Appended papers

Paper I

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Life-cycle cost analysis as a tool in the developing process for new bridge edge beam solutions

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ABSTRACT
Currently in Sweden, the life-cycle measures applied on bridge edge beams may take up to 60% of the total costs incurred along the road bridges' life span. Moreover, significant disturbances for the road users are caused. Therefore, the Swedish Transport Administration has started a project to develop alternative edge beam design solutions that are better for society in terms of cost. The purpose of this article is to investigate whether these proposals can qualify for more detailed studies through an evaluation and comparison based on a comprehensive life-cycle cost analysis. The alternatives including the standard design are applied to typical Swedish bridges. The impact of the values of the parameters with the largest influence is investigated by sensitivity analyses. Results with different life-cycle strategies are shown. The positive influences in the total life-cycle cost of a stainless steel reinforced solution and of the enhanced construction technique are estimated. The concrete edge beam integrated with the deck seems to be favourable, which is in line with international experience observed. Different designs may be appropriate depending on the bridge case and the life-cycle strategy. The Swedish Transport Administration will carry out a demonstration project in a bridge with one of the proposals.

ABBREVIATIONS: BEBS: bridge edge beam system; LCC: life-cycle cost; LCCA: life-cycle cost analysis; INV: investment; LCM: life-cycle measures; LCS: life-cycle strategy; LCP: life-cycle plan; ADT: average daily traffic; BaTMan: the Swedish bridge and tunnel management system; TDC: traffic delay cost; VOC: vehicle operation cost; ACC: accident cost; CM: continuous maintenance; BC: bridge case

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1. Introduction

Infrastructure management is gaining more importance in the civil engineering field in order to ensure sustainability and cost efficiency. During the procurement phase, not only are the investment (INV) costs related to design and production relevant, but the life-cycle measure (LCM) costs referring to operation, maintenance and repairs need to be accounted for as well. Furthermore, the impact on society – in general – and on the infrastructure user – in particular – should be contemplated. The user costs may dominate the total costs completely and can become more than ten times higher than the LCM costs (Thoft-Christensen, 2011). Well-adjusted consideration of both the structural performance and the total cost accumulated over the entire life-cycle are required for a competent management of civil infrastructure (Frangopol & Liu, 2005).

Life-cycle cost (LCC) is the *cost* of an asset, or its parts, throughout its life-cycle while it fulfils its performance requirements. Life-cycle cost analysis (LCCA) is a methodology for systematic evaluation of the LCC over a specified period of analysis as defined in the agreed scope (ISO [International Organization for Standardization], 2008). LCCA has been used in many bridge management systems as a tool to select an optimal strategy considering the remaining life span and the condition class of existing bridges (Veganzones Muñoz & Morán Quijano, 2013). This technique has also been applied in choosing a solution among a set of proposals in the procurement method for new bridges. Moreover, not only has LCCA been used to decide on the whole bridge structure, but also for existing bridge structural members (Safi, 2013). Information related to the formulae used for the LCC calculations and life-cycle-related definitions used in this article can be found in Appendix 1.

One bridge structural member that has become an increasing concern for bridge managers is the bridge edge beam system (BEBS), especially in cold climate regions. The harsh conditions due to weather, frost, splashed salt water and car collisions that the BEBS is exposed accelerates its deterioration, which results in, *inter alia*, steel corrosion and concrete cracking and spalling. Consequently, high LCM costs and the subsequent user disturbances caused by a service interruption are associated with the BEBS.

A large part of the research contributions concerning BEBS has lately been carried out in Sweden. Due to the scarcity of available publications, the methodology to obtain information has typically been through international surveys sent to companies

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and transport authorities. With respect to design, Ehrengren (2000) published a State-of-the-art inventory of edge beam designs used in countries with climates similar to that of Sweden. It was shown that in Canada, Switzerland, Norway, Finland and Denmark, edge beams were cast *in situ* with the bridge deck, as in Sweden. In Germany and Austria, prefabricated concrete elements were used. In a latter edition, Troive (2008) illustrated the main functions the BEBS should fulfil along with the advantages and disadvantages of the different designs. The aforementioned countries were still using the same basic design. References to other countries were included. In Hungary, Poland and Czech Republic prefabricated edge beams were used, whereas in France, a mix of types was present, with a special emphasise to aesthetical concerns.

Actually, aesthetics may be of interest since the BEBS is the most visible part of the bridge. Architects have become focused on producing attractive designs. In Germany, an edge beam was designed to be used in all bridges of the light rail network in order to be both aesthetically pleasing and distinctive for the new transportation network (Lüthi & Zwicky, 2007). However, these designs sometimes lead to ineffective and costly solutions from a constructability and life-cycle perspective (Karim, 2011). The draining system in the BEBS has also been a subject of study. Gustafsson (2010) proposed design alternatives with regard to more efficient drainage mechanisms.

Currently, the Swedish regulations state that the edge beam must be geometrically designed according to the vehicle crash tests performed on railings. The design must ensure a good crack distribution as well. Nevertheless, in contrast to other Nordic countries such as Denmark, the edge beam may not be taken into account for as a load-bearing member of the structure. The rationale is that the bridge should function while the edge beam is being replaced. This fact has sometimes led to crack width problems in edge beams with a considerable size that were inadequately reinforced with respect to global effects (Ansnaes & Elgazzar, 2012). Designers nowadays generally account for local failure of the edge beam and of the railing caused by a vehicle collision to calculate the reinforcement needed.

From a life-cycle perspective, the life span of the BEBS, which includes preventive and corrective maintenance, as well as the BEBS implications in LCCAs have been the subject of recent study. Mattson, Sundquist, & Silfwerbrand (2007) revealed that one-third of the bridge damage noted in their large sample of Swedish bridges is related to the BEBS. In the same study, a survival analysis concluded that the real median life span for edge beams located in European graded roads in Sweden was 58 years and for other roads 75 years. The repair and replacement of the BEBS is one of the principal contributions to bridge LCCAs (Salokangas, 2013; Safi, 2013). Samuelsson (2005) studied the influence of cooling in the formation of concrete cracks when replacing edge beams. Silfwerbrand (2008) carried out a LCCA to investigate the economic benefit of impregnation of edge beams, and concluded that it is more cost-effective in old bridges than in modern ones. For Öland's bridge (Sweden), a LCCA was applied to decide on a life-cycle strategy (LCS) that assured 75 years of edge beam's life span (Maglica, 2012). In this article, a LCS is defined as a set of life-cycle plans (LCPs) that have to be carried out at certain points in time throughout the life span of a structure or a bridge structural member, so that it can fulfil its performance requirements – see Appendix 1. Each LCP includes several LCMs executed concurrently. An example of a LCM is an edge beam replacement. In order to ensure an adequate performance of the BEBS, a good execution of the LCMs is essential, as shown in Figure 1.

Nonetheless, nowadays there is a gap between the practice of the BEBS design and the account for life-cycle perspective. According to the Swedish Transport Administration (in Swedish, 'Trafikverket'), up to 60% of the LCM costs of the entire bridge can be referred to the BEBS alone. Apart from the design, there is need for an optimal LCS which reduces simultaneously user and society costs. Because of that need, 'Trafikverket' created the 'Edge Beam Group' (in Swedish, 'Kantbalksgruppen'), comprised of bridge experts, and tasked it to develop better edge beam designs for the society (builder, designer, maintenance and user).

