Reliability-based life cycle design of resilient highway bridges

Zoubir Lounis, Ph.D., P.Eng.

National Research Council Canada, 1200 Montreal Rd., Ottawa, ON, K1A0R6;
Tel: (613) 993-5412; email: Zoubir.Lounis@nrc-cnrc.gc.ca

ABSTRACT

Highway bridges are critical links in Canada's transportation network, which enable personal mobility and transport of goods that support trade and economic development of neighbouring communities. Highway bridges should be designed and maintained to last at least 75 years with minimum maintenance. The average service life of bridge structures vary from 30 years to 100 years, which are continually extended by using different maintenance and rehabilitation strategies. Different technologies are used for bridge life extensions, including different combinations of protective systems, repair, strengthening, rehabilitation, and replacement actions of decks, superstructures, substructures and entire bridges. The growing concerns with aging bridges, increased load and reduced strength, environmental protection and vulnerability to extreme events require the development of resilient transportation infrastructure that minimizes traffic disruption and ensures social, economic and environmental sustainability and resilience over the entire life cycle of the bridge. Given the considerable uncertainty that is associated with the key parameters and physical models that affect the life cycle performance of highway bridges, there is a need to develop robust mechanistic and stochastic models to predict the service life of bridges. This paper presents a practical reliability-based approach for the life cycle design of resilient concrete bridges that enables to achieve long life bridges with an acceptable probability of failure, which minimizes traffic disruption and reduces the life cycle costs to the bridge owners and users. An example illustrates the benefits of implementing a life cycle-based design approach through the construction of high performance concrete highway bridge structures that yield lower risk of failure when compared to conventional normal concrete construction, in terms of lower traffic disruption, life cycle costs to the bridge owners and users; lower CO_2 emissions and volume of construction waste materials; and reduced accident costs.

INTRODUCTION

Highway bridges constitute a critical link in Canada's transportation network that enable transportation of people and goods, and are critical to the economy, quality of life and sustainability of communities. Highway bridges are designed and maintained to withstand the demands imposed by their service requirements, and by natural hazards, such as winds, snow, earthquake, and salt-induced corrosion of steel, and man-made hazards. In addition, socio-economic and political pressures have contributed to an increase in the loads and/or decrease in the capacity due to structural deterioration (due to inadequate maintenance). Furthermore, some of the bridges may be subjected to low probability, high consequences natural and man-made hazards such extreme winds, flooding, earthquakes, permafrost, fires, and blasts from explosives due to terrorist attacks.

Considerable and numerous sources of uncertainties are associated with the life cycle performance of highway bridges, which in turn lead to different risks of failure that must be managed and kept at acceptable levels using difference mitigation measures, including technical solutions, regulations, change of demands/hazards on structures, etc. The growing concern for the protection of the environment, climate change, conservation of non-renewable resources and the growing awareness about social equity have resulted in a growing movement towards sustainable development in several domains, including construction, infrastructure, and community development. Furthermore, the severe damage to infrastructures, communities and regions from recent natural or man-made hazards have prompted a growing recognition that much more can be done to create resilient infrastructures and communities.

A resilient bridge should have the ability to reduce the magnitude and/or duration of structural damage and loss of functionality when subjected to normal or extreme shocks. The 2007 collapse of the I35W Bridge in Minneapolis, Minnesota killed 13 people and injured 145 others (FHWA 2011). Much of the nation's bridges are vulnerable to the effects of the aggressive environment that reduce their capacity to resist natural and/or man-made hazards, including earthquake, wind, and blast. Physical damage to highway bridges can lead to serious reductions in levels of services, such as delays in flow of goods and people, disruption of traffic that can have serious socio-economic and environmental impacts. The risk across large, disaster-prone regions of the nation is substantially greater now than ever before due to the combined effects of urban development and population growth.

Given the limited resources available and the emerging needs for sustainable and resilient highway bridges, transportation network and overall communities, a reliability-based decision making approach is proposed to help decision-makers optimize the design, evaluation and management of highway bridges structures to support the selection of the most sustainable and resilient risk mitigation strategy.

