

## NRC Publications Archive Archives des publications du CNRC

### **Towards sustainable design of highway bridges**

Lounis, Z.; Daigle, L.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /  
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

#### **Publisher's version / Version de l'éditeur:**

*IABMAS 2010: Bridge Maintenance, Safety, Management and Life-Cycle Optimization: 11 July 2010, Philadelphia, USA [Proceedings], pp. 1-7, 2010-07-11*

#### **NRC Publications Archive Record / Notice des Archives des publications du CNRC :**

<https://nrc-publications.canada.ca/eng/view/object/?id=02be4265-a869-41ae-ad9d-9c9ec3eda9db>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=02be4265-a869-41ae-ad9d-9c9ec3eda9db>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.



<http://www.nrc-cnrc.gc.ca/irc>

## **Towards sustainable design of highway bridges**

---

**NRCC-53225**

Lounis, Z.; Daigle, L.

July 2010

A version of this document is published in / Une version de ce document se trouve dans:  
IABMAS 2010 - Bridge Maintenance, Safety, Management and Life-Cycle  
Optimization, Philadelphia, USA, July 11-14, 2010, pp. 1-7

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>



National Research  
Council Canada

Conseil national  
de recherches Canada

**Canada**



# Towards sustainable design of highway bridges

Z. Lounis & L. Daigle

*National Research Council, Ottawa, Canada*

**ABSTRACT:** The design and preservation of bridges have been driven, for a long time, by the concerns to minimize costs and improve asset condition. The growing concerns for environmental protection and the shift towards achieving sustainable transportation infrastructure are now requiring the use of approaches that seek to achieve an adequate balance between social, economic and environmental performance over the entire life cycle of the bridge. This paper discusses some performance indicators, such as safety, serviceability, costs, traffic disruption, greenhouse gas emissions, which can be used for life cycle design of highway bridges. An example, taken from the North American context, illustrates how different design and rehabilitation approaches can contribute to achieve the desirable balance between social, economic and environmental sustainability criteria.

## 1 INTRODUCTION

### 1.1 *General*

Highway bridges provide a core public service and are needed for a very long time to support the sustainable development of neighbouring communities. They are critical links in Canada's transportation network that should be kept safe and functional during their service lives to enable personal mobility and transport of goods to support the economy and ensure high quality of life. The average service lives of these assets vary from 50 years up to 100 years, which are continually extended by using different management strategies that include different combinations of preservation, rehabilitation, strengthening, replacement, mitigation and adaptation actions.

### 1.2 *Management practices*

Bridge management can be defined as a systematic process of operating, maintaining, upgrading and expanding physical assets effectively throughout their life cycles. It combines engineering principles with sound business practice and economic theory for resources allocation and utilization. The actual bridge management problem can be defined as a multi-objective optimization problem in which the decision maker is seeking to select the best decisions that achieve the best trade-offs between different competing objectives, such as maximizing public

safety, minimizing environmental impacts, maximizing the levels of services and minimizing the life cycle costs. However, most of the current decision-making approaches and bridge management systems are based on the optimization of a single objective, namely the minimization of life cycle costs. The state-of-art approaches to asset management have focused primarily on three objectives, namely: (i) preserving the physical condition of assets; (ii) ensuring acceptable levels of services (e.g. mobility); and (iii) minimizing the life cycle costs. It is clear that limited or no consideration has been given to assessing the life cycle or "cradle to grave" impacts on the environment and the society that result from the construction, operation, maintenance, failure, and replacement of bridge assets. Furthermore, there is also a need to assess the life cycle impacts on the environment of the service provided by these assets, such as vehicle emissions, impacts on environment due to traffic disruption, etc. The implementation of effective sustainable asset management approaches requires the development of approaches that can predict the performance of bridges and the service they provided with regard to society, economy and environment over their life cycles using appropriate performance measures.