The aim of this article is to provide a basis for bridging the gap between design and LCCA, and to use the latter as a tool that can lead to developments in bridge design. Under this perspective, the main goal is to analyse whether edge beam design solutions alternative to the standard type can turn out better for the society in terms of cost and, thus, qualify for more detailed studies. The objectives will be the evaluation and comparison of each new developed BEBS type with the aid of a comprehensive LCCA. Typical Swedish bridge cases will be introduced. The influence on the outcome of identified critical factors is addressed by sensitivity analyses. Although a recommended LCS by the authors will be used, the results from the application of other different LCSs will also be presented. A design proposal with stainless steel applied to one solution type is assessed from a LCC perspective. Finally, a reflection of the positive economic impact due to more stringent regulations along the last decades will be shown. The article deals with road bridges. The analysis considers a BEBS that is newly built together with the bridge structure.

2. The edge beam and the BEBS

The edge beam is a bridge structural member whose main function is to serve as support for the railing to prevent bridge users from falling off. It may also help to distribute concentrated loads, provide stiffness to the bridge deck, help in draining functions and support the pavement. The bridge edge beam system (BEBS) is a term used in infrastructure management by 'Trafikverket' to

Figure 1. A replaced BEBS in a bridge in the south-west of Sweden.

define a group of structural and non-structural bridge members whose principal elements are the edge beam and railing. Other secondary elements often included refer to the drainage system, waterproofing layer, walkway, lightning poles and other such elements.

2.1. The edge beam in Sweden

The most common edge beam solution in Sweden is the concrete integrated alternative, named as type I (Figure 2a). The edge beam is cast *in situ* with the bridge deck. Its usual design is raised with the top edge having elevation of between 80 and 120 mm from the pavement level. This is a recommendation according to the Swedish standards but that may be a requirement in case of water bodies, or road or railway traffic underneath the bridge (Trafikverket, 2011). Non-raised edge beams are also found in Sweden, but in a minor proportion (Safi, 2013).

3. Proposals studied

The BEBS proposals developed by Swedish and international contractors and consultants are grouped into 4 types according to the nature of the edge beam (Figure 2). The containment level of the railing is H2 (CEN [European Committee for Standardization], 1998; AB Varmförzinkning, 2015). Type II (Figure 2b) does not have an actual edge beam; railing posts are connected to steel supports attached to the deck. In order to support the pavement and contribute to the drainage system, a continuous L-steel profile anchored to the bridge deck slab is placed at the road sides. In type III (Figure 2c), railing posts are supported on a

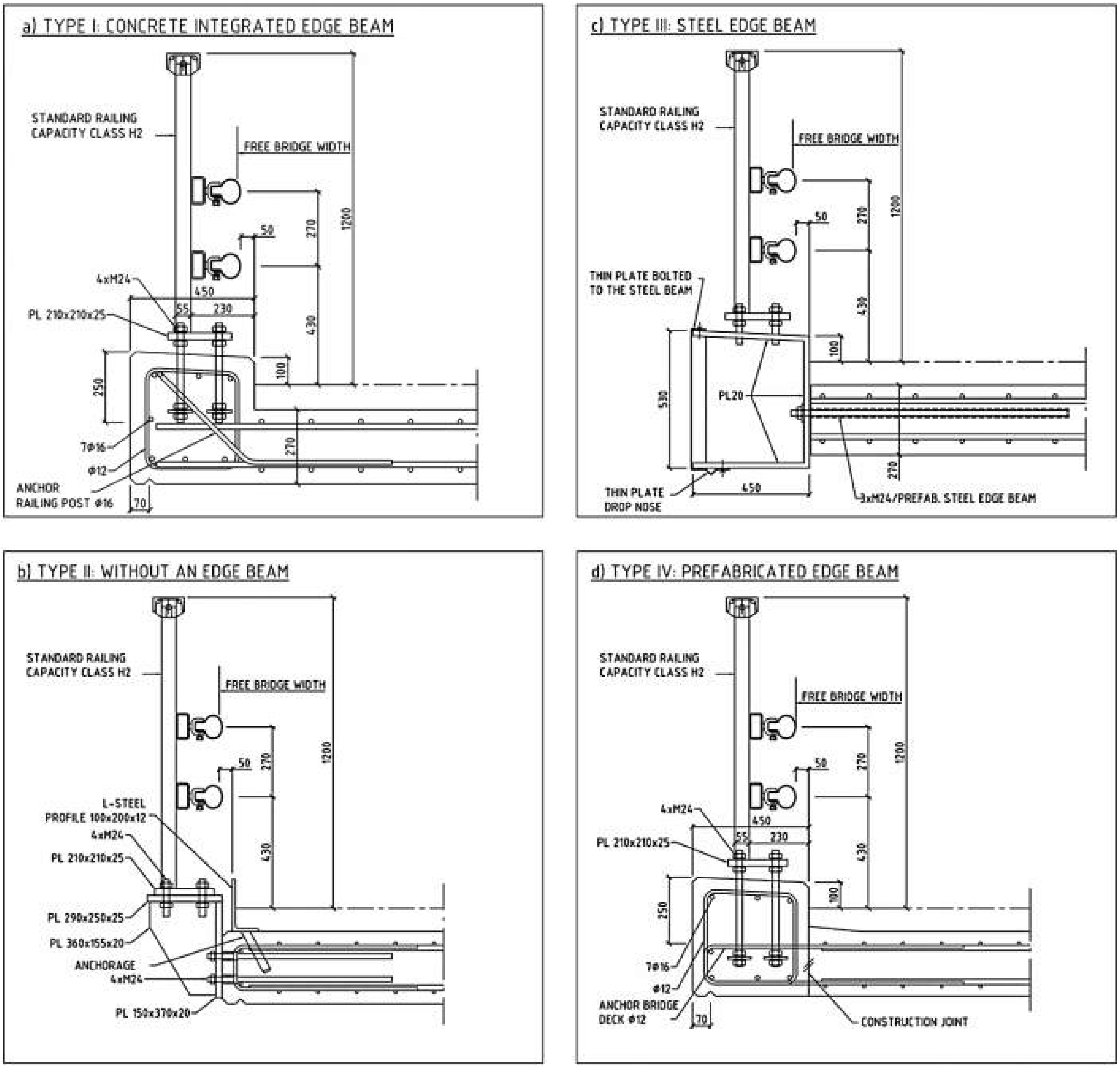


Figure 2. BEBS types: (a) type I: concrete integrated, (b) type II: without an edge beam, (c) type III: steel edge beam, (d) type IV: prefabricated edge beam. Source: Pettersson and Sundquist (2014).

U-shaped steel beam anchored in the concrete slab along the bridge length. It is covered by a bolted external thin plate. Two internal transversal vertical steel plates are placed at each railing post to provide stiffness. Types II and III have never been tried in real bridge projects in Sweden.

The prefabricated edge beam solution identified as type IV (Figure 2(d)) is constructed in advance on the bridge site (Figure 3(a)). Then, it is lifted and integrated into the formwork of the deck, where the concrete will be cast subsequently (Figure 3(b)). This provides an enhanced working environment for type IV (Figure 4(a)) over type I (Figure 4(b)), which also normally leads to better concrete quality. Moreover, the shrinkage resulting from the concrete cast in the bridge deck leads to a prestressing action in the edge beam, which is favourable in preventing the formation of cracks. Due to the length restrictions, construction joints are needed in between the prefabricated elements on long bridges, which is an inconvenience. These construction joints require a complicated formwork arrangement to cast the concrete between the elements. In addition, concrete often acquires a different colour. In case a gap is left between the prefabricated elements, cracking may be precipitated in the bridge deck at this location. This solution differs from the aforementioned ones in Germany and Austria, where permanent joints exist between the elements and the bridge deck (Pettersson & Sundquist, 2014).