OVERVIEW OF BRIDGE SUSTAINABILITY AND RESILIENCE

Sustainability has gained prominence since the release of Bruntland's World Commission on Environment and Development (WCED) report referred to as "Our Common Future", which defined sustainable development as the "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*" Sustainability is now recognised as a key issue which much be addressed in the design, construction and long term maintenance of civil engineering infrastructures. For example, highway bridges in North America built in the 1950's-70's had design lives of 50 to 100 years; however many were showing signs of deterioration after only 20-40 years. This led to the spending of considerable funds to reduce the risk of bridge failure through different mitigation strategies, including repair, rehabilitation and replacement of components and overall bridges. In some cases, posting was required given the limited load carrying capacity of the bridge and the unavailability of funds to retrofit the structurally deficient bridges. The key to sustainable infrastructures is long life with minimum maintenance materials and structures and resilient structural systems. Resilience is a pre-requisite to infrastructure sustainability as shown in Figure 1. Figure 2 shows a simple schematic representation of a sustainable and unattainable design of a structural system.

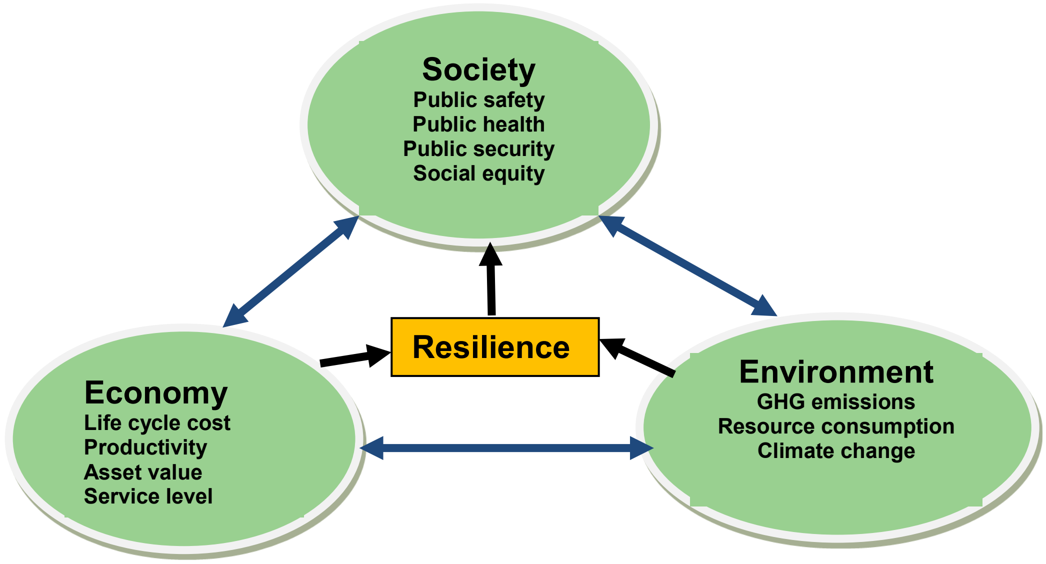

Figure 1. Triple bottom line approach to sustainable and resilient bridges

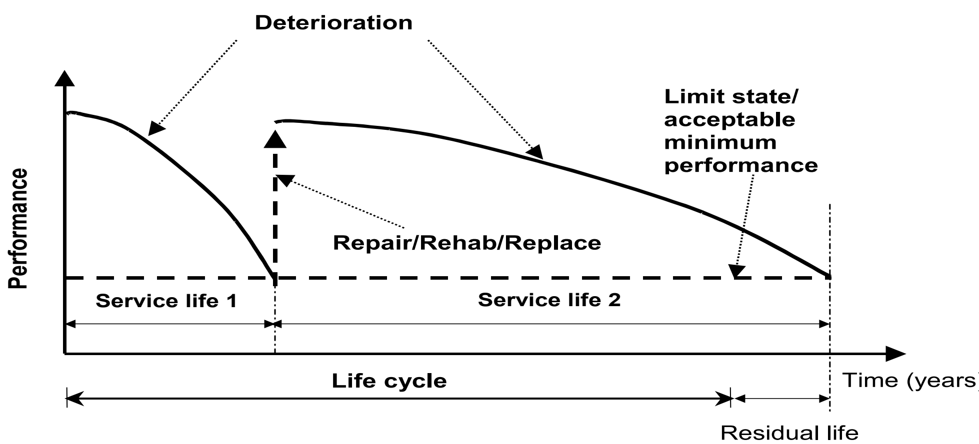

Figure 2. Schematic representation of life cycle performance of highway bridges

The construction, operation and maintenance of highway bridges consume considerable amounts of energy, materials, water and land, which in turn are responsible for large impacts' on the environment, including green house gas emissions, smog, water contamination, etc. There is a need to protect the natural environment by developing design and rehabilitation strategies for highway bridges that minimize the impacts on the natural environment, including air, water, soil, flora and fauna. In addition to satisfying environmental sustainability, it is also imperative to ensure that highway bridge infrastructures contribute to socio-economic sustainability by ensuring public safety, health and security, service reliability, access to service, and low life cycle costs.

Seven sustainability measures have been identified in a Model Framework for the assessment of public infrastructure performance (NRC 2009), which included: public safety, public health, public security, mobility, environment quality, social equity and the economy, against which the performance of infrastructures is assessed. These measures 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 can be developed to measure the performance of the infrastructure towards reaching sustainability.