The implementation of sustainability principles in asset management decisions and activities has become a "need or a necessity" rather than a "desire" to curb the consumption and emissions, protect the

environment and improve the efforts towards social equity and social progress. This concept has gained momentum and consensus since the publication of the Brundtland commission report (1987) in which sustainable development was first coined and defined as a “*development that meets the needs of current generation without compromising the ability of future generations to meet their own needs.*”

## 2 KEY CONCEPTS AND APPROACH TO SUSTAINABLE DESIGN OF BRIDGES

### 2.1 Sustainability objectives and indicators

Seven key objectives: public safety, public health, public security, mobility, environment quality, social equity and the economy, against which the performance of public assets is assessed, are identified in a Model Framework for the assessment of public infrastructure performance (NRTSI/NRC 2009). These objectives derive from the so-called “*Triple Bottom Line*” evaluation approach or pillars of sustainability, i.e. social equity, environmental protection, and economic prosperity. For each of these objectives, several assessment criteria or performance indicators are provided to measure the performance of the asset towards reaching the objective. The selection of specific performance indicators or completeness of assessment will depend on many factors, namely (not exclusively):

- Availability of data.
- Size and scope of project.
- Relevance of pursuing particular objectives due to nature or context of the project.
- Use of governing criteria for social, economic and environmental sustainability.

The selected performance indicators should provide a “fair” picture of the performance of the asset throughout its life cycle, including an estimate of the uncertainty associated with the future values of performance indicators

The following example illustrates the use of selected performance indicators to make a comparative evaluation of two rehabilitation alternatives in terms of their economic, social and environmental performance over the life cycle of reinforced concrete (RC) highway bridge decks.

### 2.2 Service life prediction

Highway bridges age and deteriorate with time, which require different preservation actions over their service lives to ensure that they perform as required. The life cycle of a bridge should not be confused with its service life. The life cycle can be de-

finied as the time period over which the cost or environmental impact are assessed, while the service life is the time over which the asset deteriorates and reaches a maximum level of damage or minimum performance level, which is referred to as a limit state, which can indicate unacceptable safety or serviceability of the asset, as shown in Figure1. The service life can also be defined as the time when the service provided by the highway bridge reaches a minimum acceptable level. Bridge deterioration shown on Figure 1 is due to wear and tear cumulative damage and does not include random shock-induced damage.

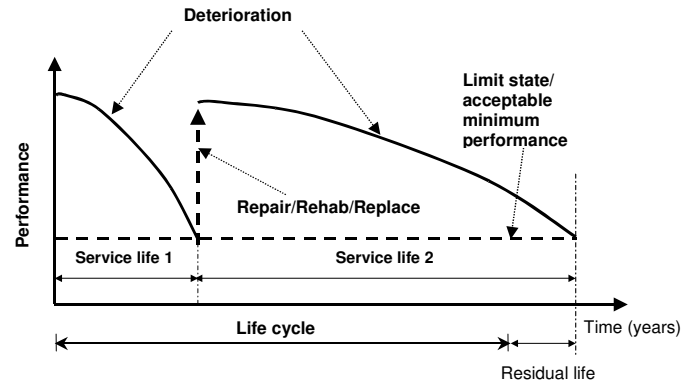


Figure 1. Bridge life cycle performance.

The knowledge of the service life of a bridge is required before undertaking a life cycle cost analysis, a life cycle environmental impact or life cycle social impact assessment (Fig. 2). The prediction of the deterioration or service life of a bridge require models that can forecast its future condition taking into account all the factors that contribute to its degradation.

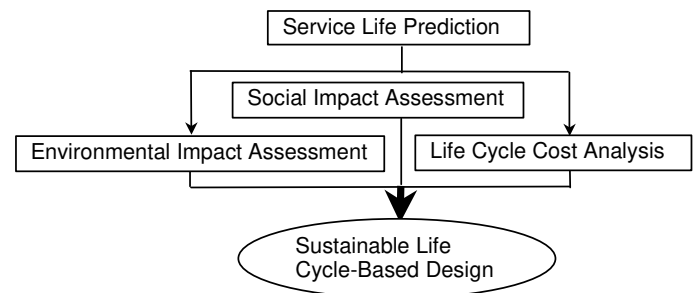


Figure 2. Service life prediction input in sustainable management approach.