4. LCC contributions and economic analysis tools

The different contributions in a LCCA of a given structure can be divided into parts, as different parties in the society will be either responsible for or affected by the costs occurring as a consequence of building or utilising the structures (Sundquist & Jutila, 2007). Owner, society and user costs can be distinguished to calculate the LCC of an infrastructure, according to (Troive, 1998):

$$\mathrm{LCC}_{\mathrm{infrastructure}} = \mathrm{LCC}_{\mathrm{owner}} + \mathrm{LCC}_{\mathrm{user}} + \mathrm{LCC}_{\mathrm{society}} \quad (1)$$

All costs will be presented in SEK (Swedish currency), while 1 SEK is equivalent to .1077 € (European Central Bank, 21 April 2015). For simplicity, society costs will be included henceforth as part of user costs. More detailed LCCA can be oriented from a holistic approach considering other contributions such as cultural or aesthetic values (Safi, Du, Sundquist, & Karoumi, 2013). In this study, these factors are not accounted for due to their nature. Furthermore, some LCCA include failure costs considering accidents and the probability of collapse. This contribution is excluded in this article because they are considered negligible in comparison with the other cost components.

5. Methodology

To carry out an extensive analysis, all bridges were grouped into categories representing the most common groups in Sweden,

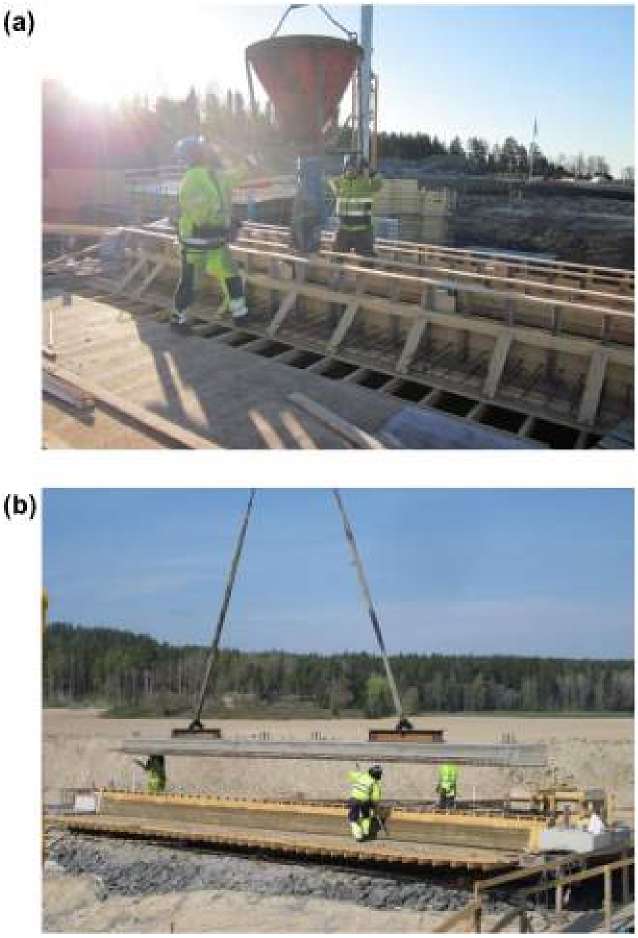


Figure 3. Prefabricated edge beam (type IV): (a) concrete pouring with a V-funnel, b) lifting to the bridge deck formwork. Source: Kelindeman (2014).

Figure 4. Edge beam construction in real bridge projects: (a) type I, and (b) type IV. Source: Kelindeman (2014).

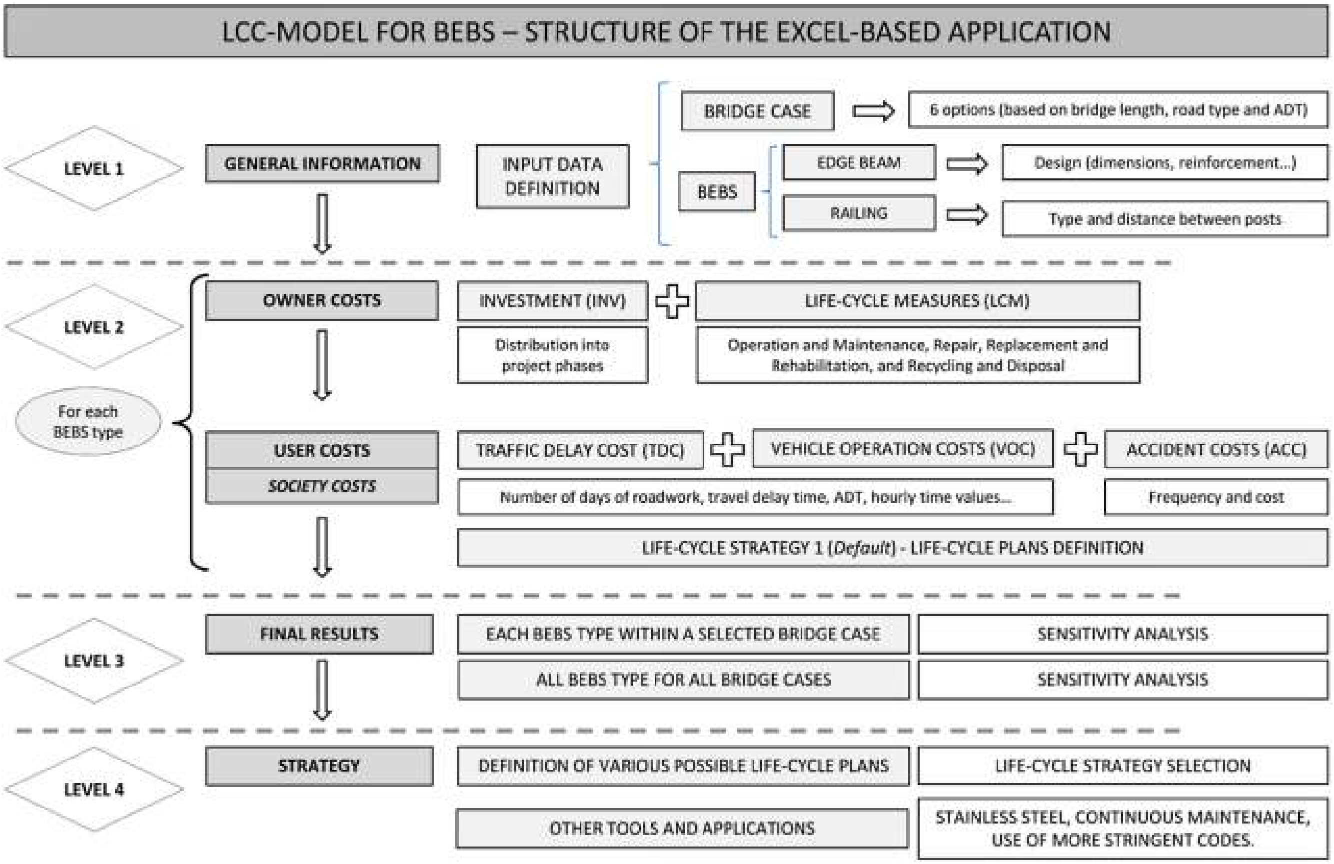


Figure 5. Structure of the LCC model integrated into with the different levels that exist in the Excel-based application.

using certain parameters. Subsequently, for the design solution types of BEBS, LCC calculations were performed from owner and user-society perspectives. The structure of the LCC model depicted in Figure 5 was integrated into an Excel-based application developed for this purpose. The results and a comparison between different solutions are presented. A defined default life-cycle strategy (LCS) based on real information and on assumptions was adopted. Sensitivity analyses show the influence of the value of different parameters. The results of other LCSs, including continuous maintenance, and a scenario where stainless steel is used to extend the life span are presented. Finally, based on the more stringent code requirements, better knowledge in the parameters affecting the deterioration of the edge beam, and improvement of the material quality, an estimation of the impact in the total LCC of the BEBS is illustrated.