Infrastructure resilience or robustness became a major design criterion since the Rona Point Building progressive collapse in 1968 in the UK. Progressive collapse has played a role in such catastrophic events as the collapse of the Alfred P. Murrah Federal Building (Oklahoma City, 1995), World Trade Center towers (New York, 2001), and the I-35W bridge collapse (Minnesota, 2007). Progressive collapse of structures is a situation where the initial failure of one or more load bearing components results in a series of subsequent failures of other components. Since the events of September 11th, 2001, research on progressive collapse has intensified covering two fronts: (i) design and retrofit for resilient structures; and (ii) consideration of extreme malicious attack using bomb explosives and plane impact. Several definitions of resilience or robustness are given in the literature. In this paper, the definition given in the Eurocode (2006) is used: "*Robustness is the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause.*" In simpler terms, resilience can be defined as the insensitivity of bridges to local failure.

Hazards

Bridge failures can result from a number of hazards with different likelihood of occurrence and consequences of failures. The hazards can be grouped under two categories:

- Normal loads: are those loads that have likelihood of occurrence and in general low to medium consequences of failure, e.g. vehicular loads on bridges, de-icing salts, seawater, freeze-thaw cycles, etc. Damage associated with these loads is in general cumulative and progressive.
- Extreme/abnormal loads: are those loads that have low likelihood of occurrence and high consequences of failure (e.g. earthquakes, tornadoes, bomb explosion, impact by vehicle/plane/ship, fire, construction/user error, etc. Damage associated with these loads is in general extreme and sudden.

Probability of failure

If each hazard is represented by H_i, then the total probability of bridge failure can be determined as follows (JCSS 2008):

$$P_f = \sum_{i=1}^{n_H} p(H_i) \sum_{j}^{n_D} \sum_{k=1}^{n_S} p(D_j | H_i) p(S_k | D_j) \quad (1)$$

Where n_H is the number of hazards; n_D number of damage (D) levels; and n_S number of post-damage structural behaviors (S).

Consequences of failure

The consequences of failure can be grouped under three broad categories that correspond to three pillars of sustainability of Figure 1, namely:

(i) Social consequences: fatalities, injuries, illnesses, psychological, reputation loss, increase of public fears, loss of political support

(ii) Economic consequences: damage to the structure; damage to the vehicles, damage to content, loss of income, loss of productivity, cost of detours and delays; cost of increased accidents

(iii) Environmental consequences: irreversible environmental damage; reversible environmental damage, impact on fauna and flora.