## 3 ILLUSTRATIVE EXAMPLE

### 3.1 General

The long-term efficiency of high performance concrete (HPC) containing supplementary cementing materials (SCM) for the construction and rehabilita-

tion of concrete bridge decks is evaluated and compared to that of normal performance concrete (NPC) in terms of service life, life cycle cost, environmental impacts and social impacts. SCMs are reclaimed industrial by-products that improve concrete physical performance and extend the service life of RC structures as a result of concrete reduced permeability.

The HPC deck contains 25% of fly ash and has a 28-day compressive strength of 45 MPa. The NPC deck water/cement ratio of 0.4 is associated to a 28-day compressive strength of 30 MPa. The reinforcement consists of #10M conventional black steel rebars with a yield strength of 400 MPa for both alternatives. Dimensions and traffic data are presented in Table 1 (Lounis & Daigle 2008).

Table 1. General information on highway bridge example.

Bridge width	12.57 m
Bridge length	47.5 m
Deck thickness	225 mm
Isotropic reinforcement percentage for both mats	0.3%
Annual Average Daily Traffic (AADT)	22000
Annual Average Daily Truck Traffic (AADTT)	4500
Normal traffic speed (km/hr)	100

### 3.2 Service life

In North America, the extensive deterioration of highway bridge deck is mainly caused by chloride-induced corrosion of the reinforcement. The primary source of chlorides derives from deicing salts applied to roadways and bridges during winter. Given this predominant deterioration mechanism, most RC bridge deck failures are due to loss of serviceability and functionality and not loss of strength and collapse.

The service life of the RC deck built in a corrosive environment is obtained using reliability-based analytical models that predict the time it will take before chloride ingress and subsequent corrosion-induced damage mechanisms reduce the serviceability of the deck to an unacceptable level. These models, based on a reliability approach, take into account the variability of the main physical parameters and the different types of uncertainties associated with the modeling of complex processes.

The time estimation of chloride ingress into concrete cover is modeled using Crank's (1975) solution of Fick's second law of diffusion, which is given by:

$$C(x,t) = C_s \left[ 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{D_c t}} \right) \right] \quad (1)$$

where  $C(x,t)$  = chloride concentration at depth  $x$  after time  $t$ ;  $C_s$  = chloride concentration at the deck

surface;  $D_c$  = coefficient of diffusion of chloride ions into concrete; and  $\operatorname{erf}$  = error function. The time to corrosion initiation ( $t_i$ ) is estimated by replacing, in Equation 1, the chloride concentration ( $C$ ) with a chloride threshold value ( $C_{th}$ ) or chloride concentration at which corrosion initiation is expected to occur, and the variable  $x$  (the depth from the surface) with the effective cover depth ( $c$ ) of the reinforcing steel. Equation 1 then becomes:

$$t_i = \frac{c^2}{4D_c \left[ \operatorname{erf}^{-1} \left( 1 - \frac{C_{th}}{C_s} \right) \right]^2} \quad (2)$$

In this chloride contamination model, both the diffusion coefficient  $D_c$  and the surface concentration  $C_s$  are assumed to be constant in space and time.

Times to reach different limit states of corrosion-induced damage (internal cracking, surface cracking, spalling, delamination) are estimated based on the thick-wall cylinder model (Timoshenko 1956). This model allows the calculation of the rebar diameter increase related to the different corrosion-induced damage limit states. Complete development of the thick-wall cylinder equations as applied to the different limit states of reinforced concrete deterioration is presented in Lounis *et al.* (2006). Chloride ingress and corrosion-induced damage models with associated corrosion propagation time are described in more in details in Lounis & Daigle (2008).

For this example, it is considered that the end of service life or serviceability limit state of RC decks in corrosive environments is reached when an estimated 30% of the deck area is spalled. Using the models briefly described above, it is estimated that this condition is reached after 22 years for the NPC deck and after 40 years for the HPC deck. The data for the service life parameters of both replacement alternatives are given in Table 2.

Table 2. Service life parameters.

