in the whole life (day) |
| ☑ | Cleaning the bridge of salt | 1 | 79 | 545.10 |
| ☑ | Maintenance of parapets,gardrail& railing | 1 | 79 | 136.28 |
| ☑ | Maintenance of surface finish and laning | 1 | 79 | 1090.20 |
| ☑ | Deck repair & maintenance | 12 | 6 | 156.40 |
| ☑ | Deck overlay & resurfacing | 26 | 2 | 9.55 |
| ☑ | Deck replacement | 44 | 1 | 112.91 |
| ☑ | Expansion joints repair | 4 | 19 | 45.60 |
| ☑ | Expansion joints replacement | 12 | 6 | 20.40 |
| ☑ | Bridge seat & bearings replacement | 40 | 1 | 5.52 |
| ☑ | Gradrail,railings& parapets replacement | 20 | 3 | 69.00 |
| ☑ | Edge beam impregnation & repair | 25 | 2 | 12.65 |
| ☑ | Edge beam replacements | 50 | 1 | 10.35 |
| ☑ | Superstructure replacements | 50 | 1 | 165.60 |
| ☑ | Substructure replacement | 50 | 1 | 41.40 |
| ☐ | Others | 0 | 0 | 0.00 |

**Figure 3:8** *BUC computer model window No. 3 (Tasks Activation)*

### 3.6.5 Calculation Sheets

The time delay calculation sheets are hidden sheets within the model. Consequently, using the above mentioned example, the time delay calculation sheets which present the computation system are presented in Table 3:11 and Table 3:12 as follow.

**Table 3:3** *BUC Computer model, Time Delay Calculation Sheets*

| Unrestricted Flow Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Design Speed $V_0$(km/h) | 30.00 | 40.00 | 50.00 | 60.00 | 70.00 | 80.00 | 90.00 | 100.00 | 110.00 | 120.00 |
| $L_1$ (*m*) | 23.66 | 35.32 | 45.25 | 55.31 | 65.77 | 85.19 | 96.22 | 108.56 | 134.76 | 161.75 |
| $L_0$ (*m*) | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| $L_3$(*m*) | 0.43 | 1.04 | 1.37 | 1.71 | 2.05 | 3.35 | 3.86 | 4.37 | 6.18 | 8.17 |
| $T_1$ (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_2$(*hr*) | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_3$(*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Affected Bridge length L(*m*) | 224.08 | 236.35 | 246.62 | 257.02 | 267.82 | 288.54 | 300.08 | 312.92 | 340.94 | 369.92 |
| The Travel during work zone $T_{wz}$(*hr*) | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Normal Travel time $T_0$(*hr*) | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Travel Time Delay T (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Travel Time Delay T (*Sec.*) | 4.84 | 6.12 | 3.71 | 2.49 | 1.80 | 2.25 | 1.75 | 1.41 | 1.69 | 1.91 |

| Forced Flow Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Design Speed $V_0$(km/h) | 30.00 | 40.00 | 50.00 | 60.00 | 70.00 | 80.00 | 90.00 | 100.00 | 110.00 | 120.00 |
| $L_1$ (*m*) | 30.03 | 44.99 | 63.90 | 86.23 | 113.17 | 142.67 | 172.75 | 210.25 | 252.83 | 293.31 |
| $L_q$ (*m*) | 26.68 | 26.68 | 26.68 | 26.68 | 26.68 | 26.68 | 26.68 | 26.68 | 26.68 | 26.68 |
| $L_0$ (*m*) | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| $L_2$ (*m*) | 0.01 | 0.01 | 0.03 | 0.04 | 0.06 | 0.07 | 0.09 | 0.12 | 0.14 | 0.15 |
| $L_3$(*m*) | 199.99 | 199.99 | 199.97 | 199.96 | 199.94 | 199.93 | 199.91 | 199.88 | 199.86 | 199.85 |
| $L_4$(*m*) | 0.43 | 1.04 | 1.37 | 1.71 | 2.05 | 3.35 | 3.86 | 4.37 | 6.18 | 8.17 |
| $T_1$ (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_q$ (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_2$ (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_3$ (*hr*) | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_4$ (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Affected Bridge length L(*m*) | 257.14 | 272.70 | 291.96 | 314.62 | 341.90 | 372.70 | 403.29 | 441.29 | 485.69 | 528.16 |
| The Travel during work zone $T_{wz}$(*hr*) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| The Normal Travel time $T_0$(*hr*) | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Travel Time Delay T (*hr*) | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| The Travel Time Delay T (*Sec.*) | 16.03 | 19.11 | 18.96 | 19.87 | 21.28 | 23.04 | 24.40 | 26.06 | 27.66 | 29.01 |

| Circuity (Detour) Flow Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Design Speed $V_0$(km/h) | 30.00 | 40.00 | 50.00 | 60.00 | 70.00 | 80.00 | 90.00 | 100.00 | 110.00 | 120.00 |
| L (*m*) | 115.00 | 115.00 | 115.00 | 115.00 | 115.00 | 115.00 | 115.00 | 115.00 | 115.00 | 115.00 |
| $L_D$ (*m*) | 345.00 | 345.00 | 345.00 | 345.00 | 345.00 | 345.00 | 345.00 | 345.00 | 345.00 | 345.00 |
| $V_D$ (*m*) | 25.50 | 34.00 | 42.50 | 51.00 | 59.50 | 68.00 | 76.50 | 85.00 | 93.50 | 102.00 |
| $T_0$ (*hr*) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $T_D$ (*hr*) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| T (*hr*) | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| The Travel Time Delay T (*Sec.*) | 34.91 | 26.18 | 20.94 | 17.45 | 14.96 | 13.09 | 11.64 | 10.47 | 9.52 | 8.73 |

**Table 3:4** *BUC Computer model, Queued Vehicles Calculation Sheet*

| Time Period (Hour) From | To | Traffic Distribution Factor(%ADT) | Exist Directional Traffic(Veh/hr) | Bridge Directional Normal Capacity (Veh/Dir /hr) | Bridge Directional Up normal Capacity (Veh/Dir /hr) | Queue Rate | Queue Vehicles | Average Queue Vehicles | Average Queue Vehicles per Queue Period per Direction |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 3 | 1.30% | 387 | 4200 | 1300 | -913 | 0 | 0 | Average Queued Vehicles per Queue Period per Lane |
| 3 | 4 | 1.30% | 387 | 4200 | 1300 | -913 | 0 | 0 | |
| 4 | 5 | 1.40% | 416 | 4200 | 1300 | -884 | 0 | 0 | |
| 5 | 6 | 2.10% | 625 | 4200 | 4200 | -3575 | 0 | 0 | 2 |
| 6 | 7 | 3.70% | 1101 | 4200 | 4200 | -3099 | 0 | 0 | |
| 7 | 8 | 4.90% | 1457 | 4200 | 4200 | -2743 | 0 | 0 | Vehicles That Travel Forced Flow Conditions |
| 8 | 9 | 4.90% | 1457 | 4200 | 4200 | -2743 | 0 | 0 | |
| 9 | 10 | 5.20% | 1547 | 4200 | 4200 | -2653 | 0 | 0 | 2600 |
| 10 | 11 | 5.50% | 1636 | 4200 | 4200 | -2564 | 0 | 0 | |
| 11 | 12 | 5.80% | 1725 | 4200 | 4200 | -2475 | 0 | 0 | Vehicles That Travel Unrestricted Flow Conditions |
| 12 | 13 | 5.70% | 1695 | 4200 | 4200 | -2505 | 0 | 0 | |
| 13 | 14 | 5.90% | 1755 | 4200 | 4200 | -2445 | 0 | 0 | |
| 14 | 15 | 6.30% | 1874 | 4200 | 4200 | -2326 | 0 | 0 | 27144 |
| 15 | 16 | 6.90% | 2052 | 4200 | 4200 | -2148 | 0 | 0 | |
| 16 | 17 | 7.20% | 2142 | 4200 | 4200 | -2058 | 0 | 0 | |
| 17 | 18 | 6.60% | 1963 | 4200 | 4200 | -2237 | 0 | 0 | |
| 18 | 19 | 5.30% | 1576 | 4200 | 4200 | -2624 | 0 | 0 | Vehicles That Travel Circuity Flow Conditions (Detour) |
| 19 | 20 | 4.40% | 1309 | 4200 | 1300 | 9 | 9 | 4 | |
| 20 | 21 | 3.80% | 1130 | 4200 | 1300 | -170 | 0 | 4 | |
| 21 | 22 | 3.40% | 1011 | 4200 | 1300 | -289 | 0 | 0 | 0 |
| 22 | 23 | 2.90% | 863 | 4200 | 1300 | -437 | 0 | 0 | |
| 23 | 24 | 2.40% | 714 | 4200 | 1300 | -586 | 0 | 0 | |

### 3.6.6 Results Window

The forth window is the output window. Obviously the bridge user cost is shown according to Figure 3:1, which presents the costs according to the project stages and according to the user cost type. Figure 3:9 illustrate the result of the above mentioned example.

| Output | | Bridge User Cost Component | | | | |
|---|---|---|---|---|---|---|
| | | Traffic Delay Cost | Vehicle operation Cost | Accident Cost | Failure cost | Subtotal |
| Project Stage | Construction & Installation | $366,836 | $255,890 | $0 | $0 | $622,726 |
| | Operation & Maintenance | $178,123 | $124,252 | $82,184 | | $384,558 |
| | Inspection | $0 | $0 | $0 | | $0 |
| | Repair, Replacement & Rehabilitation | $65,292 | $45,545 | $30,125 | | $140,963 |
| | Demolition & landscaping | $10,183 | $7,103 | $0 | | $17,286 |
| Subtotal | | $620,433 | $432,790 | $112,309 | $0 | |
| Total BUC | | $1,165,533 | | For Service Life Of | 80 | Year |

**Figure 3:9** *BUC computer model window No. 4 (Output)*

# 4. BRIDGE AESTHETICAL AND CULTURAL VALUE

## 4.1 Introduction

This chapter is a development, adaption, and modification to the appreciating work which carried out in *ETSI II* project /*SP 3* subproject, by project group which consisting of following persons:

- Dipl. Eng. *Seppo Aitta* from the *Finnish Road Administration*
- Civ. Eng. *Hans Bohman* from the *Swedish Road Administration*
- Civ. Arch. *Eldar Høysæter* from the *Norwegian Road Administration*
- Dr Tech. *Aarne Jutila* from *Insinööritoimisto Extraplan Oy*.

### 4.1.1 Background

Bridges have been part of human settlement for thousands of years. Historic bridges stand as evidence of the power and influence of past societies. They vary greatly in style and reflect the culture and engineering innovation of their society.

Bridges are often seen more or less as sculptures and icons to which the citizens may relate as the soul of the city. This atmosphere and the will to identify the town and its values with an icon may motivate for bold and spectacular solutions. Some projects have exceeded all cost estimates but still it has been possible to fulfill them with success.

Modern bridges exploit the latest technologies and construction techniques. They allow us to challenge the landscape in new ways and so impose our hand on the landscape. It is important to do so well. Location of a bridge, cultural values of the surroundings, landscape, viewpoints of local people, and our understanding of the context should guide our solutions. In short, our bridges should be beautiful.

### 4.1.2 Objective

The aim of this chapter is to facilitate the evaluation of bridge aesthetical and cultural values and relate them to the other important aspects of bridge design and construction, i.e., functionality, economics and techniques.

The second target is to setup some basic design guidelines which can help design teams to produce bridges of aesthetic value, or at least keep them aware of the bridge aesthetics evaluation process.