A deterministic approach was adopted. The reason for this was that the life-cycle related information of a standard edge beam (type I) was considered well known. The source of this information was the Swedish Bridge and Tunnel Management System (BaTMan). The information accounted for the conjunct process resulting from (1) deterioration of a certain structural member and (2) the decision-making from the bridge manager to distribute the LCMs into several LCPs along the bridge's life span. With respect to the solutions that have not been constructed yet in Sweden (types II and III), a probabilistic analysis was not carried out since there was no life-cycle-related input data available. Therefore, a reliable probability distribution could not be elaborated. Their LCSs were based on the engineering knowledge of the bridge edge beam expert group from 'Trafikverket'. The influence of these assumptions on the final outcome was addressed through the definition of two additional LCSs, in which the principal parameters of types II and III were varied.

5.1. Bridge cases

The following three parameters were combined to obtain six general BCs that represent the majority of bridges in Sweden (Figure 6):

- Bridge length: short bridges (10–15 m) and long bridges (100–200 m).
- Road type: one or two 3.5-m lanes with 2.0-m shoulder in each direction, and a 2.5-m median strip in the latter case.
- Urban or non-urban area, defined in terms of the average daily traffic (ADT): high (2,500 vehicles per lane/day) or low (10,000 vehicles per lane/day)

The remaining BCs – long or short bridge with two lanes in each direction in a non-urban area – were excluded since their presence in Sweden is rare (Trafikverket, 2013b). Nevertheless, the LCC model for the BEBS can be used to obtain results for these cases as well.

Figure 6. The six BCs accounted in the LCCA identified by the combination of the parameters and with an existing Swedish bridge example for each case.

5.2. Definition of the design solutions

The representative design solution for each BEBS type was the ones shown in Figure 2. The dimensions were the same as the visualised ones.

5.3. Assumptions and limitations

- A possible influence from the edge beam design on other bridge elements was not taken into account.
- The design life span of the bridge was assumed to be 120 years. This choice does not considerably influence the final results in terms of total LCC since the value of money is discounted. This means that LCMs on the bridge at the end of the life span of the bridge have less impact from an economical point of view than the LCMs taking place in the beginning.
- The design life span of the BEBS elements did not depend on the ADT or the type of road. With regard to the former, there may be a relationship between them because, due to bigger risk of accident, greater amount of salt used, more splashed water, etc., the probability that the BEBS deteriorates may increase for higher ADT. In reference to the latter, the distribution of vehicles within the road, the probability of accidents and the traffic speed may influence the life span of the BEBS. These factors are difficult to assess since all processes contribute and influence each other and nowadays there is no accepted demonstrated reliable method comprising them that can be applied to LCCA.
- All the BEBS proposals were assumed to meet the load-bearing capacity design requirements. Only costs are handled in this article.
- The main BEBS elements included in the LCCA were the edge beam and the railing. The waterproofing layer was considered when defining the LCS. The drainage system and other secondary elements were included as means of operation and maintenance.
- Since six general BCs were considered, more detailed study might be required for particular bridge condition, different edge beam dimensions or other BEBS design proposals. For the calculation of the user costs, an averaged reduced speed in case of road works was used which accounts for possible detours or formation of traffic queues.
- The user costs were incurred due to the LCMs carried out along the life span of the BEBS. The user costs related to the new construction of the BEBS together with the bridge were not included. In this case, the user costs would refer to the entire bridge and the part corresponding solely to the BEBS is negligible.
- The discount rate used was set equal to 4.0%, which is the recommended value in Sweden (Salokangas, 2013).

5.4. Calculations

5.4.1. Owner costs

The INV costs for types I and IV are based on data from real BCs in Sweden (Kelindeman, 2014). Since types II and III have not been constructed as of the present, an estimate is based on data from the other alternatives. The phases considered are design, transportation, unloading of materials and construction. These latter include formwork installation and removal, arrangement of reinforcement and anchoring bolts, concrete cast and railing installation. All phases consider the cost of materials, machinery and labour. The contractor and project leader costs, overhead costs and other unexpected costs are also contemplated.

To evaluate the LCM costs, and also the user costs they incur, the LCS needs to be defined and the bridge management process should be considered. The bridge management process refers to the series of actions or steps taken to organise and coordinate the LCMs in order for the bridge to fulfil its performance requirements. The decision-making procedure directly affects the performance of the BEBS and, thus, the road user.The bridge manager has to contemplate whether a specific LCM must be carried out and, if so, when it should be done. For example, repairing or replacing a BEBS at a bridge in a secondary road, even with significant damage, can be considered a minor need. The resources available for maintenance are generally prioritized to those bridges in urban areas or on primary roads (personal communication with ‘Trafikverket’ bridge manager).

Such prioritization needs to be considered before drawing conclusions. A ‘Survival Analysis’ showed that non-raised edge beams are more likely to have a longer life span than raised ones (Sobhit, 2014). This may seem contradictory as these designs allow contaminated water to run-off the bridge and expose concrete to harsher conditions. However, this alternative is mostly used for roads graded as secondary or lower (Trafikverket, 2013b), which can explain its ‘remarkable’ resistance. Mattson et al. (2007) shows that edge beams in a European Road in Sweden are usually replaced earlier than other road types because of increased wear due to higher ADT and use of greater amounts of salt.

In addition, an enhanced planning of the LCSs leads to an improvement of the bridge management process, as an action to effectively coordinate the LCMs. Traditionally, the goal has been to define a LCS with the objective of maximising or minimising a lifetime performance indicator and minimising the present value of the LCM costs (Frangopol, 2010). Adey and Hajdin (2005) proposed to use inventory theory to bundle LCMs in order not to perform them in successive years because of the user disturbances and showed that optimal LCSs could be determined. Recently, Mirzaei and Adey (2014) applied this methodology on a real bridge and led to optimal LCS grouping interventions. Huang and Huang (2012) presented a model to define an optimal LCS for concurrent maintenance of bridge elements where the goal was to integrate the timings of the LCMs of different bridge elements to reduce the user costs. In this regard, this article refers to the BEBS, not only the edge beam itself. When the edge beam is repaired or replaced, ‘Trafikverket’ may ‘take advantage’ to carry out other LCMs related to the railing or the waterproofing layer and vice versa (personal communication with ‘Trafikverket’ bridge manager). Thus, the following principle is applied: ‘when many different LCMs must be carried out they should be included in the same package’ (Pettersson & Sundquist, 2014). This package refers to the LCP where certain LCMs are grouped. A set of LCPs along the bridge’s life span constitutes a LCS. The purpose of this is to aim for optimisation, choosing a better LCS and, most importantly, reducing traffic interruptions.