Parameter	Mean value	COV*
Concrete cover depth (mm)	70	25
Bar spacing (mm)	150	5
Bar diameter (mm)	9.5	-
Surface chloride content (kg/m <sup>3</sup> )	6	25
Chloride (apparent) coefficient of diffusion (cm <sup>2</sup> /year) - NPC	0.40	25
Chloride (apparent) coefficient of diffusion (cm <sup>2</sup> /year) - HPC	0.20	25
Threshold chloride content (kg/m <sup>3</sup> )	0.70	20
Corrosion rate (μA/cm <sup>2</sup> )	0.5	20

\* COV = coefficient of variation (%)

### 3.3 Performance indicators

A limited number of performance indicators are chosen to illustrate the proposed approach to sustainable design, which include:

- Economy: life cycle agency costs and life cycle user costs.
- Environment: CO<sub>2</sub> emissions and volume of construction waste materials.
- Social: Accident cost and traffic congestion.

Accident cost is used in this example as an indicator of social impact as these costs are mainly covered by insurance premiums (material damages) and health services paid for by a large portion of the society. Traffic congestion is a problem that directly and indirectly affects all three pillars of sustainability and it is directly or implicitly considered in the following analyses. Time lost by drivers has an impact on the economy, especially for those whose jobs include a period of driving. Traffic congestion also contributes to an increase in CO<sub>2</sub> emissions and finally traffic congestion affects people quality of life (traffic delays for extended period of time).

### 3.4 Measures of economic performance

The analysis time period (or life cycle) is taken as 40 years and the discount rate used is 3%. The components of the agency or owner's costs include labour, equipment, material, etc. of the initial construction and all required maintenance, repair, rehabilitation and replacement (MR&R) activities throughout the bridge deck life cycle. The initial construction costs (in-place costs for the steel and concrete mixes) of the two alternatives are presented in Table 3. Additional construction costs are not specified for the two alternatives as they are considered to be approximately the same. Figure 3 summarizes the timing and costs of the different MR&R activities of both alternatives. The cost and time data presented in this example are taken from various sources referenced in Lounis & Daigle (2008) or assumed. The cost of the patch repairs includes:

- Cost of removing the contaminated or deteriorated concrete.
- Cost of concrete patching.
- Cost of traffic control when the bridge is partially opened to traffic.

Table 3. In-place costs of materials.

Material	Unit Cost
Normal concrete (NPC)	460 (\$/m <sup>3</sup> )
High performance concrete (HPC)	520 (\$/m <sup>3</sup> )
Conventional ("black") steel	1.80 (\$/kg)

In this example, patch repairs are made when the deck spalling area reaches 10% and 20%. Times corresponding to these damage states are predicted using the reliability-based service life models mentioned above. It is assumed that after 22 years, the damaged NPC deck is replaced with a similar type of deck (i.e. normal concrete with black steel reinforcement in both top and bottom mats). The replacement cost includes the initial construction cost and the costs of demolition and disposal that were assumed equal to \$70/m<sup>2</sup>. Since the end of life of the HPC deck is equal to the analysis period, its replacement is not included in the life cycle cost analysis (LCCA). At the end of the analysis period, the HPC alternative will have no residual service life or value whereas the NPC deck will have a four-year residual life and a residual value calculated as 18% (remaining service life over predicted service life) of the replacement cost. For the NPC alternative, the schedules of MR&R activities for the deck replacement (year 22 and after) are similar to those of the initial deck construction (up to year 22).