## 4.2 Issues to be Considered

Ranking of bridges and bridge design proposals is a difficult task. Especially difficult it is, if we have to make aesthetical and cultural values of bridges measurable with other values like cost. At the first sight the easiest way seems to be to establish some kind of jury to evaluate different proposal. Of course the judgment of the jury would be based on individual opinions without an exact scale of measuring. However, an open question still remains: how to convert the judgment to money that seems to be the only common value available when comparing different things. It is generally acknowledged, that such a jury in the case of bridge construction should consist of experts with right education, profession and position, e.g. owners, bridge engineers and architects. In some cases even ordinary people of the local community could be represented.

For the decision making and to bases the work of the jury, some guiding principles have to be setup. The main issue to be clearly stated is where to put weight when comparing different alternatives. This is even more important, if the bridge has special dignity.

In the decision making the following issues have to be considered:

- Classification of bridge sites and its corresponding acceptable additional relative costs
- The considered items and issues and to give them appropriate weights

### 4.2.1 Bridge site classification

**In Finland** the so-called *classification of bridge sites* is used. This system was developed by the *Finnish Road Administration* (*Finnra*). It considers the value of the scenery. A publication "*Siltapaikkaluokitusohje*" (*Guide for Grading a Bridge Site*) already exists (in Finnish).

A four-grade system is used for evaluation of a bridge site:

- Class I Very demanding considering the landscape and city view.
- Class II Demanding considering the landscape and city view.
- Class III Remarkable considering the landscape and city view.
- Class IV Ordinary considering the landscape and city view.

**Class I,** "*very demanding*". This means that the site includes nation wide valuable views or city views, culturally valuable landscape or the most important joints in the transport network. Also the most remarkable waterway crossings within the country and museum bridges belong to this group.

**Class II**, "*demanding*", possess similar characteristics as those belonging to the previous class but their importance is local, for instance remarkable city or village objects and big bridges crossing waterways with less modest views.

**Class III**, "*remarkable*", consists of bridge sites including ordinary waterway crossings and bridge sites at crossings with heavy traffic located outside city or village areas.

**Class IV**, "*ordinary*", consists of bridge sites including roads with low amount of traffic located in an ordinary landscape outside city or village areas as well as sites with low importance where a road or railway crosses a waterway. These kinds of bridge sites usually do not require any special environmental or aesthetical consideration or design.

### 4.2.2 Cost and aesthetics can be complementary

Bridges of aesthetic merit need not be more expensive than ugly bridges. For example the shape of a parapet, abutment or pier might have a negligible impact on costs but a significant improvement visually. However if a bridge is designed to be as cheap as possible then it is unlikely that it will be of aesthetic value. This is not to say that the cheapest bridge is necessarily the ugliest bridge, however it does mean that cost and aesthetics as driving forces in the design process need to be balanced.

‘It is unwise to pay too much. But it is worse to pay too little’

### 4.2.3 Corresponding acceptable additional costs

The acceptance of some additional cost due to the bridge site class and the aesthetics demands may be reasonable; consequently an excellent design or bridge may be 30 % more expensive than a poor solution and could still be chosen.

The relative shares of bridges in the different classes suggested in the "Siltapaikkaluokitusohje" (Guide for Grading a Bridge Site) are given in Table 4:1. Consequently, the additional costs compared to the cheapest possible solution are given in the same table.

**Table 4:1** *corresponding additional relative costs in percentage in the different classes*

| Item | Bridge Site Class | | | |
|---|---|---|---|---|
| | I | II | III | IV |
| Number of Bridges (%) | 1…2 | 5…15 | 65…75 | 15…25 |
| Additional cost allowed | 0…30 | 0…20 | 0…10 | 0 |

No additional cost is allocated to bridges belonging to *Class IV*

## 4.3 Bridge Aesthetics Design Guidelines

For aesthetics to be successful, it must first be considered. It should be an integral part of design and must be considered both in the general form and all the details that support it. The parts must be considered as to how they contribute to the whole.

Generally bridges seem aesthetically more pleasing if they are simple in form, the deck is thinner (as a proportion of its span), the lines of the structure are continuous and the shapes of the structural members reflect the forces acting on them.

The aesthetics of a bridge should be considered at the conception of a project and through every stage of development. Aesthetics is not something that can be added on at the end, it is the final product of the planning, design and procurement process, from initial route selection, through environmental assessment, to detail design and construction.

### 4.3.1 Sensitivity of the bridge type to the context and simplicity

Perhaps the most fundamental response to context is the choice of bridge structure. In most instances it is span length that is the most significant factor in determining the form (and cost) of a bridge. Bridges with a horizontal form are generally preferable to bridges on a grade over flat simple landscapes and significant expanses of water. This can be shown in the following figure.

***Bridges with a horizontal form are generally preferable***

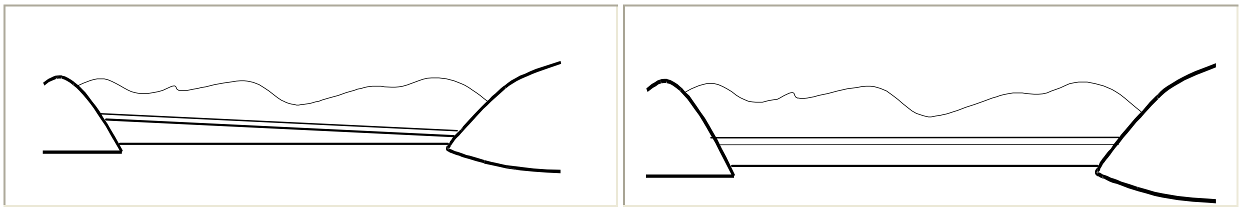


**Figure 4:1** *Proper bridge horizontal form*

The accepted approximate relationship between span and superstructure type is as follows.

- Short span (up to approximately 18m): pre-stressed concrete plank bridges.
- Short to medium span (approximately 18-40m): pre-stressed concrete girders or pre-stressed concrete voided slabs.
- Medium span (approximately 40-80m): steel or post-tensioned concrete box girders or incrementally launched girders.
- Medium to long span (up to approximately 300m): balanced cantilever.
- Long span (up to approximately 800m): cable stay.
- Very long span (longer than 800m): suspension bridges.

### 4.3.2 The bridge form as a whole

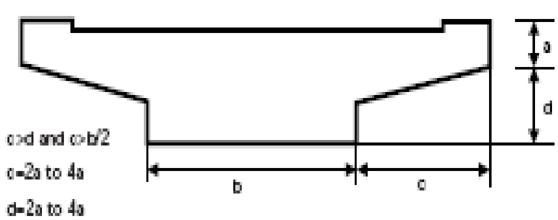
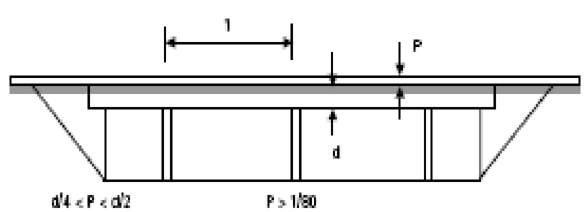
***<u>Proportion</u>***

The dictionary defines proportion as the proper relationship between things or parts.

***Depth to span ratio***

The proportion between depth of superstructure and bridge spans is an important ratio. It is referred to the slenderness of the bridge and is defined as the span length divided by beam depth. Common ratios can vary from 5 to 30. The ratio of five can result in a very chunky bridge although with appearance of strength while 30 can lead to very slender bridge. For a common pier and girder bridge, ratios generally vary between 15 and 20. These notations and recommendations are given in Table 4:2.

**Table 4:2** *Proper proportions guidelines*

<table>
<tr><th colspan="2">Depth to span ratio</th></tr>
<tr><td></td><td></td></tr>
<tr><td>Bridge with a slenderness ratio of approximately 1:12.</td><td>Captain Cook bridge, a slenderness ratio of approximately 1:18.</td></tr>
<tr><td>Deck to parapet depth ratio</td><td>Span to parapet depth ratio</td></tr>
<tr><td>The ratio of deck overhang relative to parapet depth is also considered a significant aesthetic proportion and guidelines have been developed by Cardiff University School of Engineering.<br><br></td><td>A ratio has been developed by Frederick Gottemoeller in his book for the relationship between span and depth and parapet height. These formulae form the basis for a guide to visual proportions.<br><br></td></tr>
</table>

***Symmetry, Order and rhythm***

Symmetrical bridges are often more aesthetically pleasing than nonsymmetrical bridges and symmetry should not be departed from unless for a good reason. Figure 4:2 schematically present the affects.

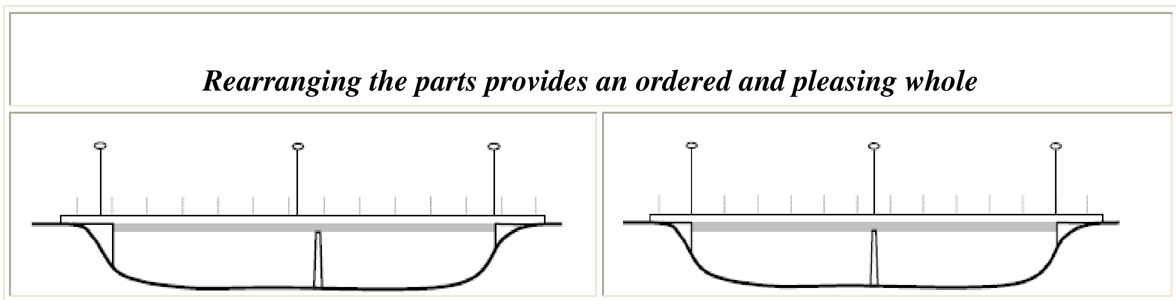



**Figure 4:2** *Bridge Symetry apperancess*

***Unity of design and detail important***

Careful consideration of interrelationship of each element, and their relationship with the whole is necessary at all stages of the design process. Good detailing is essential to good bridge design and lack of attention to detail can spoil an otherwise beautiful bridge.

### 4.3.3 The bridge Parts

***Superstructure***

***Parapet***

The outer face of the parapet can be one of the most important aesthetic elements of a beam bridge. It is the highest piece of the bridge and often the most dominant in long distance views. The following principles (Figure 4:3) should be considered in the design of the parapet.

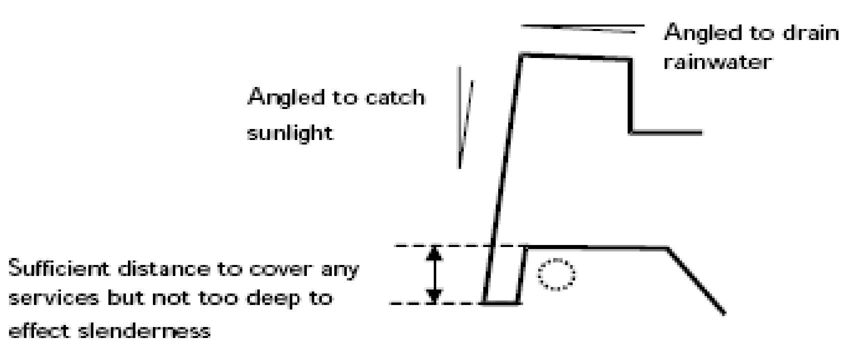
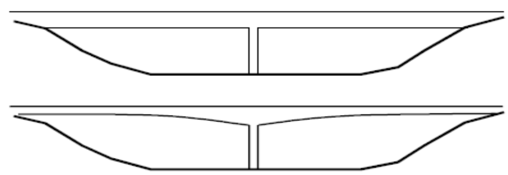
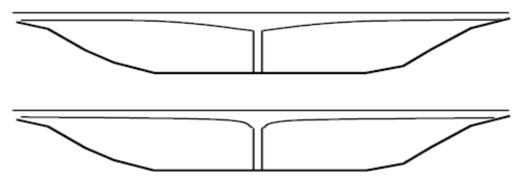
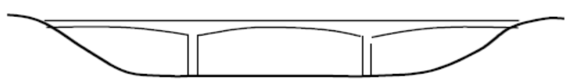
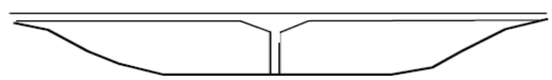