	Type I – CONCRETE INTEGRATED EDGE BEAM				Type II – WITHOUT AN EDGE BEAM				Type III – STEEL EDGE BEAM				Type IV – CONCRETE PREFABRICATED EDGE BEAM				
	Life-cycle Plan	Year	Days		Life-cycle Plan	Year	Days		Life-cycle Plan	Year	Days		Life-cycle Plan	S		L	
			S	L			S	L			S	L		Year	Days	Year	Days
1	**Life-cycle Plan 1**	20	5	15	**Life-cycle Plan 1**	20	10	30	**Life-cycle Plan 1**	25	5	15	**Life-cycle Plan 1**	25	5	20	15
	Concrete rep. 0-30 mm				L-steel-profile exchange				Steel repainting				Concrete rep. 0-30 mm				
	Impregnation				*Concrete rep. 0-30 mm*				*Minor railing activities*				*Impregnation*				
	Minor railing activities				*Minor railing activities*								*Minor railing activities*				
2	**Life-cycle Plan 2**	40	8	20	**Life-cycle Plan 2**	40	10	30	**Life-cycle Plan 2**	50	17	50	**Life-cycle Plan 2**	50	8	40	20
	Concrete rep. 30-70 mm				L-steel-profile exchange				Edge beam replacement				Concrete rep. 30-70 mm				
	Impregnation				*Minor railing activities*				*Concrete rep. 30-70 mm*				*Impregnation*				
	Minor railing activities				*Concrete rep. 0-30 mm*				*Railing replacement*				*Minor railing activities*				
3	**Life-cycle Plan 3**	60	25	70	**Life-cycle Plan 3**	60	15	45	**Life-cycle Plan 3**	75	5	15	**Life-cycle Plan 3**	75	25	60	70
	Edge beam replacement				Steel support replacem.				Steel repainting				Edge beam replacement				
	Railing replacement				*L-steel-profile exchange*				*Minor railing activities*				*Railing replacement*				
	Impregnation				*Concrete rep. 30-70 mm*								*Impregnation*				
					Railing replacement												
4	**Life-cycle Plan 4**	80	5	15	**Life-cycle Plan 4**	80	10	30	**Life-cycle Plan 4**	100	17	50	**Life-cycle Plan 4**	100	5	80	15
	Concrete rep. 0-30 mm				L-steel-profile exchange				Edge beam replacement				Concrete rep. 0-30 mm				
	Impregnation				*Concrete rep. 0-30 mm*				*Concrete rep. 30-70 mm*				*Impregnation*				
	Minor railing activities				*Minor railing activities*				*Railing replacement*				*Minor railing activities*				
5	**Life-cycle Plan 5**	100	8	20	**Life-cycle Plan 5**	100	10	30					**Life-cycle Plan 5**	-	-	100	20
	Concrete rep. 30-70 mm				L-steel-profile exchange								Concrete rep. 30-70 mm				
	Impregnation				*Concrete rep. 0-30 mm*								*Impregnation*				
	Minor railing activities				*Minor railing activities*								*Minor railing activities*				
	For all BEBS types, *Cleaning from salts and gravel* is carried out every year, and *Cleaning from vegetation* every 2 years																

Figure 7. LCS1 for each BEBS type including the different life–cycle plans (LCPs) with the associated life–cycle measures (LCMs). The 'Slave' LCMs are italicised under the 'Master' LCM.

Table 1. Parameters used for the user cost calculations.

Parameter	Symbol	Unit	Value
Traffic growth	r_{tg}	–	1.1%
Percentage of heavy vehicles from all ADT	r_t	–	7%
Expected travel time delay in case of roadwork	T	h	
Affected roadway length	L_t	m	
Short bridge			500
Long bridge			2000
Speed reduction	$v_s - v_r$	km/h	
Road type 1, Low ADT			80–60
Road type 1, High ADT			60–50
Road type 2, Low ADT			110–60
Road type 2, High ADT			90–50
Hourly time value for a heavy vehicle	w_t	SEK/h	540
Hourly time value for a passenger vehicle	w_p	SEK/h	145
Hourly operating costs for a heavy vehicle including goods	O_t	SEK/h	440
Hourly operating costs for a passenger vehicle	O_p	SEK/h	130
Accident frequency under normal conditions	A_r	accidents/veh-km	3.15E–07
Accident frequency under road works	A_n	accidents/veh-km	1.15E–06
Costs of an accident for the society	C_{acc}	MSEK/accident	4.8

The approach taken in this article has been to define each LCP governed by a so-called ‘Master’ LCM out all the needed LCMs, which are dubbed ‘Slaves’. In other words, LCMs that would take place at different time points of the structure are grouped in several LCPs whose intervention time is decided by a certain ‘Master’ LCM. This ‘Master’ LCM, apart from being relevant for the BEBS performance, is the one that requires longer time to be executed than the ‘Slave’ LCMs.

Figure 7 depicts the LCS, referred as LCS1, for each type of BEBS. The LCPs and their associated LCMs are also presented. The definition of LCS1 is based on information of actual Swedish bridges (Trafikverket, 2013b) and engineering knowledge from the bridge edge beam expert group (Pettersson & Sundquist, 2014). The LCMs presented are the most frequently performed ones in Sweden (Safi, 2013). An example of a ‘Master’ LCM in the LCPs depicted in Figure 7 is the edge beam replacement. In this article, the intervention year for a ‘Master’ LCM is defined to synchronise with the intervention times related to the waterproofing layer and the wearing course works. For instance, in the LCS for type I, the waterproofing layer can be replaced during the LCP2 in year 40 and LCP4 in year 80 and supplemented during the rest of LCPs. Operation- and maintenance-related LCMs are not considered to contribute to disturbances in the traffic since they can be carried out at night.

The cost of each LCM is taken from ‘BaTMan’ (Trafikverket, 2013a). For types II and III, an estimate is made, similarly to INV costs. Inspections are not accounted for since they are carried out on all bridges regardless of the BEBS type, and their influence on the total LCC is negligible. In the application, all LCMs may be defined in terms of probability of action necessity, since they are not carried out in all bridges (i.e. not all BEBS are always replaced today). Safi (2013) suggests that the probability of replacing type I is 20% after 50 years. In this regard, if the edge beam life span is extended, the probability of replacement would tend to 100% due to advanced deterioration. However, bridge management considerations may affect the real value of this probability. Since no data are available for type II and III, the probability of action necessity of all LCMs is set to 100%. In the light of the available information this is thought to provide a fair study. This assumption may be relaxed in future work when more information is available.