The risk of failure is obtained by multiplying the probability of failure in Eq.(1) by the consequences of failure. Ellingwood and Dusenberry (2005) provided alternative solutions to design against abnormal loads and avoid progressive collapse. Frangopol and Curley (1987) proposed a reliability-based robustness index:

$$RI = \frac{P_{f(damaged)} - P_{f(intact)}}{P_{f(intact)}} \quad (2)$$

where $P_{f(damaged)}$ is the probability of failure of a damaged bridge and $P_{f(intact)}$ is the probability of failure of an undamaged or intact bridge. The probability of failure can be calculated as follows:

EXAMPLE: DESIGN OF RESILIENT HIGHWAY BRIDGE DECKS

In North America, the extensive deterioration of highway bridge decks 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 hazard, most RC bridge deck failures are due to loss of serviceability and functionality. The probability of collapse of bridge decks is rather low due the considerable reserve of strength against punching failure. Tests on model bridge deck slabs in Canada revealed that this enhancement of strength was attributed to the compressive membrane arching action. A conservative design method is used in the Canadian bridge design standard (CSA 2006) as only nominal reinforcement, 0.3% was required to resist concentrated wheel loadings. The long-term efficiency of high performance concrete (HPC) containing fly ash as a supplementary cementing material (SCM) that replaces some of the cement for the construction and rehabilitation of concrete bridge decks. HPC decks are compared to normal performance concrete (NPC) in terms of the three measures of sustainability defined above, including service life, life cycle cost, environmental impacts and social impacts. 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.

Table 1. General information on investigated highway bridge.

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

Hazards and consequences of failure

The main hazard considered here is the reinforcement corrosion that is induced by de-icing salts that are used on Canadian roads during winter for public safety. The consequences include:

(i) Social impacts: public safety; users impacts due to traffic delays;

(ii) Environmental: CO_2 emissions and potential for climate change and waste generated during repair and rehabilitation of bridge decks; and

(iii) Economic: life cycle costs for bridge owner and bridge users.

Probabilistic modeling of time-varying performance of bridge decks in corrosive environments

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 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 solution of Fick's second law of diffusion, which is given by:

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D_C t}}\right)\right] \quad (3)$$

The error function is related to the cumulative distribution Φ as follows:

$$\mathrm{erf}(x) = 2\Phi(x\sqrt{2}) - 1 \quad (4)$$

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 *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 3 than becomes:

$$t_i = \frac{c^2}{4D_c\left[erf^{-1}\left(1 - \frac{C_{th}}{C_s}\right)\right]^2} \quad (5)$$

The 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 determination of the rebar diameter increase related to the different corrosion-induced damage limit states. For this example, it is considered that the end of service life of RC decks in corrosive environments is reached when 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. Material, structure and environmental data for highway bridge deck

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^3)	6	25
Chloride (apparent) coefficient of diffusion (cm^2/year) - **NPC**	0.40	25
Chloride (apparent) coefficient of diffusion (cm^2/year) – **HPC**	0.20	25
Threshold chloride content (kg/m^3)	0.70	20
Corrosion rate (μA/cm^2)	0.5	20

* COV = coefficient of variation (%)

Assessment of maintenance, repair and rehabilitation costs

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 in-place costs of materials are: \$460/m^3 for normal concrete (NPC); \$520/m^3 for high performance concrete; and \$1800 per ton of carbon reinforcing steel. The cost and time data presented in this example are taken from various sources referenced in Lounis & Daigle (2008) and Lounis (2013) or assumed.

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^2. 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).