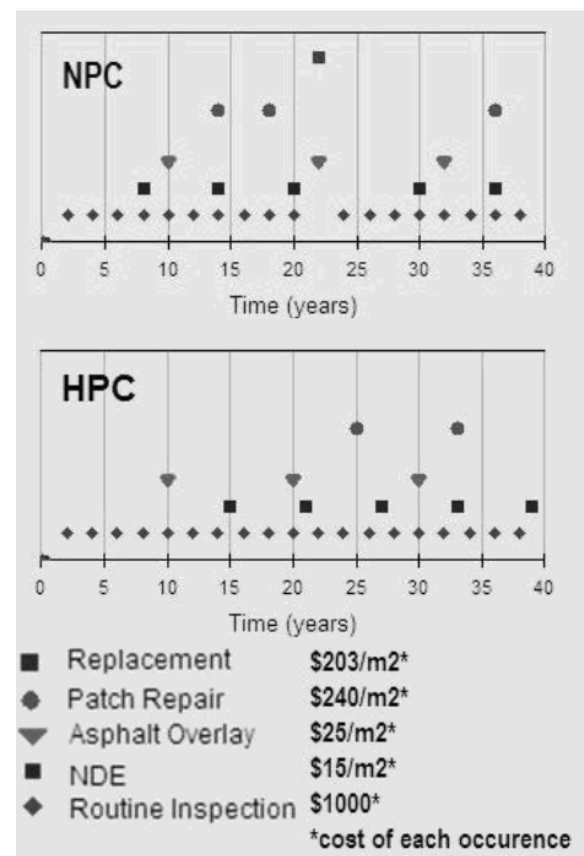


Figure 3. Costs and schedule MR&R activities for NPC and HPC decks over life cycle.

Users costs considered in this example include cost incurred by the users of the bridge (lost driver's time and increased vehicle operating costs) due to traffic delay caused by MR&R activities. Duration of each (MR&R) activity (average for both ways),

length of affected road during the activity (average for both ways), and reduced traffic speed during the activity (Table 4) are used to estimate life cycle user costs. These values are considered to be the same for both deck alternatives except for the replacement, which is used only on the NPC deck. The different unit or hourly user costs are found in Table 5. Details on user cost estimation are found in Daigle & Lounis (2006).

Table 4. Data related to user cost estimation.

Activities	Duration (days)	Length affected (km)	Traffic speed reduced to (km/hr)
Routine inspection	0.35	0.1	80
Detailed inspection	0.5	0.5	50
Asphalt overlay	1.5	1	40
Patch repair	2.5	1	30
Replacement	15	1	30

Table 5. Unit user costs.

Average value of driver's time (\$/hr)		
Car		12
Truck		20
Vehicle operating cost (\$/hr)		
Car		8.85
Truck		8.85

Figure 4 illustrates the results of the life cycle cost analysis (LCCA) that was evaluated using the present value life cycle cost (PVLCC) approach detailed in Equation 3 (Hawk 2003):

$$PVLCC = C_0 + \sum_{t_i=1}^T \frac{C_i(t_i)}{(1+r)^{t_i}} - \frac{R_v}{(1+r)^T} \quad (3)$$

where  $C_0$  = Initial construction cost (including design costs);  $C_i(t_i)$  =  $i^{\text{th}}$  expenditure at time  $t_i$  (e.g. inspection, maintenance, repair, demolition, disposal, etc.);  $r$  = discount rate;  $T$  = life cycle; and  $R_v$  = residual (or salvage) value at the end of the life cycle.

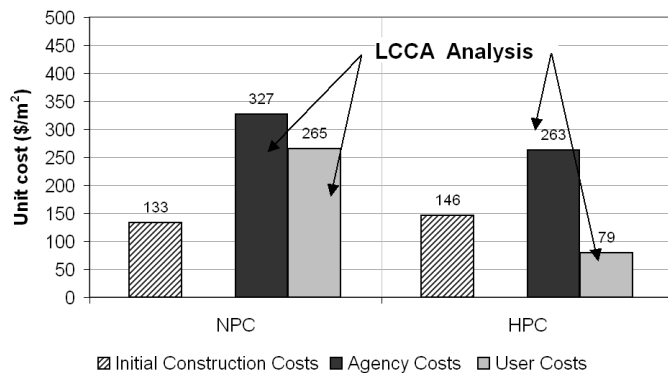


Figure 4. Costs and schedule MRR activities for NPC and HPC decks over life cycle.

The difference between the agency and user life cycle costs of the two alternatives favours the use of the HPC deck as there is a reduction of 20% and 70% in these costs, respectively. When based only on initial (partial) construction costs, the NPC deck alternative would seem to be a slightly better choice.