**Figure 4:3** *Proper parapet design principle*

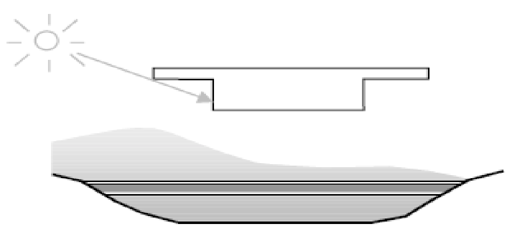
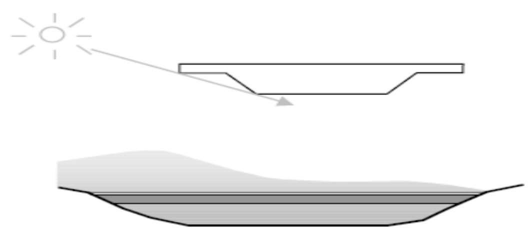
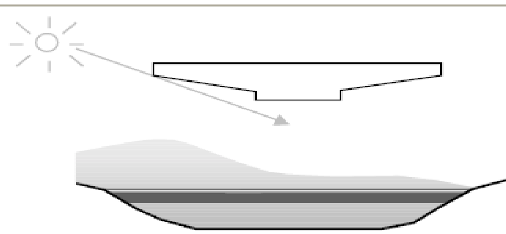
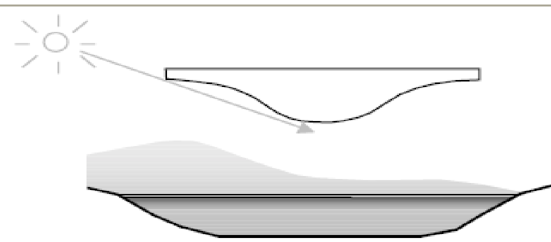
### *Girder elevation*

**Table 4:3** *Proper girder elevation design guidelines*

| | |
|---|---|
| Hunched girders are expressive and responsive to the forces in the bridge. They can often be more distinctive and elegant than single depth beams | Long haunches smoothly tapering out are much more graceful and responsive than short abrupt haunches. |
|  |  |
| Three or five span haunches are aesthetically very elegant balanced structures. | Avoid a sharp angle between haunch and beam. |
|  |  |

### *Girder cross section*

**Table 4:4** *Proper girder cross section design guidelines*

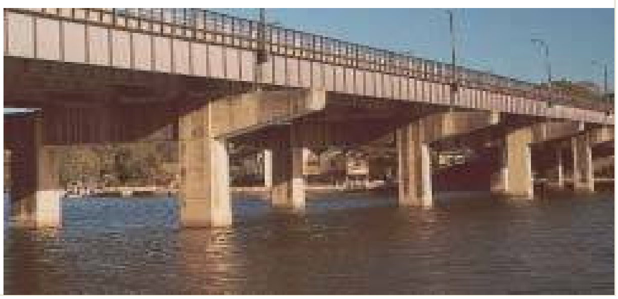
| | |
|---|---|
| Maximizing the overhang will increase the shadow | An angled connection will minimize this effect |
|  |  |
| A very acute angle provides a deep shadow nearly all of the time | A curved soffit will provide a gradation of tone and minimize a sharp line at the base of the beam. |
|  |  |

## ***Substructure***

### *Headstock*

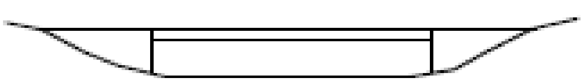
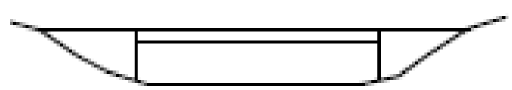
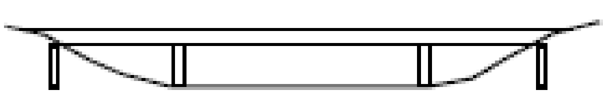
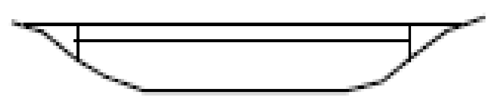
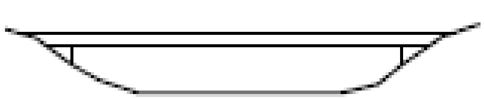
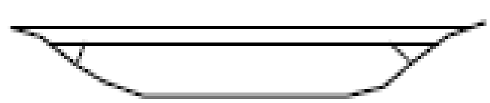
When they are used they draw attention to the pier and the method of support, if avoided they better allow the superstructure to dominate the bridge view. Table 4:5 schematically present the affects.

**Table 4:5** *Proper Headstock design guidelines*

| | |
|---|---|
| The headstock and pier combination on this bridge adds unnecessary complexity and detail | If possible headstocks should not extend across the outer face of the girder. This introduces unnecessary complexity and appears in elevation as if the headstock is supporting the deck rather than the girder |
|  |  |

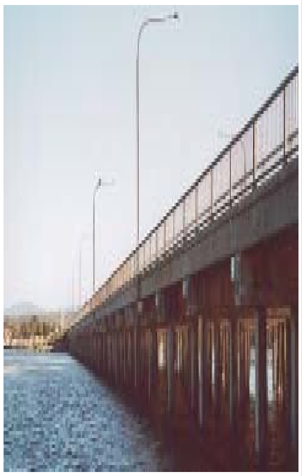
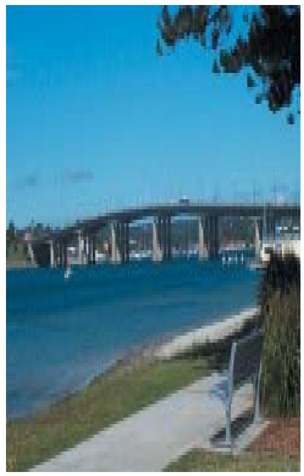
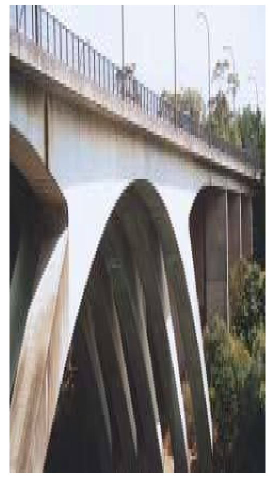
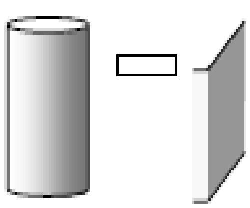
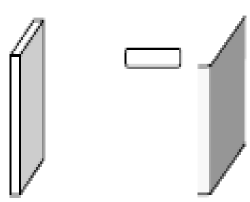
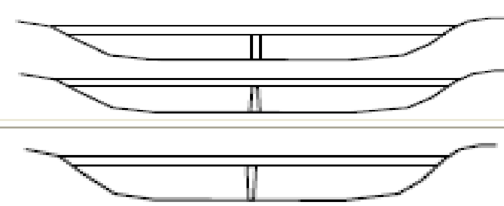
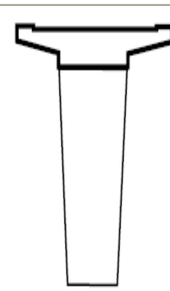
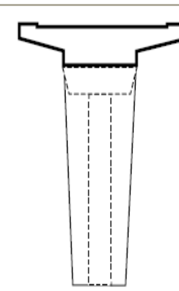
### *Abutment*

**Table 4:6** ***Proper abutment design guidelines***

| | |
|---|---|
| Visible size<br>Spill through abutments allow open views to the landscape and better visibility to the road beyond. | Reducing the abutments can create a more refined and better looking bridge. It does however increase the span and therefore depth of beam. |
|  |  |
|  |  |
| Placement<br>Continuing the superstructure or the parapet allows the shadow line to reduce the dominance of the abutment, and makes the bridge appear longer and more elegant. | Shape<br>Angling the abutments provides a more open sleek look and helps visually anchor the span. |
|  |  |

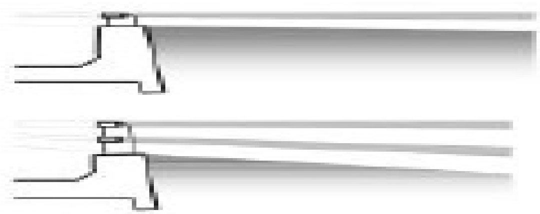
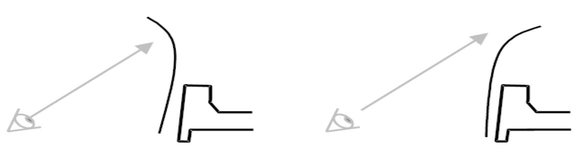
### *Piers*

**Table 4:7** *Proper Headstock design guidelines*

| | |
|---|---|
| Longitudinal pier spacing<br>Too many piers can appear cluttered, while too few piers can result in an overly dominating deep beam, a balance is required | Multiple piers<br>When placed too closely multiple piers can appear complex or wall like, Collecting multiple piers into pairs or clusters can open up views below the deck and also give rhythm and elegance to the supports. |
|   |   |
| Pier cross section<br>Pier shapes with only two lines of symmetry (e.g. ellipses or rectangles) and transverse to the centerline of the deck are preferable to squares and circles as they present the thinnest edge to the side view. Rounding off the corners of rectangular piers provides a softer form, which may be preferable in certain contexts | Pier short elevation<br>Pier shapes which have a slight taper can add elegance by visually adding weight to the bottom where stresses are greatest, economically a taper of around 1:80 is desirable the reverse taper should only be used where the appearance of rigidity is required between superstructure and pier. |
|   |  |
| Pier long elevation<br>A taper can appear elegant and better represents the structural forces acting upon the pier<br>One significant advantage with a reverse taper is that it facilitates the elimination of the headstock |   |

## ***Details***

**Table 4:8** *Proper bridge details design guidelines*

| | |
|---|---|
| Joints and connections<br>A nice joint can enhance the bridge design and provide another level of detailed aesthetic interest. | Bridge barriers & Railings<br>A two rail barrier is better than a single rail barrier in this respect |
|   |   |
| Safety screens<br>An outward curving screen creates a more open feeling for bridge users and reduces the opaqueness of the top of the mesh for road users. However it presents a greater apparent depth of structure for onlookers.<br>The screens should extend to the ends of the bridge span. | Lighting and color<br>The light columns should relate to the other bridge elements in position and form. Where possible lighting on bridges should be minimized or avoided.<br>A neutral palette of black, grays and white colors tend to give a clear definition of the bridge as an object in the landscape. |
|   |  |

## 4.4 Unique Evaluation System

### 4.4.1 Body of the system

The system is based on the idea that points given to different things according to a given scheme and the opinion of the evaluators. The *number n of things* to be considered can be freely chosen and each thing can have different *weight* $w_i$ of importance.

The evaluator rule is to give a numerical values or *points* $p_i$ on a chosen scale to each thing $i$ that is considered.

For each *thing i* the scale can be different, but essential is, that the *extreme values* $p_{imin}$ and $p_{imax}$ are related to each other so that always

$$Pi\min = -Pi\max$$

For evaluating the effect of aesthetical and cultural aspects, *Aesthetical coefficient* $k_{AES}$ calculated by the equation

$$k_{AES} = -a \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_{i\max}\ p_{i\max}}$$

Here $a$ is another non-dimensional *scaling factor* by which the effect of these aspects can be regulated. Finally, the ***r**elative **a**esthetical and **c**ultural **v**alue cost* $\boldsymbol{C_{RACV}}$ of a design or a bridge, is then obtained by equation

$$C_{RACV} = k_{AES} C_{AG}$$

Here $C_{AG}$ is the *Agency cost* obtained by cost calculation considering the construction, repair, maintenance and demolishing costs of the bridge from its whole lifetime. Consequently, the final *life cycle cost* of the bridge *LCC* is

$$LCC = C_{AG} + C_{USER} + C_{RACV} + C_{REI}$$

Where:

- $C_{AG}$ is the corresponding ***Ag**ency cost*.
- $C_{USER}$ is the corresponding ***User** cost*.
- $C_{RACV}$ is the corresponding ***R**elative **A**esthetical and **C**ultural **V**alue cost*.
- $C_{REI}$ is the corresponding ***R**elative **E**nvironmental **I**mpact cost*.