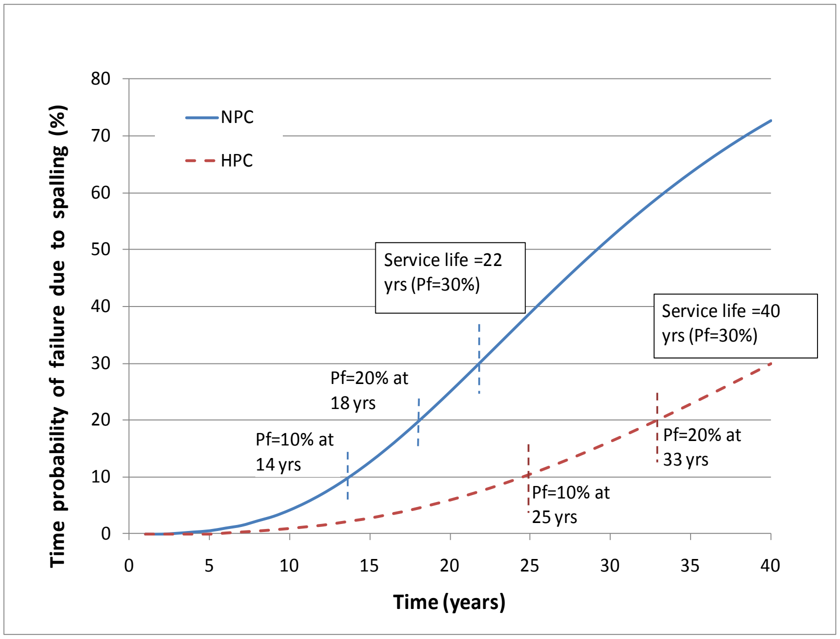

Figure 3. Time-varying probability of failure of bridge deck

Social consequences

The social consequences include the costs incurred by the road users, which include:

- time lost by drivers;
- increased vehicle operating costs due to traffic delay; and
- increased accident caused by MR&R activities.

The duration of each (MR&R) activity (average for both ways), the length of affected road during the activity (average for both ways), and reduced traffic speed during the activity (Table 3) 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 average value of driver's time is estimated at 12/hr for a car and $20/hr for a truck. The vehicle operating costs are estimated as $8.85/hr.

The normal accident rate on the highway is 2.1/million vehicle.km. In the construction zone during repair and rehabilitation work, the accident rate is 6/million vehicle.km and the average accident cost is estimated at $33,000 (Transport Canada 1994, 2006; Statistics Canada 2003; Walls & Smith 1998). Figure 4(a) 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.

Table 3. 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

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

$$PVLCC = C_0 + \sum_{t_i=1}^{T} \frac{C_i(t_i)}{(1+r)^{t_i}} - \frac{R_v}{(1+r)^T} \qquad (6)$$

where C_0 = Initial construction cost (including design costs); $C_i(t_i)$ = i^{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.