### 3.5 Measures of environmental performance

Environmental impacts, in terms of greenhouse gas emissions and waste production are estimated for all activities occurring during the life cycle of both concrete deck alternatives as outlined in the economic performance analysis. Pertaining to the production of CO<sub>2</sub> emissions, these estimates include the major components that illustrate the difference between the two alternatives, namely: (i) cement production; (ii) additional transportation needed for the SCMs included in the HPC mix; and (iii) CO<sub>2</sub> emitted by cars/trucks delayed by the maintenance, repair, and replacement activities. The CO<sub>2</sub> released by the production of reinforcing steel is not accounted but would typically be the same for both deck alternatives. In this example, it is found that the CO<sub>2</sub> emissions for the normal concrete deck alternative are almost three times higher than those of the HPC deck alternative (Fig. 5). This difference is mainly due to the lower cement consumption of the HPC mix that uses supplementary cementing materials as a replacement material for a portion of the cement. The shorter service life of the normal concrete deck, which leads to an increase in traffic disruption due to earlier replacement, also accounts for the higher CO<sub>2</sub> emissions of the NPC deck.

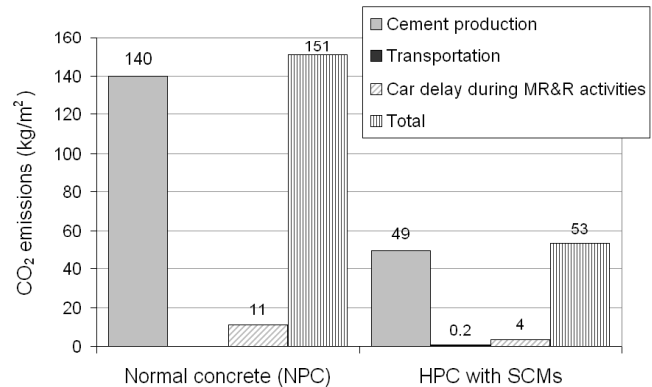


Figure 5. CO<sub>2</sub> emissions within life cycles of bridge decks.

A comparison of the waste produced (or landfill use) for the two deck alternatives is shown in Figure 6, which includes the volume of waste material produced during the replacement of asphalt overlay, patch repairs, and replacement.



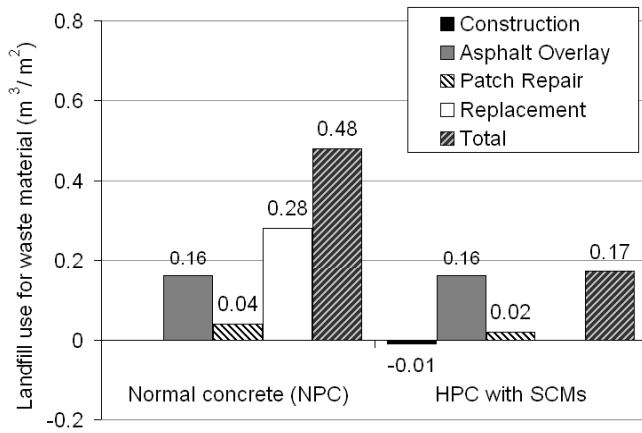


Figure 6. Volume of construction waste materials from HPC and NPC bridge decks.

### 3.6 Measures of social performance

Average accident costs and the normal accident rate are taken from statistics published by Transport Canada (1994, 2006) and Statistics Canada (2003). Considering the lack of statistical data on accident in work zones, a rule of thumb of three times the normal accident rates is used as suggested by Walls & Smith (1998). Data taken for this example are presented in Table 6.

Table 6. Accident rates and cost.

Normal accident rate (/million vehicle * km)	2.1
Accident rate during MR&R activities (/million vehicle * km)	6.0
Average accident cost (\$)	33000

Figure 7 shows the accident cost per deck area for both deck alternatives, as well as the total time lost by drivers due MR&R activities. As for environmental impacts, the shorter service life of the NPC deck and its required replacement after 22 years, which causes an increase in traffic disruption, greatly affect the social performance of the NPC deck.

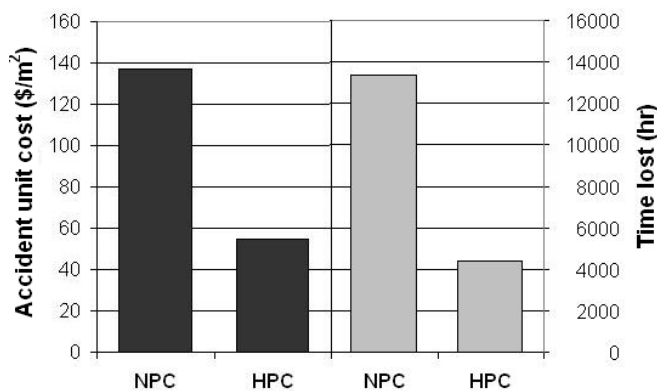


Figure 7. Social impacts - Accident unit cost and time lost for NPC and HPC deck alternatives.