The system described above enables comparison between different design proposals, existing bridges and bridge types as well as evaluation of even different construction methods.

### 4.4.2 Numerical values for $p_i$ and a

The scale for *points* $p_i$ and the corresponding individual values should be chosen so that an evaluator has enough possibilities to distinguish the different designs or bridges, but at the same time not too many categories to keep the evaluation process simple. That is why it is proposed that

a) The scale for each item is the same,

b) The scale varies from -2 to +2

c) Only five categories with even steps are used.

When so, the extreme values $p_{imax}$ have a constant value $p_{max} = 2$ and the categories are as presented in Table 4:9.

**Table 4:9** *Numerical values for the evaluation system and its meaning*

| Category | Explanation |
|---|---|
| -2 | Poor |
| -1 | Modest |
| 0 | Medium |
| 1 | Good |
| 2 | Excellent |

For the non-dimensional *scaling factor a* numerical value ***a* = 0.30** is recommended as it used also in (Guide for Grading a Bridge Site) are given in Table 2. That means that in the extreme cases the Aesthetical coefficient $k_{AES}$ varies between -0.30 and +0.30. This may be reasonable, because consequently an excellent design or bridge may be 30 % more expensive than a poor solution and could still be chosen.

With the values mentioned above *Eq. (2)* takes a reduced form

$$k_{AES} = -a \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_{i\max}\ p_{i\max}} = -0{,}3 \frac{\sum_{i=1}^{n} w_i p_i}{2\sum_{i=1}^{n} w_{i\max}} = -{,}15 \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_{i\max}}$$

To demonstrate the system above, let us take a simple artificial example. Let us assume our bridge is belonging to class II, and we have only two things to consider: aesthetics and culture. Let us consider weight $w_{1max} = 3$ and the latter one weight $w_{2max} = 2$ (weights belonging to the maximum case, case I). Let say in bridge case II the former one have weight $w_1 = 2$ and the latter one weight $w_2 = 1$. Let us further assume that our bridge was given 2 points for its aesthetical values, *i.e.*, $p_1 = 2$, and 1 point for cultural values, *i.e.*, $p_2 = 1$. Thus the Aesthetical coefficient $k_{AES}$ takes the value

$$k_{AES} = -{,}15 \times \frac{(2 \times 2) + (1 \times 1)}{2 \times (3 + 2)} = -{,}15 \times \frac{5}{10} = -{,}075$$

Which means that, because the bridge proposal that we are evaluating is beautiful or have a good value of aesthetics and culture, so it will reduce the agency cost by = 0,075 = 7,5 %.

In case where $k_{AES}$ is (+ *ve*), that's mean the proposal that we are evaluating is ugly or have bad aesthetical and cultural value, so it will increase the agency cost by the value of $k_{AES}$

### 4.4.3 Bridge site classes

The same four classes which used in the publication "*Siltapaikkaluokitusohje*" (*Guide for Grading the Bridge Site*) mentioned above. According to that publication, there are four different bridge site classes as follows in Table 4:10

**Table 4:10** *Bridge site classes and its meaning*

| Class | Explanation |
|---|---|
| Class I | Very demanding |
| Class II | Demanding |
| Class III | Remarkable |
| Class IV | Ordinary |

That means that *Class IV* is the lowest one and does not require any special aesthetical attention, where no additional cost is allocated to bridges belonging to this class (*Table 3.2*).

### 4.4.4 Recommended considered evaluation items

The numerical values $w_i$ recommended here are dependant on the bridge site classes. For a computer program to be developed, the user is then supposed to evaluate these items according to the proposed scale. Depend on particular cases, the user is supposed to change these values to more suitable values or some times neglect or add other things, if needed. The recommended consider items are presented in Table 4:11 as follow.

**Table 4:11** *List of the evaluation considered items and its weight factors in each bridge site class*

| **The Considered Items:-** | | | | **Weight Factors $w_i$** | | | |
|---|---|---|---|---|---|---|---|
| | | | | Class I | Class II | Class III | Class IV |
| Bridge type sensitivity to the context and structure simplicity | | | | 12 | 8 | 4 | 0 |
| The Bridge Form as a Whole | Symmetry, Order & Rhythm | | | 6 | 4 | 2 | 0 |
| | Unity of design & Harmony of spans | | | 6 | 4 | 2 | 0 |
| | Proportion | Depth to span ratio | | 4 | 3 | 1 | 0 |
| | | Deck to parapet depth ratio | | 3 | 2 | 1 | 0 |
| | | Span to parapet depth ratio | | 3 | 2 | 1 | 0 |
| The Parts | Superstructure | Parapet design & shape | | 6 | 4 | 2 | 0 |
| | | Girder | Elevation | 6 | 4 | 2 | 0 |
| | | | Cross section | 6 | 4 | 2 | 0 |
| | Substructure | Headstock and pier combination | | 8 | 5 | 3 | 0 |
| | | Piers | Longitudinal pier spacing | 4 | 3 | 1 | 0 |
| | | | Pier cross section | 4 | 3 | 1 | 0 |
| | | | Pier short elevation | 3 | 2 | 1 | 0 |
| | | | Pier long elevation | 4 | 3 | 1 | 0 |
| | Abutments | Visible size | | 3 | 2 | 1 | 0 |
| | | Placement | | 4 | 3 | 1 | 0 |
| | | Shape | | 3 | 2 | 1 | 0 |
| | Details | Joints and Connections | | 4 | 3 | 1 | 0 |
| | | Barriers & Railings | | 5 | 3 | 2 | 0 |
| | | Lighting, Color & Embellishments | | 6 | 4 | 2 | 0 |
| | | $\Sigma$ | | 100 | 68 | 32 | 0 |

## 4.5 Practical Application and Testing

### 4.5.1 The case background

As a practical application of how we handle aesthetics, we can look at the current (2009) bridge over the *Motala Bay* in the Middle of Sweden. In order to get a nice and beautiful bridge, a bridge design competition was arranged. Seven architectural firms were invited to participate. Nine different proposals were sent in to the Swedish National Road Administration.

The proposals on, how to design the bridge, should contain a lot of documents describing the bridge from a lot of different aspects as:

The *Motala Bay Bridge* is located in a small town called *Motala*. The town was founded in 1822 and has 30 000 inhabitants. It is situated in the western part of *Östergötland* by the *Göta Canal* outlet into Sweden's second largest lake, *Lake Vättern*, right between *Stockholm* and *Gothenburg*. The bridge - still in design phase in early 2009 - crosses the *Motala Bay* and will be about 600 meters long. The map of the building site is shown in Figure 4:4


**Figure 4:4** *Map of the Motala Bay Bridge area.*

### 4.5.2 The considered design proposals

Three design proposals are considered here.

***Proposal Nr. 1*** is a continuous steel-concrete composite box girder bridge with inclined struts supporting the side cantilevers and inclined V-shape legs made from steel around the main span that is 156 meters long. The side spans are 72 and 123 meters on one side and 123, 72 and 42 meters on the other, altogether six spans. The sum of spans is 588 meters and the total length 610 meters (Figure4:5 and Figure 4:6).

On both sides of the bridge there is a pedestrian and cycling lane slightly below the road level. The cross-section is symmetric with respect to the center line of the bridge and constant throughout the bridge. The steel box part of the superstructure is supported by the sub-structure. Longitudinally the bridge is symmetric with respect to the waterway, but outside that area it is not. Due to the modest structural depth, 4 meters, the height of the bridge remains relatively small reducing the maximum slope to 35 ‰. Vertical clearance under the bridge is 22,5 meters on a length of 40 meters. Embankments are not steeper than 1:2. Indirect lighting and spotlights on the inclined legs will be provided. The traffic density on the bridge will be about 6300 vehicles per day.

**Figure 4:5** *Side view of the bridge according to Proposal Nr. 1.*

**Figure 4:6** *Perspective view of the bridge according to Proposal Nr. 1*

**Figure 4:7** *Side view of the bridge according to Proposal Nr. 2*

***Proposal Nr. 2*** is a continuous steel-concrete composite box girder bridge with a long arch span, 191 meters, in the middle. The bridge consists of nine spans: 40+3x48+191+3x48+40 = 559 meters. The arch is made from steel. The width of the bridge is 23 meters. The height of the bridge is 25,5 meters and vertical clearance in the main span is 22,5 meters on a length of 40 meters. The arch is curved in horizontal plane just as the girder, too. There is a pedestrian and cycling lane on one side of the deck (Figure 4:7 and 4:8 and 4:9). The traffic density on the bridge will be about 6300 vehicles per day. The design life length of the bridge is planned to be 120 years.

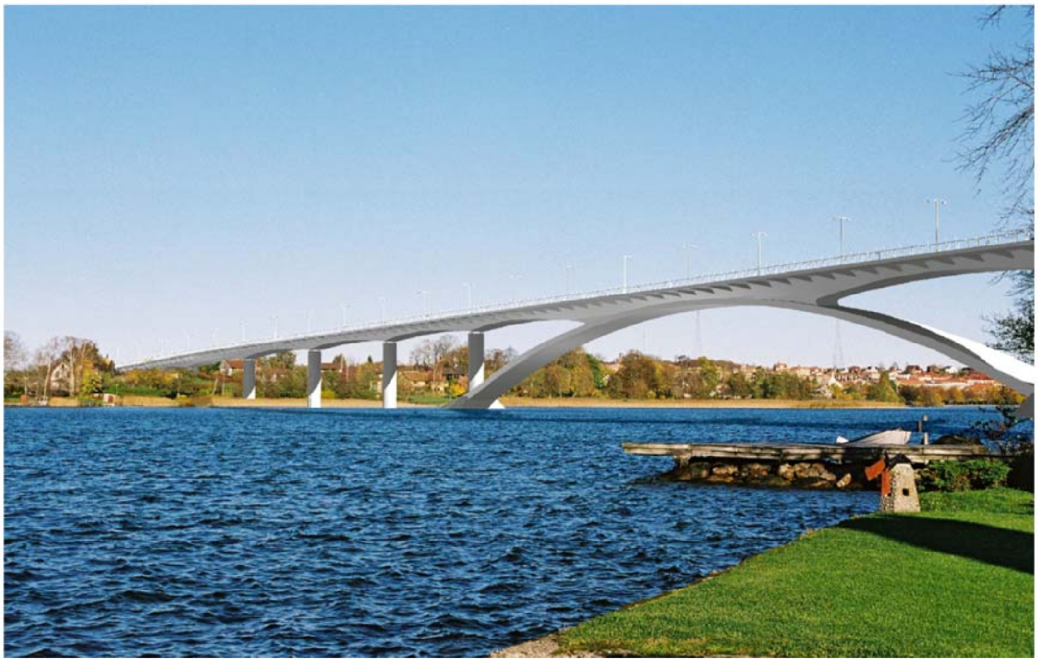


**Figure 4.8** *Perspective view of the bridge according to Proposal Nr. 2.*

**Figure 4.9** *Perspective view of the bridge according to Proposal Nr. 2.*

10

**Figure 4.*10*** *Perspective view of the approaching span according to Proposal Nr. 2.*

***Proposal Nr. 3*** is a continuous prestressed concrete box girder bridge whose 6 out of 13 spans are supported by cables. So the bridge actually is a combined box girder and cable-stayed bridge. Its spans are 36+2x54+60+4x72+60+3x54+42 = 756 meters. The total width of the deck is 24,7 meters. In the cable-supported spans there are four and in the other spans 5 boxes side by side. The deck is unsymmetrical with respect to the center line of the bridge and to the cable planes that are located in the middle of the bridge. There is a pedestrian and bicycle lane only on one side of the bridge. The five pylons supporting the stay-cables form a monolithic structure with the superstructure without any joints. At the other piers, however, and at the abutments the superstructure is supported by bearings. The design life length of the bridge is planned to be 120 years. Photomontage views of the bridge are shown in Figure 4:11, 4:12, and 4:13.

