Papers

Volume 7: 2004-2008

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Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

CHAPTER 132

USER COSTS IN LIFE-CYCLE COST-BENEFIT (LCCB) ANALYSIS OF BRIDGES[1]

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ABSTRACT

In this paper a very brief presentation of a study of the importance of including user costs in life-cycle cost analysis in management systems for bridges is shown. A limited number of excerpts related to the importance of estimating user costs when repair of bridges are planned and when optimized strategies are formulated are shown. These excerpts clearly show that user costs in several cases completely dominate the total costs. In some cases the user costs are more than ten times higher than the repair costs. A simple example of how to relate and estimate user costs related to repair of a single bridge is shown. Finally, it is discussed how the total maintenance costs (including user costs) may be estimated for a large bridge stock.

1. INTRODUCTION

It is a fact that user costs are usually not included when optimal maintenance strategies and decisions are made, although authors often mention that user costs ought to be included. The life-cycle costs are minimized for the considered structure without considering the often significant costs for the users of the bridge and even without considering the long-term effects of the decision. Unfortunately, the maintenance decisions are often political decisions which are not easy to accept for the community. There is clearly a need to convince the decision-makers that user costs should be considered when major decisions are made.

Life-Cycle Cost (LCC) analysis is based only on the direct costs such as inspection and repair (preventive and essential). User costs are usually not included in an LCC analysis.

Life-Cycle Cost-Benefit (LCCB) analysis is an extended LCC analysis where all kinds of indirect costs such as user costs are included. User costs are discussed in more

[1] Proceedings (CD) of the IABMAS'06 Conference, Porto, Portugal, July 16-19, 2006.

detail later in this paper,

To illustrate the importance on including user costs in an LCCB bridge management system, a brief review of a few reports and other documents is presented in chapters 2 and 3. Notice, that in these (and most) documents user costs are modelled deterministically although user costs are always very uncertain. Therefore, user costs must be modelled by stochastic variables or stochastic processes. However, a deterministic modelling based on statistic documentation is a good starting point for a stochastic modelling of user costs.

The first major research on combining stochastic modeling, expert systems and optimal strategies for maintenance of reinforced concrete structures in an LCCB bridge management system was sponsored by EU from 1990 to 1993; see Thoft-Christensen [1]. The research project is entitled *"Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems"*. The methodology used in the project is analytic using traditional numerical analysis and rather advanced stochastic modeling. In chapter 4, modelling of user costs is discussed on the basis of a simple bridge example analysis in this research project.

Designing a LCCB bridge management system is briefly presented in chapter 4 for a single bridge, and in chapter 5 for a bridge stock.

2. FIVE USER COST REPORTS

2.1 Corrosion cost and preventive strategies in the United States

This section is based on the technical report of a project entitled "Corrosion Cost and Preventive Strategies in the United States". The authors are Koch et al. [2] and the project is sponsored by the Federal Highway Administration. The following excerpts are taken from the Highway Bridge section of the report:

> "There are 583,000 bridges in the United States (1998). Of this total, 200,000 bridges are steel, 235,000 are conventional reinforced concrete, 108,000 bridges are constructed using prestressed concrete, and the balance is made using other materials of construction. Approximately 15 percent of the bridges are structurally deficient, primarily due to corrosion of steel and steel reinforcement. The annual direct cost of corrosion for highway bridges is estimated to be \$8.3 billion, consisting of \$3.8 billion to replace structurally deficient bridges over the next ten years, \$2.0 billion for maintenance and cost of capital for concrete bridge decks, \$2.0 billion for maintenance and cost of capital for concrete substructures (minus decks), and \$0.5 billion for maintenance painting of steel bridges. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than ten times the direct cost of corrosion maintenance, repair, and rehabilitation."
>
> "Overall, approximately 15 percent of all bridges are structurally deficient, with the primary cause being deterioration due to corrosion. The mechanism is one of chloride induced corrosion of the steel members, with the chlorides coming from deicing salts and marine exposure."

It is interesting to notice that Koch et al. [2] estimate the user costs due to traffic delays and lost productivity to be more than ten times the direct cost of maintenance, repair, and rehabilitation. User costs are estimated as the product of additional travel time and the value of time.

2.2 Development of road user cost methods

This section is based on the technical report of a project entitled “Development of Road User Cost Methods”. The authors are Daniels et al. [3], and the project is sponsored by the Texas Department of Transportation. In the project “road user costs (RUC) are defined as the estimated daily cost to the traveling public resulting from the construction work being performed” namely detours and rerouting that add to travel time, reduced road capacity, and delays in the opening of a new or improved facility. The total road user costs can be expressed as

$$RUC = VOC + AC + VOT \tag{1}$$

VOC is the vehicle operating cost component and includes the costs of fuel, tires, engine oil, maintenance, and depreciation, AC is the accident costs (fatal accidents, non-fatal injury accidents, property damage accidents), and VOT is a function of the hourly wage rate. VOT is in most cases the most relevant component. In the report the mean value of VOT for a number of states in USA is estimated as $ 11.38 for passenger cars and $ 27.23 for trucks. To-day these values are much higher due to inflation etc.