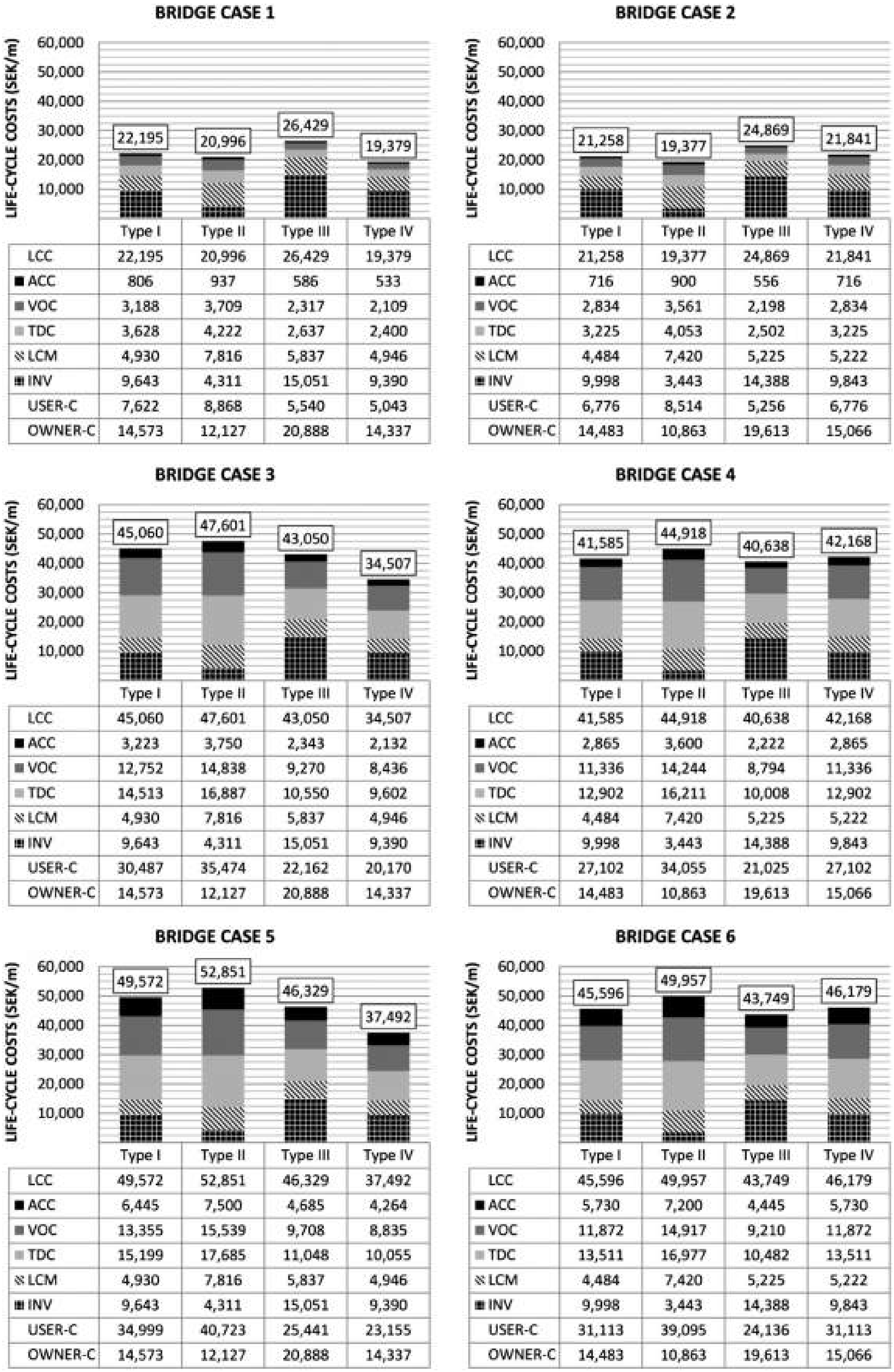
5.4.2. User costs

The user costs are incurred under each LCP and are divided into traffic delay costs (TDC), vehicle operation costs (VOC) and accident costs (ACC) – see Appendix 1. Table 1 shows the values of the parameters utilised in the calculations, which are based on different literature sources (American Transportation Research Institute [ATRI], 2013; Federal Highway Administration [FHWA] – US. Department of Transportation, 2014; Karim, 2011; Liikenneviraston Ohjeita [Finnish Transport Agency], 2010; Safi, 2012; Salokangas, 2013; Trafikverket, 2014; WSP Group, 2007/2008). About Thirty-five percent of the heavy vehicles are buses. Since the article deals with general BCs, it was not possible to calculate accurately the travel delay time considering aspects such as the detour length and/or the formation of queues. Not all bridges will necessarily have a detour alternative. For example, in a 2-lane/direction bridge, only one of the lanes could be closed and the traffic could still be open. The approach used accounts for these aspects implicitly as mentioned above. Expected travel delay in case of a roadwork was calculated over 1) the affected roadway length, which depends on the bridge length and 2) the speed reduction, which depends on the road type and the ADT. Certainly, if the LCCA is performed in a specific bridge, detailed conditions should be accounted for.

Work trips, commuting trips and transfers, and other leisure trips are included within the hourly time value for a passenger car and a heavy vehicle. Fuel costs, truck and trailer lease or purchase payments, repair and maintenance, truck insurance premiums, permits and licences, tires, tolls, driver wages and driver benefits are included within the hourly operating cost. The cost of an accident for the society was calculated considering a probability for death (1.9%), for serious and minor injuries (9.8 and 29.4%, respectively) and for property damage (58.9%).

6. Results and discussion

Figure 8 shows the total LCC in SEK/m divided into owner costs (INV and LCM) and user costs (TDC, VOC and ACC) for all BEBS types for all the BCs. Even though the INV cost hold the biggest share, up to 35% of the total corresponds to the LCM cost, which highlights the need to account for them in the design. The almost negligible difference in INV costs between



BRIDGE CASE 1

	Type I	Type II	Type III	Type IV
LCC	22,195	20,996	26,429	19,379
■ ACC	806	937	586	533
■ VOC	3,188	3,709	2,317	2,109
■ TDC	3,628	4,222	2,637	2,400
▨ LCM	4,930	7,816	5,837	4,946
▦ INV	9,643	4,311	15,051	9,390
USER-C	7,622	8,868	5,540	5,043
OWNER-C	14,573	12,127	20,888	14,337

BRIDGE CASE 2

	Type I	Type II	Type III	Type IV
LCC	21,258	19,377	24,869	21,841
■ ACC	716	900	556	716
■ VOC	2,834	3,561	2,198	2,834
■ TDC	3,225	4,053	2,502	3,225
▨ LCM	4,484	7,420	5,225	5,222
▦ INV	9,998	3,443	14,388	9,843
USER-C	6,776	8,514	5,256	6,776
OWNER-C	14,483	10,863	19,613	15,066

BRIDGE CASE 3

	Type I	Type II	Type III	Type IV
LCC	45,060	47,601	43,050	34,507
■ ACC	3,223	3,750	2,343	2,132
■ VOC	12,752	14,838	9,270	8,436
■ TDC	14,513	16,887	10,550	9,602
▨ LCM	4,930	7,816	5,837	4,946
▦ INV	9,643	4,311	15,051	9,390
USER-C	30,487	35,474	22,162	20,170
OWNER-C	14,573	12,127	20,888	14,337

BRIDGE CASE 4

	Type I	Type II	Type III	Type IV
LCC	41,585	44,918	40,638	42,168
■ ACC	2,865	3,600	2,222	2,865
■ VOC	11,336	14,244	8,794	11,336
■ TDC	12,902	16,211	10,008	12,902
▨ LCM	4,484	7,420	5,225	5,222
▦ INV	9,998	3,443	14,388	9,843
USER-C	27,102	34,055	21,025	27,102
OWNER-C	14,483	10,863	19,613	15,066

BRIDGE CASE 5

	Type I	Type II	Type III	Type IV
LCC	49,572	52,851	46,329	37,492
■ ACC	6,445	7,500	4,685	4,264
■ VOC	13,355	15,539	9,708	8,835
■ TDC	15,199	17,685	11,048	10,055
▨ LCM	4,930	7,816	5,837	4,946
▦ INV	9,643	4,311	15,051	9,390
USER-C	34,999	40,723	25,441	23,155
OWNER-C	14,573	12,127	20,888	14,337

BRIDGE CASE 6

	Type I	Type II	Type III	Type IV
LCC	45,596	49,957	43,749	46,179
■ ACC	5,730	7,200	4,445	5,730
■ VOC	11,872	14,917	9,210	11,872
■ TDC	13,511	16,977	10,482	13,511
▨ LCM	4,484	7,420	5,225	5,222
▦ INV	9,998	3,443	14,388	9,843
USER-C	31,113	39,095	24,136	31,113
OWNER-C	14,483	10,863	19,613	15,066

Figure 8. LCC results of all BEBS types for all BCs expressed in terms of owner costs (INV and LCM costs) and user costs (TDC, VOC and ACC) for LCS1.

short BCs (1, 3 and 5) and long ones (2, 4 and 6) is due to the type of machinery, the amount of labour work and the costs of LCM that depend on the bridge length. INV has the largest contribution for types I, IV and, especially, III. In type II, it is not so significant because no concrete works are included; only the steel support, the L-steel profile and the railing. Nonetheless, LCM costs are higher due to the need for continuous maintenance of the L-steel profile which is greatly damaged by the snow removal machines.

With reference to user costs, first TDC and then VOC are the most important contributions, whereas ACC are of lesser importance. Type II implies more costs for the road user since more LCMs need to be applied. Types I and IV require greater time for the replacement of the edge beam since concrete is cast *in situ*. Conversely, type III has remarkably reduced user costs in comparison, due to a faster replacement.