**Figure 4:11** *Side view of the bridge according to Proposal Nr. 3*

**Figure 4.*12*** *Perspective view of the bridge according to Proposal Nr. 3.*

**Figure 4.*13*** *Perspective view of the approaching span according to Proposal Nr. 3*

The following figure presents the three design proposals including superstructure and the whole bridge cross section for each alternative.

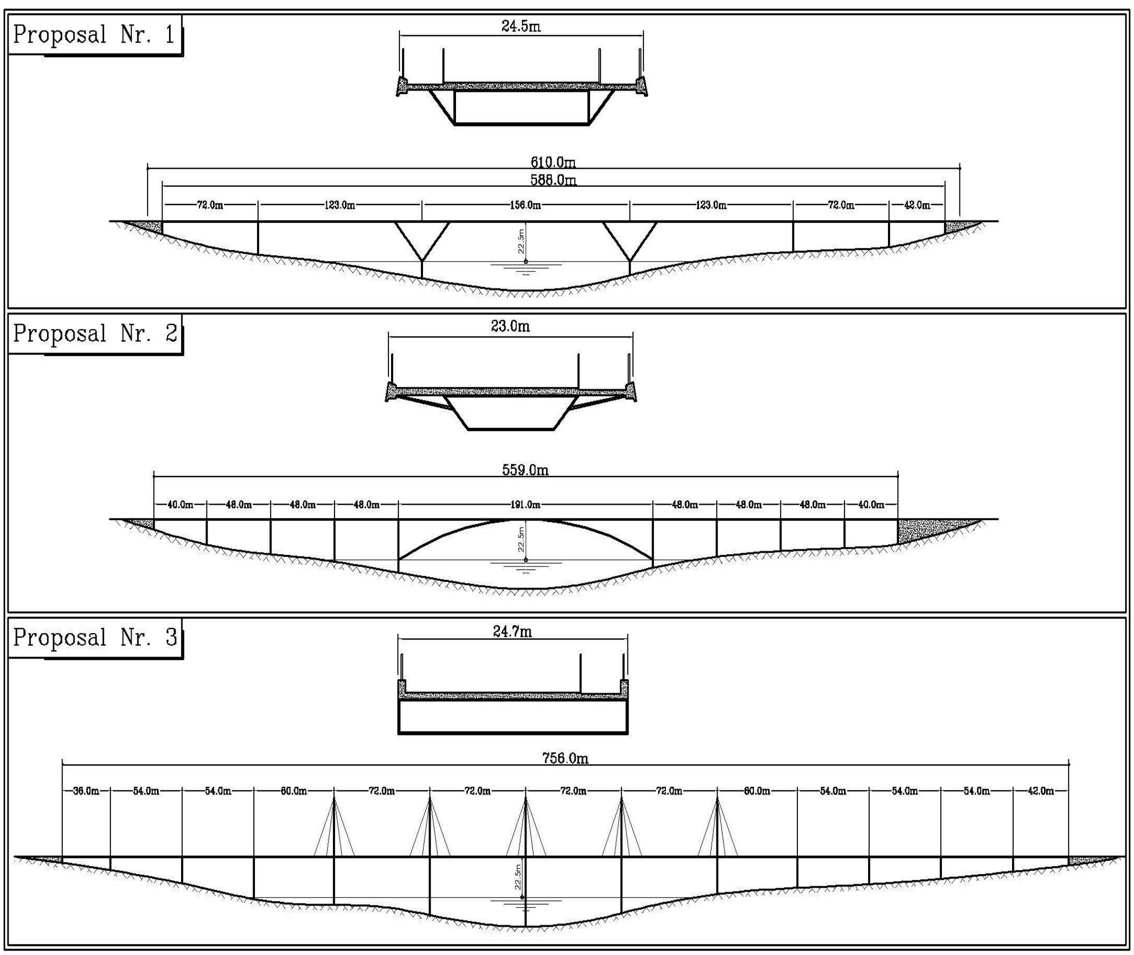



**Figure 4:14** *Conclusion of the given data in the three proposals*

### 4.5.3 The evaluation process

The testing procedure was carried out so that each of the four evaluators studied the documents available and then individually tried to evaluate first the bridge site and then the proposals themselves. Finally the outcome was compared and discussed.

#### *The bridge site classification*

Evaluation of a bridge site should be based on maps and documents available and on site visits. Four different items were evaluated and the corresponding bridge classes were determined corresponding to each item. Consequently the final bridge site class could be determined. The process is described in Table 4:12.

**Table 4:12** *The process used in the evaluation of the Motala Bay Bridge class*

| Evaluated item | Class | Arguments |
|---|---|---|
| Location of the bridge site | II | The bridge site is located between two inhabited islands. There is settlement on both shores and due to that the daily traffic is considerable. Furthermore, the road leading to the ferry is part of the archipelago ring road that is kept open for tourists in summer time. The bridge will replace the present ferry. |
| Value of the landscape | I | *Björkö* and *Mossala* villages with there storehouses on shore are considered as a valuable landscape even on countrywide level. The bridge site is part of this valuable cultural landscape. |
| Cultural value of the bridge site | II | Important environment considering the history of the area. In the vicinity there is the *Lills-Kills croft* that is protected by the support of the building protection law. |
| Aesthetical demands of the bridge | II | The bridge is part of valuable landscape. The bridge may not be a too dominating element but shall be suited to the nearby surrounding. |
| Overall evaluation of the bridge site class | I-II | Especially demanding or demanding bridge site. |

After a short discussion, however, it was not difficult for the evaluators unanimously to agree that the bridge site class in this case is *Class II* ("*Demanding*"). That fixed the weights accordingly (Table 4:11).

#### *Evaluation of the bridge proposals themselves*

The most difficult part is to define the considered items and the weight factors for the different items in each of the three cases, followed. Consequently, value 0,30 for the *scaling factor a* was accepted. The item list was agreed to be the one proposed in this report Table4:11.

Consequently, according to *Table 4.11Class II*

$$\sum_{i=1}^{n} w_{i\max} = \sum_{i=1}^{20} w_{iclassI} = 12+6+6+4+..........+6 = 100$$

Thus, Consequently:

$$\sum_{i=1}^{n} w_{i\max}\ p_{i\max} = 2\sum_{i=1}^{20} w_{iclass\ 1} = 2\times 100 = 200$$

The complete results of the evaluation are presented in a compact mathematical form below. The *Aesthetics coefficient* $k_{AES}$ is of main concern. In this particular case (bridge site class II)

$$k_{AES} = -a\frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_{i\max}\ p_{i\max}} = -0.30\frac{\sum_{i=1}^{20} w_{i(classII)}\, p_i}{200} = -.0015\sum_{i=1}^{20} w_{i(classII)}\, p_i$$

According to *Table 3.12 Class II,* to cover all evaluation cases, a matrix presentation is used. Thus, *weight vector* $\{w_i\}$ is:

$$\left[w_{i(classII)}\right] = \left[8\quad 4\quad 4\quad 3\quad 2\quad 2\quad 4\quad 4\quad 4\quad 5\quad 3\quad 3\quad 2\quad 3\quad 2\quad 3\quad 2\quad 3\quad 3\quad 4\right]$$

Where $\{k_{AES}\}$ is the final *Aesthetics coefficient vector dimension 1x5*, ($p_i$) is the *evaluation result matrix*, dimensions 5x20, which in this case has the value

In the case of ***Proposal Nr. 1*** the evaluation result matrix $\{p_i\}$ takes the form

$$[p_i] = \begin{bmatrix} 1 & 1 & 0 & 2 & 1 \\ 1 & 1 & 1 & 2 & 1 \\ 2 & 1 & 1 & 2 & 2 \\ 2 & 1 & 2 & 1 & 2 \\ 2 & 2 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 2 & 2 & 1 \\ 2 & 1 & 1 & 1 & 1 \\ 1 & 2 & 1 & 1 & 1 \\ 1 & 2 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 2 & 2 & 1 & 2 & 2 \\ 0 & 1 & 1 & 2 & 1 \\ 0 & 1 & 2 & 1 & 1 \\ 1 & 1 & 2 & 1 & 1 \\ 2 & 2 & 2 & 1 & 2 \\ 2 & 0 & 1 & 2 & 1 \\ 1 & 2 & 1 & 1 & 1 \\ 1 & 1 & 2 & 2 & 2 \\ -1 & -2 & -1 & 0 & -1 \end{bmatrix}$$

In the matrix, the first column represents the points which the first evaluator gave to the twenty different items. The points are listed in the same order as in Table 4:11, or in the list just above *Eq.* Similarly, the second column consists of the points given by the second evaluator, and so on until the fourth column, which is related to the fourth evaluator. The values in the fifth column are simply the roundup average values of the four previous ones on the same row.

When the operation shown by equations is carried out using the numerical values presented in above, the final results will be as follow.

$$\{k_{ASE}\} = \{-.108 \quad -.104 \quad -.102 \quad -.134 \quad -.114\}$$

The same for ***Proposal Nr. 2,*** the final *aesthetics coefficient vector* $\{k_{AES}\}$ takes the form:

$$\{k_{ASE}\} = \{-.118 \quad -.121 \quad -.122 \quad -.142 \quad -.128\}$$

Similarly for ***Proposal Nr. 3*** final *Aesthetics coefficient vector* $\{k_{AES}\}$ takes the form:

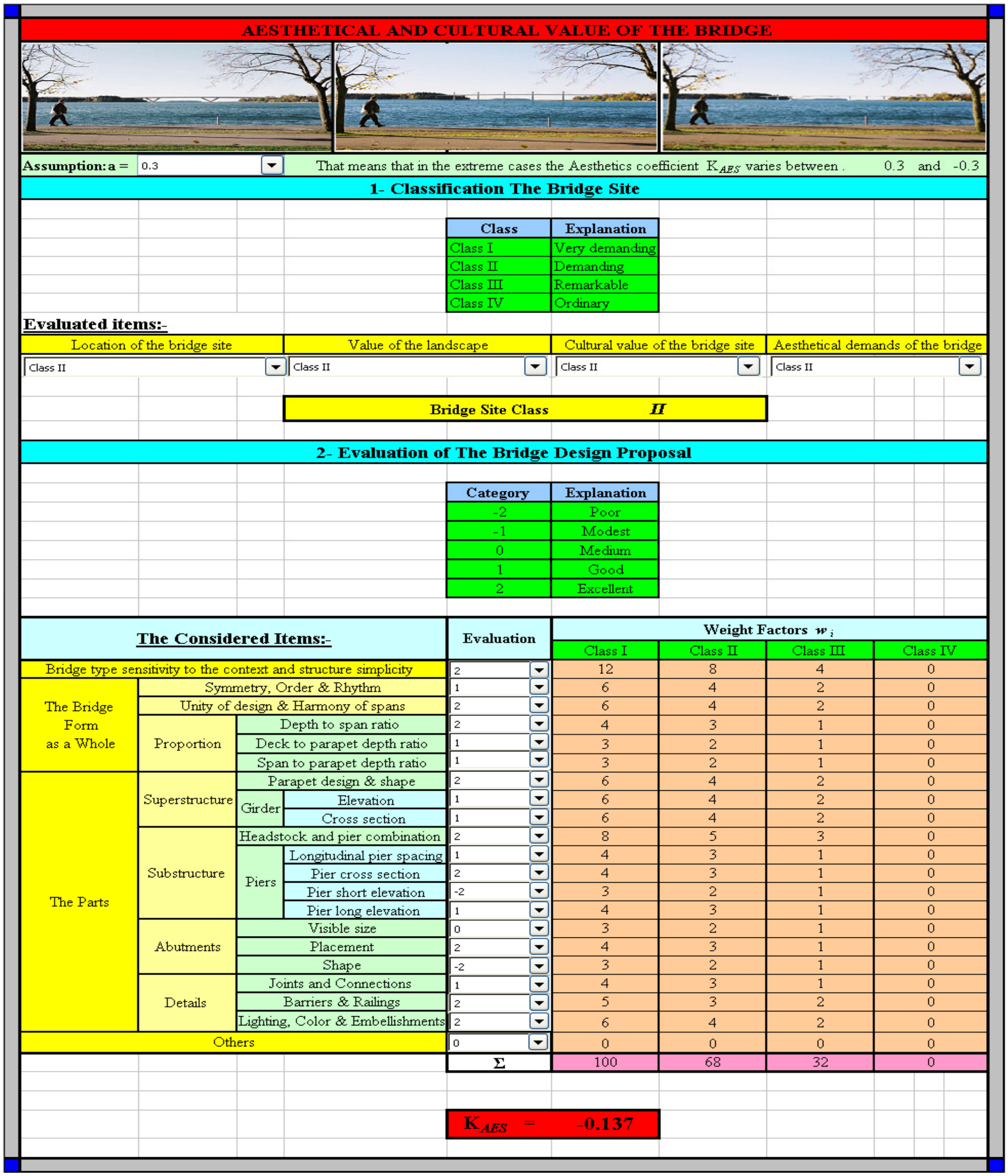
$$\{k_{ASE}\} = \{-.084 \quad -.064 \quad -.041 \quad -.091 \quad -.074\}$$