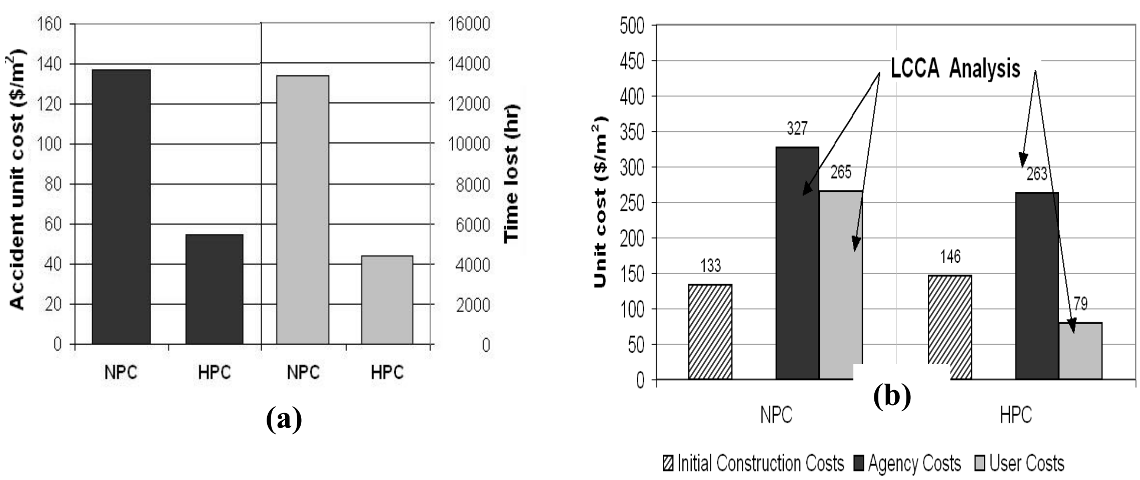

Figure 4. Socio-economic performance of NPC and HPC deck alternatives
(a) Time lost and accident costs; (b) Life cycle costs

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.

Assessment of environmental impacts

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_2 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_2 emitted by cars/trucks delayed by the maintenance, repair, and replacement activities. The CO_2 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_2 emissions for the normal concrete deck alternative are almost three times higher than those of the HPC deck alternative as shown in Figure 5(a). This difference is mainly due to the lower cement consumption of the HPC mix that uses fly ash 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_2 emissions of the NPC deck.

A comparison of the waste produced (or landfill use) for the two deck alternatives is shown in Figure 5(b), which includes the volume of waste material produced during the replacement of asphalt overlay, patch repairs, and replacement.

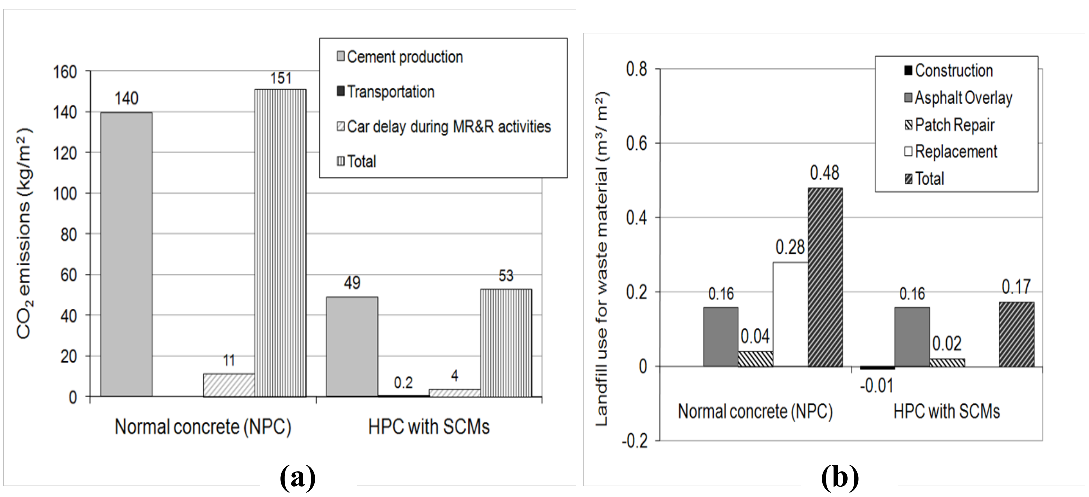

Figure 5. Environmental performance of NPC and HPC bridge decks:
(a) CO_2 emissions; (b) Generated waste materials

CONCLUSIONS

In this paper, it is shown that the implementation of a sustainable design approach would lead to the construction of high performance highway bridges that satisfy the safety and serviceability requirement and minimize the environmental impacts, users' costs and total life cycle costs. The use of high performance concrete containing fly ash results in a more sustainable bridge deck that has a longer service life, lower life cycle costs, and lower environmental and social consequences when compared to conventional normal concrete bridge decks. From the example above, the following conclusions can be drawn:

- HPC deck alternative incorporating SCMs has a service life that is almost twice as long as the service life of normal concrete deck.
- HPC deck alternative is found to be more economic than the normal concrete deck for both agency costs and user costs.
- HPC deck alternative yields a reduction of 65% in the CO_2 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. 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.

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