2.3 Development of user cost data for Florida’s bridge management system

This section is based on the final technical report of a project entitled “Development of User Cost Data for Florida’s Bridge Management System”. The authors are Thompson et al. [4], and the project is sponsored by the Florida Department of Transportation (DFOT) that applies the Pontis Bridge Management System with its user cost models. The following excerpts are taken from the report:

> “An analysis of the Pontis user cost model found that it was overly sensitive to extremes of roadway width, yielding unrealistic high benefit estimates. A new model was developed using Florida data on bridge characteristics and traffic accidents. The new model has superior behavior and statistical characteristics on a full inventory of state highway bridges”.
>
> “The user cost model developed in this study is just one small part of FDOT’s overall effort to implement the Pontis bridge management system. Pontis is intended to support improved bridge program decision-making by presenting objective information on the costs and benefits of policy and project decisions”.
>
> “The user cost model developed in this study is an important part of the system’s ability to measure the economic benefits of bridge investments”.

2.4 The costs of construction delays and traffic control for life-cycle cost analysis of pavements

This section is based on the research report of a project entitled “The Cost of Construction delays and Traffic Control for Life-Cycle Cost Analysis of Pavements”. The authors are Rister & Graves [5], and the project is sponsored by the Kentucky Transportation Center and Kentucky Transportation Cabinet. The following excerpts are taken from the report:

> “Road User Costs (RUC) has been defined by researchers at the Texas Transportation Institute as the estimated incremental daily costs to the

traveling public resulting from the construction work being performed".

> "…agree that RUC are an aggregation of tree separate cost components for ree different vehicle types. The three different cost components are; vehicle operating costs (VOC), user delay costs, and crash/accident costs. The three vehicle types are; passenger cars, single unit trucks, and combination trucks".

The VOC rates vary with the speed. As an example it can be mentioned that the VOR rates for a passenger car with an initial speed of 60 mi/h is 6.31 ($/Vehicle-Hr) in 1970 dollars and $ 27.94 for a combination truck. The user delay costs (value of time) are on average 11.58 and 22.31 ($/Vehicle-Hr) in 1996 dollars for passenger cars and combination trucks respectively. Typical fatality ranges between $ 1,091,000 and $ 1,182,000.

2.5 Strategic review of bridge maintenance costs

This section is based on the research report of a project entitled "Strategic review of bridge maintenance costs"; see Maunsell [6]. The report is produced by Maunsell Ldt., UK for the Highways Agency, London, UK. The following excerpts are taken from the report:

> "A strategic review has been undertaken of annual maintenance costs of the Highways Agency's structures. …… The object of the exercise was to predict the annual expenditure on essential and preventive maintenance which will be required in each of the next forty years on the Highways Agency' bridge stock".
>
> "Road user delay costs due to maintenance were also estimated. These ranged from relatively small amounts to over ten times the direct maintenance costs, depending on the work being done and the type of road. However, the results are very sensitive to the assumptions used and only give a broad indication of likely delay costs".
>
> "If essential maintenance were underfunded, bridges would, in time, need to be closed or restricted while awaiting repair. The main effect would be road user delay costs of the order of £4.6 million a year for each £1 million of essential maintenance not undertaken. The review showed that the cumulated effects of such underfunding would soon become unacceptable due to the disruption (see Figure 25)".

3. SOME OTHER USER COST DATA

3.1 Bridge on Interstate 10 in Oklahoma

On May 26, 2002 a barge slammed into the bridge on Interstate 10 over the Arkansas River near Webbers Falls, Oklahoma, USA; see Federal Highway Administration [7]. Four of the bridge's approach spans collapsed and fourteen people were killed. The bridge is the states most important east-west transportation link, so the collapse had a major influence on the economy. The cost of repair of the bridge was about $ 15 million and the total user cost was estimated to $430.000 per day for every day the bridge was closed. It was therefore essential to accelerate the repair which was completed in about 2 month. $12 million were spent on upgrading of the detour highways. The detours were used by approximately 17,000 vehicles every day the bridge was not open.

3.2 Replacement of structures on STH 27 in Wisconsin

Replacement of the Holcombe Flowage structure and the Fisher River structure on STH 27 in the Town of Lake Holcombe, WI, USA with two new concrete bridges is estimated to cost approximately $ 2.43 million; see Schmidt [8]. The detour will be approximately 16 miles long. With a fuel cost of $ 1.90 per gallon and a traffic volume of 4,500 cars per day, the fuel cost will be about $ 2 million for a 6 – 8 month period.