The test carried out shows that the evaluation method developed is easy to use and mathematically simple. The judgments of the four evaluators were in most cases surprisingly similar. Although some differences appeared in some details, they were greatly balanced out in the final result. The smallest differences are in the cases of *Proposal Nr. 1* and *Proposal Nr. 2*, where the *Aesthetics coefficient* $k_{AES}$ varies between -0,102 and -0,134, and -0,118 and -0,142, respectively. In the case of *Proposal Nr. 3* the variation is bigger, from -0,041 to -0,091, but even in this case every evaluator comes to the conclusion that the aesthetical and cultural values of the proposal are positive. Based on these results *Proposal Nr. 2* seems to be slightly superior to *Proposal Nr. 2* and *Proposal Nr. 3.* And it occupies the last position in this evaluation.

Better than to compare the judgments of individual evaluators might be to compare the average values. According to *Eqs.,* the variation between the different proposals is extremely small, from -0,114 to -0,128 in the average values. Maybe the average value give more objective result, when there are several evaluators, as it was the case in the test evaluation carried out. The final order between the three proposals, however, is still the same: *Proposal Nr. 2* is slightly superior to *Proposal Nr. 2* and *Proposal Nr. 3* occupies the last position

## 4.6 Developed Computer Program

As a culmination of progress in this chapter and its unique aesthetics evaluation system, a simple computer program is developed. The program is composing all of the things which is explained and mentioned in above in a very simple systematic way. The program can as easily be used by an individual as by a jury or group of evaluators. The front page shape is as shown in Figure 4:15.



AESTHETICAL AND CULTURAL VALUE OF THE BRIDGE

Assumption: a = 0.3 — That means that in the extreme cases the Aesthetics coefficient $K_{AES}$ varies between . 0.3 and -0.3

**1- Classification The Bridge Site**

| Class | Explanation |
|---|---|
| Class I | Very demanding |
| Class II | Demanding |
| Class III | Remarkable |
| Class IV | Ordinary |

**Evaluated items:-**

| Location of the bridge site | Value of the landscape | Cultural value of the bridge site | Aesthetical demands of the bridge |
|---|---|---|---|
| Class II | Class II | Class II | Class II |

Bridge Site Class *II*

**2- Evaluation of The Bridge Design Proposal**

| Category | Explanation |
|---|---|
| -2 | Poor |
| -1 | Modest |
| 0 | Medium |
| 1 | Good |
| 2 | Excellent |

| The Considered Items:- | | | | Evaluation | Weight Factors $w_i$ Class I | Class II | Class III | Class IV |
|---|---|---|---|---|---|---|---|---|
| Bridge type sensitivity to the context and structure simplicity | | | | 2 | 12 | 8 | 4 | 0 |
| The Bridge Form as a Whole | Symmetry, Order & Rhythm | | | 1 | 6 | 4 | 2 | 0 |
| | Unity of design & Harmony of spans | | | 2 | 6 | 4 | 2 | 0 |
| | Proportion | Depth to span ratio | | 2 | 4 | 3 | 1 | 0 |
| | | Deck to parapet depth ratio | | 1 | 3 | 2 | 1 | 0 |
| | | Span to parapet depth ratio | | 1 | 3 | 2 | 1 | 0 |
| The Parts | Superstructure | Parapet design & shape | | 2 | 6 | 4 | 2 | 0 |
| | | Girder | Elevation | 1 | 6 | 4 | 2 | 0 |
| | | | Cross section | 1 | 6 | 4 | 2 | 0 |
| | Substructure | Headstock and pier combination | | 2 | 8 | 5 | 3 | 0 |
| | | Piers | Longitudinal pier spacing | 1 | 4 | 3 | 1 | 0 |
| | | | Pier cross section | 2 | 4 | 3 | 1 | 0 |
| | | | Pier short elevation | -2 | 3 | 2 | 1 | 0 |
| | | | Pier long elevation | 1 | 4 | 3 | 1 | 0 |
| | Abutments | Visible size | | 0 | 3 | 2 | 1 | 0 |
| | | Placement | | 2 | 4 | 3 | 1 | 0 |
| | | Shape | | -2 | 3 | 2 | 1 | 0 |
| | Details | Joints and Connections | | 1 | 4 | 3 | 1 | 0 |
| | | Barriers & Railings | | 2 | 5 | 3 | 2 | 0 |
| | | Lighting, Color & Embellishments | | 2 | 6 | 4 | 2 | 0 |
| Others | | | | 0 | 0 | 0 | 0 | 0 |
| | | | | Σ | 100 | 68 | 32 | 0 |

$K_{AES}$ = -0.137

**Figure 4:15** *shape of the developed computer program*

## 4.6.1 Introduction

Practical use of the program is simple, only 4 steps to get the bridge proposal equivalent aesthetical and cultural coefficient $K_{AES}$ o, the user is only have to chose the alternative form a build up list of choices, he don't have to enter any other values, or perhaps he may have to, if he decided to change the weight factors of the considered items to suit down his case of study.

### 4.6.2 Working steps description

The first Step is to agree about the value the *scaling factor a*. It also needs to be determined in advance, because it has a decisive influence on the level of appreciation of aesthetical values compared to costs. The value 0,30 is recommended and its sounds reasonable, because in extreme cases it restricts the effect of aesthetics up to ±30 %, but of course also any other value between is possible. Even this value should be determined by the bridge owner. In Finland the are usually using $a$=0,30 as its mentioned in *Table 3.12*

The second step is to evaluate the bridge site by determining which class the bridge site is belongs to. However, four items have to be evaluated to reach this target and so the average value of these four items will be the class of the bridge site.

The third step is to agree about the items that will be evaluated and to determine weight of each item. This should be done before the evaluation process begins. The weights should be considered as "*fixed values*" and may not be changed during the evaluation process. One is totally free to choose any items and their number is by no means restricted.

Too detailed item may cause difficulties to the evaluator. In this program, almost a standard list of items and there weights is included, which fairly cover the general bridge aesthetics demands, it can easily be altered to meet the requirements of the project in question, whether by giving "*zero weight*" to those items that are left outside consideration or/and by adding new item by changing the last cell name form *others* to the new name, and give it the suitable weight factor in each bridge site class.

The forth and final step includes the evaluation itself, *i.e.*, the determining of *points* $p_i$ for each considered item, however, a fixed scale is determined with $p_{max} = - p_{min} = 2$, with steps equal to 1 here one has to decide between five different values, *i.e.* -2, -1, 0, 1 and 2, according to his point of view. It can be done by choosing the value form a buildup list beside each considered item.

In case of individual user, he can chose the points $p_i$ easily form each list according to his view point, simply if there is a jury or group of evaluators they can use this program by entering the average evaluation value for each consider item.

When the evaluator has decided on *points* $p_i$, it is a simple mathematical task to calculate the final values of *Aesthetics coefficient* $k_{AES}$ and all of these equations are built up in this program.

### 4.6.3 Example

Let us take a simple example, which may illustrate the procedure better, Let us consider the case of average evaluation in the previous example for proposal number 1, by keeping the same value of $a$=0,30 and the bridge site is belong to *Class II*. The average evaluation from the matrix, which is column number 5, which is as following:

$$\{Pi\} = \{1 \quad 1 \quad 2 \quad 2 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 2 \quad 1 \quad 1 \quad 1 \quad 2 \quad 1 \quad 1 \quad 2 \quad -1\}$$

**AESTHETICAL AND CULTURAL VALUE OF THE BRIDGE**

**Assumption: a =** 0.3 — That means that in the extreme cases the Aesthetics coefficient $K_{AES}$ varies between 0.3 and -0.3

**1- Classification The Bridge Site**

| Class | Explanation |
|---|---|
| Class I | Very demanding |
| Class II | Demanding |
| Class III | Remarkable |
| Class IV | Ordinary |

**Evaluated items:-**

| Location of the bridge site | Value of the landscape | Cultural value of the bridge site | Aesthetical demands of the bridge |
|---|---|---|---|
| Class II | Class II | Class II | Class II |

**Bridge Site Class** *II*

**2- Evaluation of The Bridge Design Proposal**

| Category | Explanation |
|---|---|
| -2 | Poor |
| -1 | Modest |
| 0 | Medium |
| 1 | Good |
| 2 | Excellent |

| The Considered Items:- | | | | Evaluation | Weight Factors $w_i$ Class I | Class II | Class III | Class IV |
|---|---|---|---|---|---|---|---|---|
| Bridge type sensitivity to the context and structure simplicity | | | | 1 | 12 | 8 | 4 | 0 |
| The Bridge Form as a Whole | Symmetry, Order & Rhythm | | | 1 | 6 | 4 | 2 | 0 |
| | Unity of design & Harmony of spans | | | 2 | 6 | 4 | 2 | 0 |
| | Proportion | Depth to span ratio | | 2 | 4 | 3 | 1 | 0 |
| | | Deck to parapet depth ratio | | 1 | 3 | 2 | 1 | 0 |
| | | Span to parapet depth ratio | | 1 | 3 | 2 | 1 | 0 |
| The Parts | Superstructure | Parapet design & shape | | 1 | 6 | 4 | 2 | 0 |
| | | Girder | Elevation | 1 | 6 | 4 | 2 | 0 |
| | | | Cross section | 1 | 6 | 4 | 2 | 0 |
| | Substructure | Headstock and pier combination | | 1 | 8 | 5 | 3 | 0 |
| | | Piers | Longitudinal pier spacing | 1 | 4 | 3 | 1 | 0 |
| | | | Pier cross section | 2 | 4 | 3 | 1 | 0 |
| | | | Pier short elevation | 1 | 3 | 2 | 1 | 0 |
| | | | Pier long elevation | 1 | 4 | 3 | 1 | 0 |
| | Abutments | Visible size | | 1 | 3 | 2 | 1 | 0 |
| | | Placement | | 2 | 4 | 3 | 1 | 0 |
| | | Shape | | 1 | 3 | 2 | 1 | 0 |
| | Details | Joints and Connections | | 1 | 4 | 3 | 1 | 0 |
| | | Barriers & Railings | | 2 | 5 | 3 | 2 | 0 |
| | | Lighting, Color & Embellishments | | -1 | 6 | 4 | 2 | 0 |
| Others | | | | 0 | 0 | 0 | 0 | 0 |
| | | | | Σ | 100 | 68 | 32 | 0 |

$K_{AES}$ = -0.114

**Figure 4:16** *Practical example in the developed program*

Figure 4:16 describes the usage and the application of the model. By entering this values of *points* $p_i$ in the program, consequently the value of *Aesthetics coefficient* $k_{AES}$ = -0.114 which is the same value that on equation number (11) column number 5.