In this paper, it is shown that the implementation of life cycle-based design and maintenance management approaches would lead to the construction of high performance highway bridges with reduced environmental footprints and social pressure. The use of HPC materials results in bridge decks with extended service lives, reduced life cycle costs, and better environmental and social profiles when compared to conventional normal concrete bridge decks. From the example above, the following conclusions can be drawn:

- In terms of durability, the HPC deck alternative incorporating SCMs has a service life that is almost twice as long as the service life of normal concrete deck.
- In terms of life cycle costs, the HPC deck alternative is found to be more economic than the normal concrete deck for both agency costs and user costs.
- In terms of environmental impact, it is estimated that the HPC deck alternative yields a reduction of 65% in the CO<sub>2</sub> emissions compared to the normal concrete deck.
- In terms of social impacts, time lost and accident cost associated to the HPC deck alternative are estimated to be less than half of what was estimated for the NPC deck.

The illustrative example presented above extends beyond a conventional economical performance analysis as it includes some social and environmental aspects. It is not an exhaustive environmental impact analysis or a complete analysis of social impacts, but it provides some preliminary indications on the influence of selecting an alternative on added environmental burden and social pressure caused by life cycle maintenance, repairs and rehabilitation activities of the bridge deck. In this particular example, all the performance measures used indicated that the HPC deck alternative would be a better choice. There is no need to trade off or reach an equitable balance between environment, social and economical. Only on initial construction cost would the NPC bridge deck option perform better, but this information was only shown for comparative purposes, as initial construction cost is not a suitable indicator for sustainability.

In life cycle performance analysis, the reliable estimation of service life and associated schedule and extent of MR&R activities is critical. Beyond their significant influence on economic performance, they also drive the results of the social and environmental impacts analysis. For bridges with high level of traffic, the social and environmental “costs” of frequent

and/or extended interventions should be taken into consideration to move towards a sustainable approach for the design and management of highway bridges.

## REFERENCES

- Crank, J. (1975). *The Mathematics of Diffusion* (2nd ed.), Oxford University Press, London.
- Daigle, L. & Lounis, Z. (2006). Life cycle cost analysis of high performance concrete bridges considering their environmental impacts. INFRA 2006 Conf. - Quebec City, November 20, 2006.
- Hawk, H. (2003). *Bridge Life-Cycle Cost Analysis*. NCHRP Report 483, Transportation Research Board, Washington, D.C.
- Lounis, Z., Martin-Perez, B., Daigle, L. & Zhang, J. (2006). Decision Support Tools for Service Life Prediction and Rehabilitation of Concrete Bridge Decks - Final Report, National Research Council Canada (B5318.2), 260 p.
- Lounis, Z. & Daigle, L. (2008). Reliability-based decision support tool for life cycle design and management of highway bridge decks. Annual Conf. of the Trans. Assoc. of Canada (TAC) (Toronto, Ontario, 2008-09-21), pp. 1-19.
- NRTSI/NRC (2009). *Model Framework for the Assessment of State, Performance and Management of Canada's Core Public Infrastructure*. National Round Table for Sustainable Infrastructure and National Research Council (Canada).
- Statistics Canada (2003). Canadian Vehicle Survey, Cat. No. 53-223-XIE.
- Timoshenko, S.P. (1956). *Strength of Materials. Part II: Advanced Theory and Problems*, Princeton, NJ.
- Transport Canada (2006). Road Safety in Canada – 2003. TP 13951E.
- Transport Canada (1994). Guide to Benefit-Cost Analysis in Transport Canada. TP11875E
- Walls, J., and Smith, M.R. (1998). *Life Cycle Cost Analysis in Pavement Design*. Interim Technical Bulletin, Publication No. FHWA-SA-98-079, 107 p
- World Commission on Environment and Development (WCED) (1987). *Our Common Future*. Oxford University Press, NY.