3.3 Grassy Creek bridge in North Carolina

Rehabilitation of the existing Grassy Creek Bridge (bridge No.123) in Ashe County, North Carolina, USA was considered "neither practical nor economical". Therefore, a replacement was decided. Two alternatives were considered; see Koch et al. (2003).

The total cost of the two alternatives was estimated to approximately $ 450,000 and $ 640,000. However, the winning bid for a redesign of the project was only $ 333,000. According to Koch et al. [9] "the average extra travel incurred by a motorist on the detour would be 2.6 miles, resulting in road user costs at $ 15,000 for the six month construction period".

4. AN LCCB BRIDGE MANAGEMENT SYSTEM FOR SINGLE BRIDGES

LCCB bridge management systems have a broad spectrum of applications. They are very useful for groups of bridges, but also for individual bridges. In this chapter, the EU-supported LCCB bridge management system mentioned in chapter 2 is presented to illustrate how user costs may be included in decision-making for single bridges. LCC or LCCB systems may be used in designing a new bridge, but are also very useful in connection with decision problems regarding e.g. repair of a bridge after an inspection has taken place. As indicated in chapters 2 and 3, the total cost related to maintenance or replacement of deteriorated bridges will often be strongly dominated by the user costs.

In this chapter modelling of user costs is discussed on the basis of a simple and straightforward implementation used in the above-mentioned research project entitled "*Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems*". In the model a number of issues are included such as closing down one or more lanes during maintenance. All relevant parameters are modelled as stochastic variables. The detour costs for a given bridge are estimated by considering the loss in the marginal benefits by having the bridge compared to no bridge, but only nearby routes for the traffic. This estimation is based on the average benefits for one vehicle passing the bridge by estimating the rental price of an average vehicle/km times the average detour length in km. Therefore, data on the traffic volume including increase in traffic volume per year are needed. The model may easily be extended to include other kinds of user costs such as different categories of vehicles, cost of accidents, and loss of time due to the detour.

After a detailed structural assessment of the state of the bridge at the time T_0, a difficult problem is to decide if the bridge should be repaired and if so, how and when should it be repaired? From a cost-benefit point of view the total cost including direct and indirect costs is minimized. This can also be formulated in the following perhaps more acceptable way: *After a structural assessment of a bridge, the total expected benefits minus expected repair and failure costs in the remaining lifetime of the bridge are maximized.*

This model can be used in an adaptive way if the stochastic model is updated after each structural assessment or repair and a new optimal repair decision is taken. Therefore, it is mainly the time of the first repair after a structural assessment which is of importance.

In order to decide which type of repair is optimal after a structural assessment, the following optimization problem is considered for each repair technique; see Thoft-Christensen [1]:

$$\begin{aligned} &\max W = B(T_R, N_R) - C_R(T_R, N_R) - C_F(T_R, N_R) \\ &s.t.\ \beta^U(T_L, T_R, N_R) \geq \beta^{\min} \end{aligned} \tag{2}$$

The optimization variables are the expected number of repair N_R in the remaining lifetime of the bridge. T_R is the time until the first repair after the structural assessment. W is the total expected benefit B minus the repair costs C_R capitalized to the time $t = 0$, and minus the expected failure costs C_F in the remaining lifetime T_L of the bridge also capitalized to the time $t = 0$. β^U is the updated reliability index. $\beta^{\min}$ is the minimum reliability index for the bridge.

The benefits are modelled by

$$B(T_R, N_R) = \sum_{i=[T_0]+1}^{[T_L]} B_i (1+r)^{T_0 - T_{ref}} \frac{1}{(1+r)^{T_i - T_0}} \tag{3}$$

$[T]$ signifies the integer part of T measured in years and B_i are the benefits in year *i*. T_i is the time from the construction of the bridge. The *i*th term in (3) represents the benefits from T_{i-1} to T_i. The benefits in year *i* is modelled by

$$B_i = k_0 V(T_i) \tag{4}$$

k_0 is a factor modeling the average benefits for one vehicle crossing the bridge. It can be estimated as the price of rental of an average vehicle/km times the average detour length. The reference year for k_0 is T_{ref}. It is assumed that bridges are considered in isolation. Therefore, the benefits are considered as marginal benefits by having a bridge (with the alternative that there is no bridge, but other nearby routes for traffic). V is estimated by

$$V(T) = V_0 + V_1(T - T_{ref}) \tag{5}$$

V is the traffic volume per year at the time of construction, V_1 is the increase in traffic volume per year, and T is the actual time (in years).

Application of this LCCB system to a number of realistic examples shows that the benefits (negative user costs) play an important role. In Thoft-Christensen & Hansen [10], a numerical example is shown where the user costs corresponding to different repair methods are much higher than the repair costs. Actually the repair costs are negligible compared with the user costs. In such cases the optimization should only primarily be concentrated on the user costs.