According to the proposed list of items and its weight factors and the recommended value of a=0.30, the extreme values of the *Aesthetics coefficient* $k_{AES}$ will be as followed in table 4:13.

**Table 4:13** *The extreme values of the Aesthetics coefficient* $k_{AES}$ *according to table 3.12 data*

| *a*=0.30 | Class I | Class II | Class III | Class IV |
|---|---|---|---|---|
| Excellent Design $K_{AES}$ max | -0.30 | -0.204 | -0.096 | 0 |
| Bad Design $K_{AES}$ min | 0.30 | 0.204 | 0.096 | 0 |

### 4.6.4 Practical use of the program

The program is concluding a unique system that enables to incorporate aesthetical values to bridge design or construction projects and to make them comparable with construction and lifecycle costs. The method can be used beneficially in the following cases:

- Evaluation of aesthetical values with respect to the initial construction costs.
- Comparison of different bridge design proposals within a project or in engineering skills - including bridge design - competitions.
- Comparison of different routes where bridges are involved during the feasibility study stage or construction phase.
- Rewarding - or punishing - of those involved when an aesthetically better - or worse - result is achieved than expected.

The method can as easily be used by an individual as by a jury or group of evaluators. Due to its simple mathematical formulation it can also be easily incorporated in a LCC computer program to become part of it.

# 5. BRIDGE ENVIRONMENTAL IMPACT

## 5.1 Introduction

Environmental indicators demonstrate significant impacts of current concrete infrastructure systems. Construction, maintenance and demolition of bridges demand materials and energy inputs, which in turn lead to environmental impacts. New infrastructure and maintenance of existing infrastructure has led to a global output of construction-related concrete that exceeds 12 billion tons per year (van Oss and Padovani 2002b). This enormous volume represents huge flows of material between natural and human systems, which is expected to increase significantly as world population urbanizes (UNFPA 2001). Cement production accounts for 5% of all global anthropogenic carbon dioxide ($CO_2$) emissions (Hendricks et al. 1998, Worrell 2001) and significant levels of $SO_2$, $NO_x$, particulate matter and other airborne pollutants (WBCSD 2002, US EPA 1999, US EPA 2000).

## 5.2 Issued to be Considered

### 5.2.1 Project development stages and considerations

Modeling the complete life cycle of a bridge system is complex and data intensive. When we talk about the bridge environmental impact we have to put in mind to consider all bridge life cycle stages, as shown in Figure 5:1, considering the input and the output as well. The main parameters that should be considered during the assessing process are as follow.

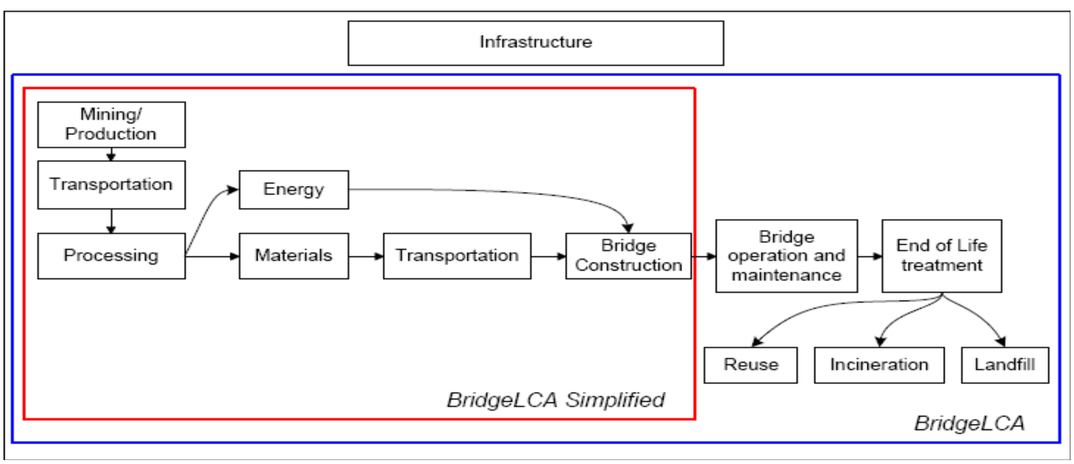



**Figure 5:1** *Bridge LCA path*

- ✓ Material resource consumption (The Usage of un renewable materials)
- ✓ Air and water pollutant emissions
- ✓ Solid waste generation
- ✓ Energy use
- ✓ Fuel consumption
- ✓ Emissions from the traffic

### 5.2.2 Toxics Classification

There are thousands of chemicals affecting human health and the environment, hundreds of different known mechanisms and many other unknown or incompletely known mechanisms. While toxicologists would not normally combine compounds unless common models of action have been demonstrated, LCA add all toxics into one overall score even if modes of actions are known to be different.

Each of all the various environmental stressors throughout the life cycle, relative to the functional unit, are summarized and then classified into impact categories, according to which environmental impact(s) the stressors contribute to. Established impact assessment methods cover various impact categories, like for instance global warming, acidification, toxicity etc. This method includes characterization factors for 10 impact categories as shown in Figure 5:2; Abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP) global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), fresh water ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP) and photochemical ozone creation potential (POCP). However, the 4 toxicity categories are, for the time being, omitted in *BridgeLCA*, due to high uncertainties in the calculation principles of these.

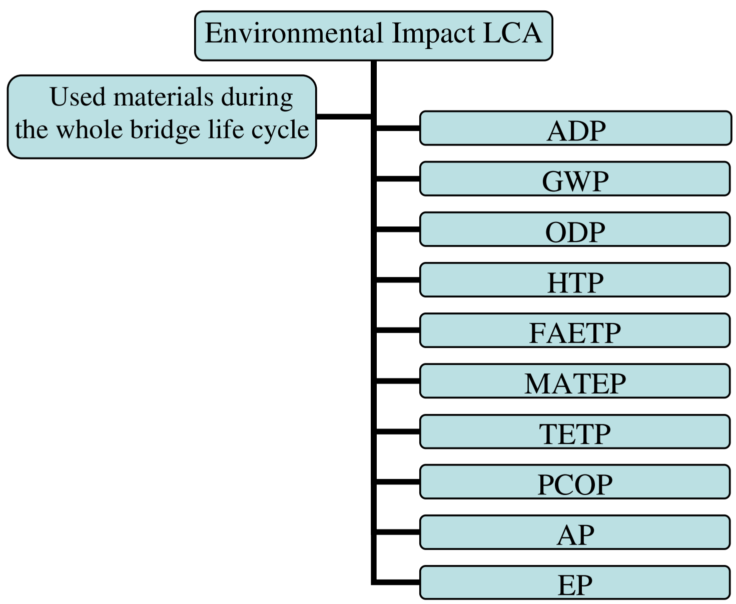



**Figure 5:2** *Bridge emissions categories*

### 5.2.3 Toxics categories weighting impacts

The best way is to calculate the environmental impact per category using characterization indicators. These indicators are based on the physicochemical mechanisms of how different substances contribute to the different impact categories. E.g. Global-warming potential is one of the environmental categories and CO2 is the equivalent for this category. Methane that is a green house gas which contributes 23 times as much to global warming than CO2, is multiplied with a factor of 23, and added to the category as CO2-equivalents.

The following graphs (Figure 5:3) present normalized and weighted results. Normalization is done by dividing the impacts per category by the average emissions (relevant for the respective category) per person per year, in Western Europe in 1995. Further, the normalized results are multiplied by weighting factors, which is a measure of the categories' relative importance. The weighting factors used here are taken from the BEES software, and are determined by the Environmental Protection Agency (USA).

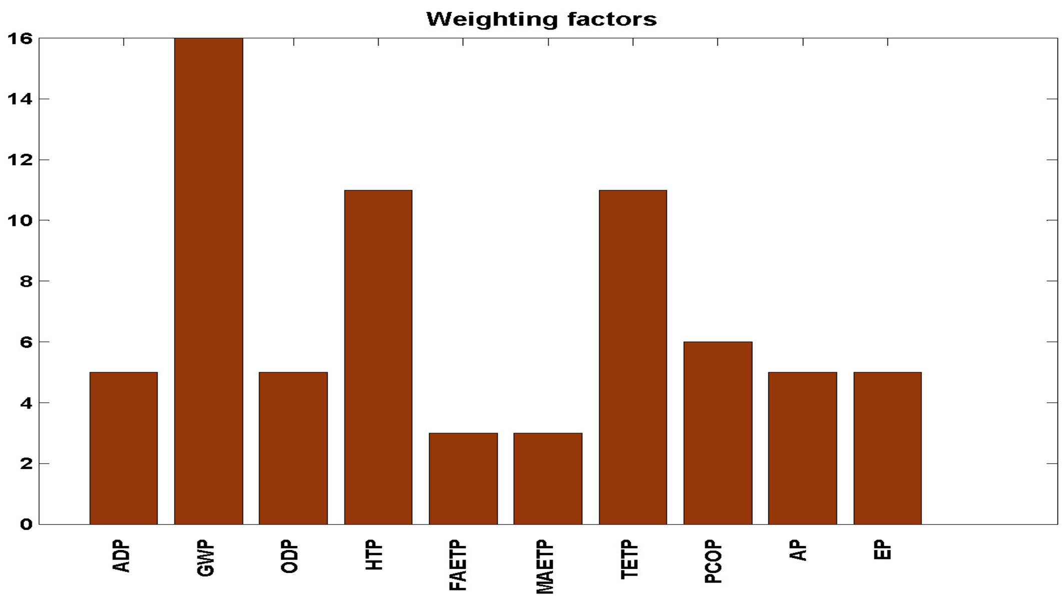



**Figure 5:3** *Environmental Protection Agency (USA) emissions weighting factors*

### 5.2.4 Life cycle assessment (LCA)

Life cycle assessment is an analytical technique for evaluating the full environmental burdens and impacts associated with a product system (ISO 1997). Life cycle assessment is a global tool, calculating burdens throughout the life cycle of a product, material or service. Its strength is that it quantifies all possible environmental burdens; its weakness is low spatial and temporal resolution.

## 5.3 Presentation of Previous Studies

There are only few scientific publications available on the topic of environmental effects of bridges; the relevant articles are briefly presented in this section.

***Comparison of different bridge deck component alternatives***

Keoleian and Kendall, compare two types of deck systems; a steel-reinforced concrete deck with conventional steel expansion joints and a steel-reinforced concrete deck with a link slab design using a concrete alternative (Figure 5:4); engineered cementations composites (ECC). ECC is fiber reinforced and has a strain capacity 500-600 times higher than normal concrete. It also prevents nearly all corrosion of girders by reducing leakage of corrosive elements usually occurring through worn expansion joints. Corrosion of steel girders is one of the main causes for replacement of deck and superstructure. The study includes material production, construction, use and end-of-life management related to bridge the decks. Initial bridge construction is similar for both studies and therefore omitted. Three reconstruction options are considered; bridge deck replacement, deck resurfacing and repair and maintenance (mainly fixing of cracks and potholes). Traffic disruption during these activities is also included. Various air and water pollutants are considered5. The ECC link slab deck is assumed a lifetime twice the lifetime of the deck with conventional joints. Conclusions made in the analysis are that the ECC deck yields significantly lower environmental impacts, for all pollutants, mainly because of less need for maintenance. For both deck systems, the construction and repair related traffic turn out to be significant for the environmental performance. It is also concluded that prediction of maintenance and repair schedules for each system is critical in evaluating the performance of alternative materials.