Figure 9 summarises the results for all BCs and all BEBS types. For all short bridges (BCs 1, 3 and 5), the prefabricated edge beam (type IV) is a recommended solution in terms of LCC, due to the enhanced quality in the concrete. For long bridges (BCs 2, 4 and 6), even though the results vary, the concrete integrated edge beam (type I) could be a suitable solution, provided the uncertainties regarding type II (without a real edge beam) and type III (steel edge beam). Type IV is not recommended due to (1) the unfavourable working environment, especially from machinery related issues and (2) the *in situ* cast joints, or alternatively the gaps between the elements. The influence of the ADT is relevant to address. For BCs 3–6, the total LCC increases, because the user costs are largely dependent on this factor contributing to 60–70%. BCs 5 and 6 are slightly higher due to the greater vehicle capacity (two lanes), but it is partly compensated since travel delay time is reduced (increased road width).

6.1. Sensitivity analysis

Since the value of money is discounted for the future, it is of interest to analyse the impact of discount rate. In this work, no attempt is made to show its influence for all BCs, but to address the importance it may acquire. Figure 10 presents the LCM costs, user costs and total LCC for BC 3 given discount rates between 2 and 7%. This is within a common interval for industrialised countries (Salokangas, 2009; Thoft-Christensen, 2011). The LCM costs can vary up to 4–5 times in magnitude, and the user costs can do so 7–9 times. The total LCC for types I, II and IV can differ up to 4,5 times each, whereas the total LCC for type III can differ up to 3,5 times. Type III is thus less sensitive to the discount rate (smaller slope in Figure 10). The reason for this is that fewer costs are incurred in the future mainly due to a reduced impact on the user. For a very low discount rate (1–2%), type III may result less costly in comparison with other alternatives for some BCs.

The value of the discount rate is based on the real interest rate which considers long rent loans, inflation and the positive or negative effect the infrastructure might cause. Normally, the inflation rate used corresponds to the one in society obtained from the net price index. Based on this, the discount rate usually varies between 3.5 and 4.5% in Sweden. Nevertheless, the costs in the construction sector generally grow more in comparison with those in society at large, which results in a higher inflation rate and lower real interest rate (Sundquist, 2011). On the other hand, the Swedish State encourages 'Trafikverket' productivity, implying a higher discount rate to be applied (ibid.). A 0% discounting would lead to more costly results in the LCCA. In such scenario, the Transport Administration would be encouraged to invest initially in more costly solutions that guarantee an enhanced quality and performance so that less money needs to be spent on future LCMs. However, since the real interest rate accounts for the nominal interest rate for long loans, it is likely to be greater than 0%.

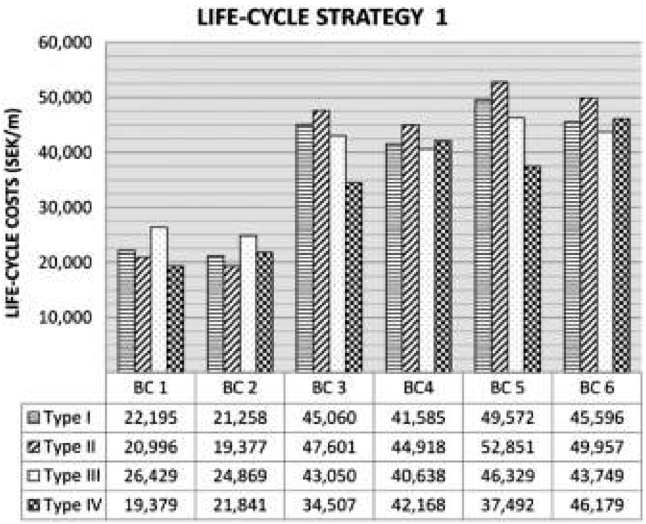
The influence of the total number of days needed (N_t) and the total affected roadway length (L_t) within the LCP comprising the edge beam replacement are also presented. This LCP is chosen because it is the one that takes higher costs and more time to execute. The parameters N_t and L_t are selected because they have more impact in comparison with other parameters considered more reliable. The results are displayed for BC 1 with BEBS type I. The parameters are varied in reasonable margins: N_t between 10 and 60 (Figure 11(a)), and L_t between 500 and 2500 m (Figure 11(b)).

For the edge beam replacement, N_t variation can increase the total user costs up to twice its value, whereas L_t can do so up to five times, thus having more impact. The results show that the user disturbances are greatly dependent on the affected roadway length that has a reduced speed, rather than the duration of the works. Therefore, the user costs may be controlled if the affected roadway length is kept within a certain interval. Figure 12 shows a direct comparison between both variables. The major influence of N_t in comparison with L_t can be utilised to control the user costs of a certain LCP to some extent. For example, in Figure 12, the dotted line illustrates that if L_t is set to approximately 875 m, the user cost will be between 10 and 20 kSEK regardless of N_t.

Obviously, the aforementioned conclusion should be handled with care since work zones will always imply a speed reduction. In addition, the consideration of traffic variations throughout the day leads to different queue formations. However, ways of optimising the work conditions can be found. For example, in some cases, the edge beam replacement can be carried out at different stages for each side of the bridge in order not to fully close the road. This would reduce L_t and increase N_t and would result in more reduced user costs than in the case where the edge beam is replaced at both sides simultaneously, which would result in less N_t but higher L_t.

6.2. Life-cycle strategies and LCP definition

The preceding results are based on the assumption of a certain LCS, referred to as LCS1. However, uncertainties related to type II and III exist. For type II, the replacement intervals for the L-steel profile and the steel support for the railing are unknown. For type III, the performance of the steel edge beam is governed by the existing surface joint between the bridge deck slab and it which needs to be protected from salt water intrusion. The results for two other strategies are displayed – LCS2 (Figure 13(a)) and LCS3 (Figure 13(b)) – where the interval of the main LCPs has been extended. The variations with respect to each LCS are presented in Table 2. The LCPs corresponding to type I and IV have been kept the same since the knowledge regarding those is more reliable.



	BC 1	BC 2	BC 3	BC4	BC 5	BC 6
▤ Type I	22,195	21,258	45,060	41,585	49,572	45,596
▨ Type II	20,996	19,377	47,601	44,918	52,851	49,957
☐ Type III	26,429	24,869	43,050	40,638	46,329	43,749
▩ Type IV	19,379	21,841	34,507	42,168	37,492	46,179

Figure 9. LCC results for all BEBS types and all BCs for LCS1.

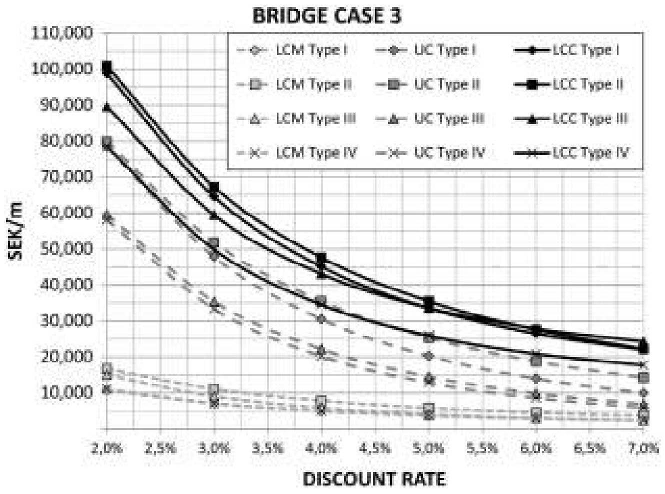


Figure 10. Sensitivity analysis with regard to the variation of the discount rate for the LCM costs, user costs and total LCC for BC 3.