5. AN LCCB BRIDGE MANAGEMENT SYSTEM FOR BRIDGE STOCKS

A bridge stock will usually consist of a large number of bridges. The objective of a bridge maintenance strategy is to minimize the cost of maintaining such a group of bridges in the service life of the bridge stock. Estimation of the service life costs is very uncertain so that a stochastic modeling is clearly needed. This can be expressed mathematically as; see Thoft-Christensen [11], [12]

$$\min E[C] = \min\left(E[C_M] + E[C_U] + E[C_F]\right) \tag{6}$$

where

$E[C]$ is the expected total cost in the service life of the bridge stock,

$E[C_M]$ is the expected maintenance cost in the service life of the bridge stock,

$E[C_U]$ is the expected user cost, e.g. traffic disruption costs due to works or restrictions on the bridges in the bridge stock,

$E[C_F]$ is the expected cost due to failure of bridges in the bridge stock.

For a *single* bridge *i* in the bridge stock, the expected cost of the bridge in its service life $E[C_i]$ can be written

$$\begin{aligned} E[C_i] &= E[C_{Mi}] + E[C_{Ui}] + E\left[C_{F_i}\right] \\ &= \sum_{t=1}^{T} \{(1+\gamma)^{-1}\left[E[C_{Mi}(t)]P(M_{it}) + E[C_{Ui}(t)]P(U_{it}) + E[C_{Fi}(t)]\,P(F_{it}(t))\right]\} \end{aligned} \tag{7}$$

where

γ is the discount rate (factor), e.g. 6 %,

$E[C_i]$ is the expected total cost for bridge *i*,

$E[C_{Mi}(t)]$ is the expected maintenance cost for bridge *i* in year *t*,

$E[C_{Ui}(t)]$ is the expected user cost for bridge in year *t*,

$E[C_{Fi}(t)]$ is the expected failure cost for bridge *i* in year *t*,

$P(M_{it})$ is the probability of the event “maintenance is necessary” for bridge *i* in year *t*,

$P(U_{it})$ is the probability of the event “user costs relevant” for bridge *i* in year *t*,

$P(F_{it})$ is the probability of the event “failure” for bridge *i* in year *t*,

T is the remaining service life or reference period (in years).

Let the number of bridges in the considered bridge stock be *m*. The expected total cost for the bridge stock can then be written

$$\begin{aligned} E[C] &= \sum_{i=1}^{m} \left\{E\left(C_{Mi}\right) + E\left(C_{Ui}\right) + E\left(C_{Fi}\right)\right\} \\ &= \sum_{i=1}^{m}\sum_{t=1}^{T} \{(1+\gamma)^{-1}\left[E[C_{Mi}(t)]P(M_{it}) + E[C_{Ui}(t)]P(U_{it}) + E[C_{Fi}(t)]\,P(F_{it}(t))\right]\} \end{aligned} \tag{8}$$

It follows from (8) that including user cost in the analysis requires data for each year on the expected user costs for every single bridge, and an estimate of the probability that user costs will occur for every single bridge. It is absolutely not a simple matter to make reliable estimates of user costs. This fact is perhaps why most of the work on LCC bridge management systems completely neglects user costs or only mentions that user costs ought to be included. What is needed is a real comprehensive study of all aspects of indirect costs based on existing databases. However, most of these databases are not sufficiently detailed to be useful in that respect.

User costs can not be satisfactory modelled deterministically. The uncertainties are so high that a stochastic modeling is needed.

6. CONCLUSIONS

The importance of including user costs, when the economic consequences of maintaining bridges are studied is discussed. It is argued that a cost-benefit analysis is needed when life-cycle analysis of maintenance (including inspection cost, repair cost, and user cost) of bridges is performed. This conclusion is based on an extensive study of documents on maintenance costs. From five of these documents a limited number of excerpts are shown. They are related to estimation of the importance of estimating user costs when repair of bridges are planned and when optimized strategies are formulated. Further reference to three other documents is made. These excerpts clearly show that user costs in most cases completely dominate the total costs. In some cases, the user costs are even more than ten times higher than the repair costs.

The main conclusion of this paper is that an LCC based bridge management system in most cases is insufficient. User costs will in general dominate the cost of inspection and repair. Therefore an LCCB analysis is more reasonable to use.

There is an enormous amount of work on user costs in bridge engineering in the literature. However, much more research is needed before an LCCB analysis in the bridge area can be made in a satisfactory way. Much of the work done until now is limited to narrow models without a wide area of application. A reliable life-cycle based tool must include direct as well as indirect cost. The bridge owners must learn to listen to the public when decisions regarding repair or replacement of structures are taken.

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