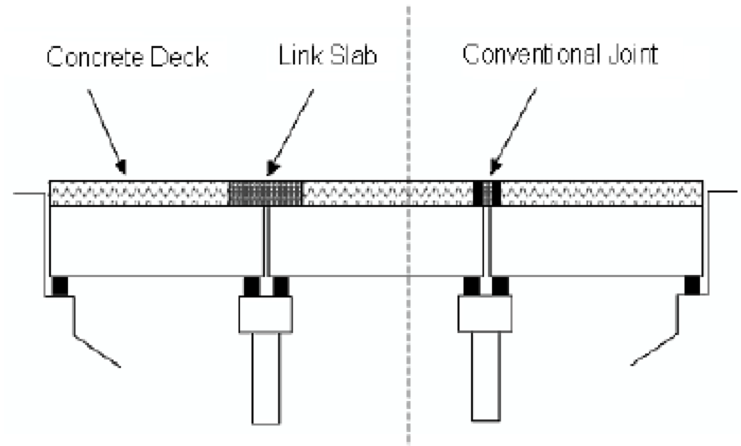



**Figure 5:4** *Keoleian and Kendall comparison case study*

### *Comparison of bridge types and designs*

Collings presents two studies where three bridge types and three bridge designs are compared, respectively. The bridge types compared are a concrete cantilever bridge, a concrete cable stay bridge and a steel arch bridge. Relative costs and CO2 emissions for the material consumptions and the use phase of the bridges are considered. The main conclusions are that both costs and emissions are highest for the steel arch bridge, actually twice as high as for the concrete cantilever bridge that gives the lowest costs and emissions. Paint, waterproofing and plastics have relatively high values per ton of embodied energy and CO2 emissions.

The bridge designs compared are a profiled girder bridge, a tied arch bridge and a cable-stayed bridge, designed for a longest span of 120 m, and 3 smaller spans (66 m in total) at each end. Three material choices for each design alternative are assessed. The embodied energy and CO2 emissions from the construction phase and the CO2 emissions during the lifetime of the bridge are given, assuming a lifetime of 120 years. Maintenance activities included are repainting, bearing replacement, re-surfacing and re-waterproofing. Traffic disruption due to maintenance is also included. The main conclusions from this study are that concrete bridges have lower embodied energy and CO2 emissions. More architectural designs like leaning or distortion of elements have larger environmental impact, as they require more materials and more complex construction. Emissions during the use phase are approximately the same for the three material alternatives. The maintenance activity causing most of the emissions in the use phase is resurfacing of the bridge. The traffic disruption due to repair and maintenance are a highly uncertain parameter, as it depends on amount of traffic, proportion of lorries and diversion distance.

## 5.4 Case study

BridgeLCA is computer program developed in the ETSI Stage 2 by Johanne Hammervold, based on the use of three case bridges; one steel bridge, one concrete bridge and one wooden bridge. The bridges are already built bridges in Norway, and are thus not planned for the same location. They differ in size and are not directly comparable. The concrete bridge, Hillersvika, has longer construction length and width, and thus requires the most materials. The steel bridge, Klenevågen, is the shortest bridge. An overview of the bridges and key parameters are given in following Table:

**Table 5:1** *BridgeLCA case study parameters*

| | Klenevågen | Fretheim | Hillersvika |
|---|---|---|---|
| Type | Steel box girder | Wooden arch | Concrete box girder |
| Span length | 42.8 m | 37.9 m | 39.3 m |
| Construction length | 44.2 m | 45.4 m | 51.9 m |
| Effective bridge width | 7.5 m | 6.1 m | 10.6 m |
| Construction width | 8.5 m | 8.7 m | 12.2 m |
| Headway | 4.1 m | - | 7 m |
| Traffic lanes | 2 | 1 | 2 |
| Pavement | 0 | 1 | 1 |

### 5.4.1 Total weighted results

Total weighted results, given in Figure 5:5, show that Klenevågen (steel box girder bridge) causes the highest impacts, closely followed by Hillersvika (concrete girder bridge). Fretheim (wooden arch bridge) causes roughly half the impacts as Klenevågen. The most important categories in total weighted results are Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP) for all three bridges. Acidification Potential (AP) is also a relatively important category, while Ozone Depletion Potential (ODP) is negligible in these results.

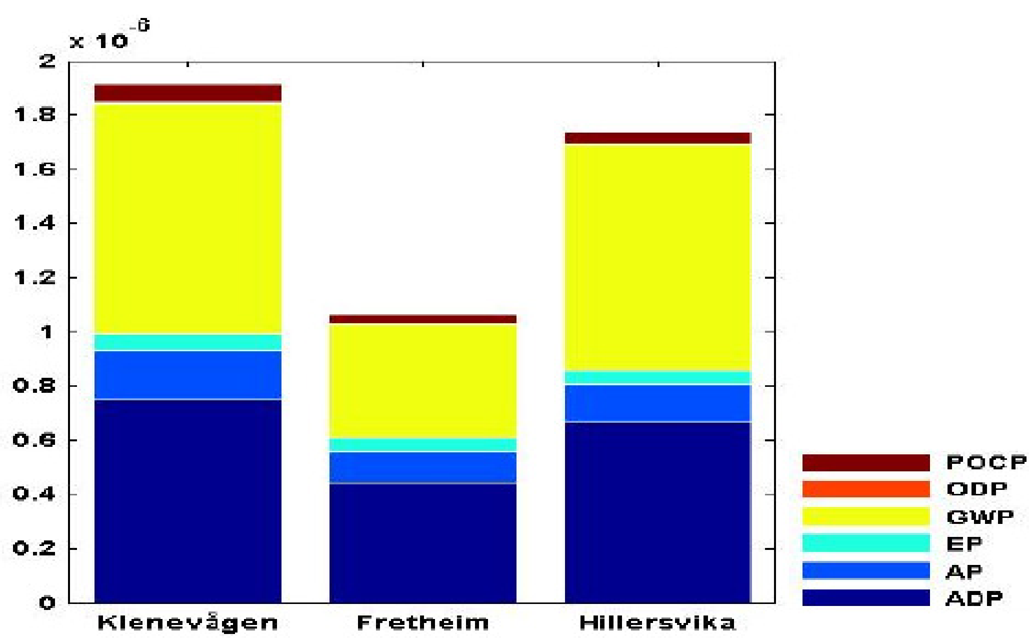



**Figure 5:5** *Case study total weighted result*

### 5.4.2 Result per bridge and category

The impacts caused by material and energy consumptions related to various bridge as totals per bridge and impact category as given in Table 5:2 below. In the category Abiotic Depletion Potential bridge equipment and the use phase (OR&M) also contribute substantial shares of the impacts. This is mainly caused by the surfacing of the bridges. The original surfacing is part of the bridge equipment, and re-asphalting is performed each 10$^{th}$ year throughout the lifetime. Asphalt, asphalt membrane and mastic are all bitumen products, which consume raw oil in production which again causes the impacts to the ADP category.

For all three bridges, the construction phase causes a small share of the impacts to all categories. The construction phase includes use of formwork and building machines and transport of workers and materials. The results show that these factors are of less importance in this analysis.

**Table 5:2** *Total results per bridge and category*

| | ADP | AP | EP | GWP | ODP | POCP |
|---|---|---|---|---|---|---|
| Unit | kg Sb eq | kg $SO_2$ eq | kg $PO_4$ eq | kg $CO_2$ eq | kg CFC-11 eq | kg $C_2H_4$ eq |
| Klenevågen | 2.2E+03 | 9.8E+02 | 1.7E+02 | 2.6E+05 | 2.7E-02 | 9.2E+01 |
| Fretheim | 1.3E+03 | 6.4E+02 | 1.3E+02 | 1.3E+05 | 1.9E-02 | 4.9E+01 |
| Hillersvika | 2.0E+03 | 7.7E+02 | 1.3E+02 | 2.5E+05 | 3.0E-02 | 6.4E+01 |

### 5.4.3 Impact per m$^2$ surface area of the bridge

Table 5:3 show the impact for each category per m$^2$ of the bridge surface area. It is important to keep in mind that a comparison per m2 will neither give directly comparable results. The material and energy consumptions, and also transport services and operation, repair and maintenance activities will not vary linearly relative to bridge size. One example is the abutments; the size of these will not change if bridge length is changed, but it will change if the width of the bridge is changed. The main load-bearing systems and their consumption of materials will differ with bridge length and width, but only to a certain degree, and definitely not linearly.

**Table 5:3** *Impacts for each category, per m2 surface area of bridge*

| | ADP | AP | EP | GWP | ODP | POCP |
|---|---|---|---|---|---|---|
| Unit | kg Sb eq / $m^2$ | kg $SO_2$ eq / $m^2$ | kg $PO_4$ eq / $m^2$ | kg $CO_2$ eq / $m^2$ | kg CFC-11 eq / $m^2$ | kg $C_2H_4$ eq / $m^2$ |
| Klenevågen | 6.5E+00 | 2.9E+00 | 4.9E-01 | 7.5E+02 | 8.0E-05 | 2.7E-01 |
| Fretheim | 5.7E+00 | 2.8E+00 | 5.5E-01 | 5.5E+02 | 8.2E-05 | 2.1E-01 |
| Hillersvika | 4.7E+00 | 1.8E+00 | 3.1E-01 | 6.0E+02 | 7.3E-05 | 1.5E-01 |

Finally, the ***R****elative* ***E****nvironmental* ***I****mpact cost* $\boldsymbol{C_{REI}}$ of a bridge, is then obtained by equation:

$$C_{REI} = k_{EI} C_{AG}$$

- $k_{EI}$ Is the environmental impact coefficient. Range from 0,0 To +0,20

Could complement information to be used in the topic, but is not presented here. For more information see ETSI Stage 2.

# 6. SUMMARY

## 6.1 Conclusion and Discussion

This master thesis was devoted as a research study within ETSI project, which is a Scandinavian contributed project. ETSI project is contributed between three Nordic countries, Sweden, Norway, and Finland. The main task of the ETSI project is to develop a Nordic unified methodology and computer program for bridge LCC calculations.

The idea behind this study is that, bridges investment decisions should consider all of the costs and considerations incurred during the period over which the alternatives are being compared. Bridges are required to provide service for many years. The ability of a bridge to provide service over time is predicated on its being maintained appropriately by the agency. Thus the investment decision should consider not only the initial activity that creates a public good, but also all future activities that will be required to keep that investment available to the public. It is important to note that the lowest agency cost option may not necessarily be implemented when other considerations such as aesthetical and cultural value, user cost, and environmental concerns are taken into account.

This research study demonstrates a unique methodology and present a new systematic way for analysis, evaluation, and optimization of the bridge life cycle indicators like agency cost, user cost, aesthetical and cultural value, and the environmental impact. Present a unique flexible system integrating all of bridge life cycle issues and make them measurable and comparable like the bridge initial cost.

Based on this unique evaluation system, two computer programs were developed to facilitate the usage, one for calculating the bridge user cost and one to evaluate the bridge aesthetical and cultural value. The application of this integrated model to bridge design highlighted a critical importance of using the life cycle modeling in order to enhance the sustainability of bridges infrastructure systems.

## 6.2 Recommendation and Further Research

The application of this integrated model to bridge design highlighted the critical importance of using the life cycle modeling in order to enhance the sustainability the bridges. Fields for future research and development can be in the following issues.

- Sorting and gathering of agency historical data to feed the LCCA process
- Degradation models for all kinds of bridges and their structural elements.
- Tools for transforming degradation models into timings for MR&R actions.
- Methodologies for describing bridges both regarding their measures, structural parts and their conditions.
- Development of the proposed two computer models

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