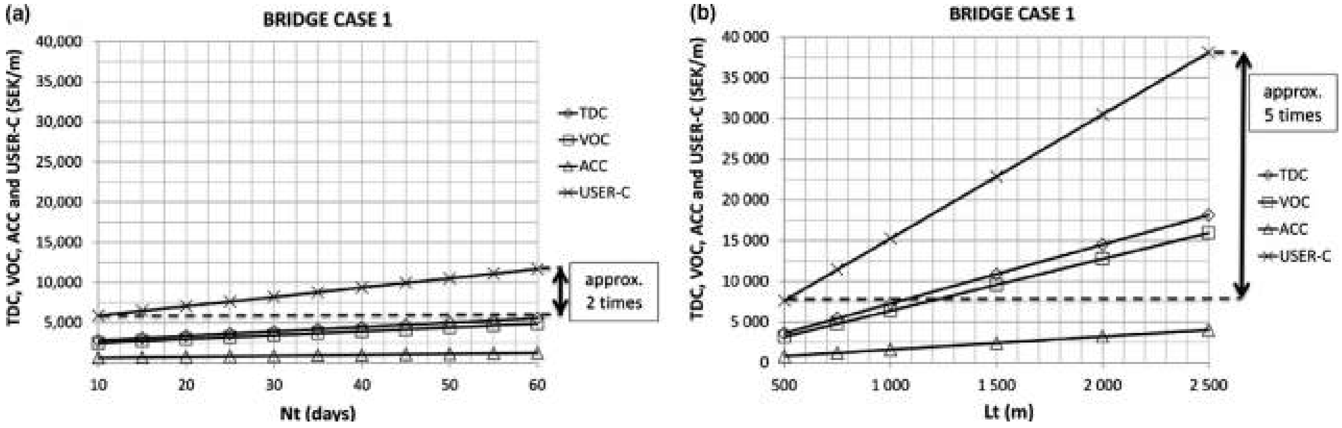


Figure 11. The influence of the variation of (a) N_t and (b) L_t on the total user costs and its components corresponding to the LCP referring to the edge beam replacement for BC 1.

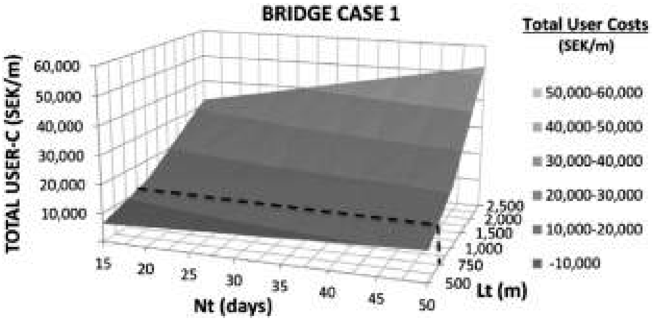


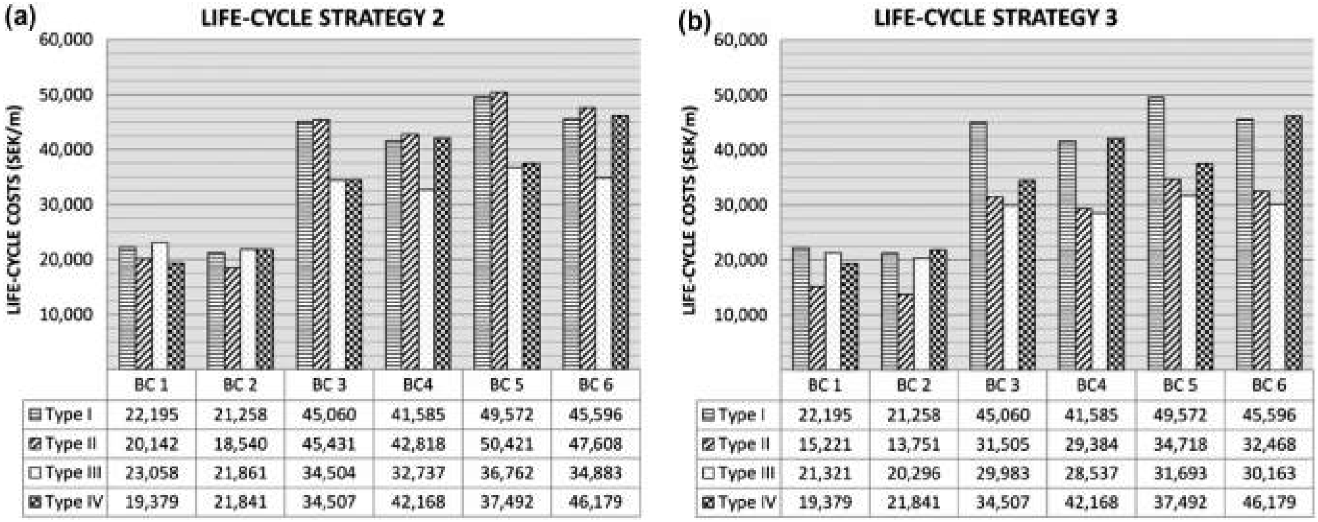
Figure 12. The influence of the variation of N_t against L_t on the total user costs and its components corresponding to the LCP referring to the edge beam replacement for BC 1.

If the LCS of BEBS types II and III is planned according to LCS2 or LCS3, these solutions may become better in terms of cost for some BCs. It is difficult to forecast the process of deterioration of the edge beam, and the change in the LCP interval affects the outcome significantly. Therefore, it is paramount that research is carried out to enclose the design value of these parameters as much as possible.

6.2.1. Strategy with continuous short interval maintenance

The trade-off between the INV costs and the LCM costs is of great interest for the owner. Sundquist (2011) illustrates that an increased quality results in higher INV but lower LCM and vice versa (Figure 14(a)). Nishibayashi, Kanjo, and Katayama (2006) presented a diagram showing the variation of the total LCC including user costs with respect to the LCP intervals in bridges (Figure 14(b)). According to this idea, an optimal design during the INV phase exists. An adequate LCS can lead to the lowest total LCC and, thus, maximum benefit for the society. As Figure 14 is intended for bridges in general, it is of interest to apply it to the BEBS with short LCP intervals, and identify the inflection point in the curve. It is assumed that in the case of continuous maintenance there would be no need to replace the edge beam, thus 'surviving' by only carrying out impregnation, concrete repairs and railing LCMs. Nonetheless, more LCPs are actually taking place. Thus, additional costs and traffic interruptions are incurred.

Figure 15(a) shows a comparison between LCS1 and a LCS with continuous maintenance called LCS-CM1. The LCPs are performed every 10 years. The results are displayed for BEBS type I in BC 1. LCS-CM1 results in greater LCC, even if the



(a)

	BC 1	BC 2	BC 3	BC4	BC 5	BC 6
▤ Type I	22,195	21,258	45,060	41,585	49,572	45,596
▨ Type II	20,142	18,540	45,431	42,818	50,421	47,608
☐ Type III	23,058	21,861	34,504	32,737	36,762	34,883
▩ Type IV	19,379	21,841	34,507	42,168	37,492	46,179

(b)

	BC 1	BC 2	BC 3	BC4	BC 5	BC 6
▤ Type I	22,195	21,258	45,060	41,585	49,572	45,596
▨ Type II	15,221	13,751	31,505	29,384	34,718	32,468
☐ Type III	21,321	20,296	29,983	28,537	31,693	30,163
▩ Type IV	19,379	21,841	34,507	42,168	37,492	46,179

Figure 13. (a and b) Total LCC for all BEBS types and all BCs for (a) LCS2 and (b) LCS3.

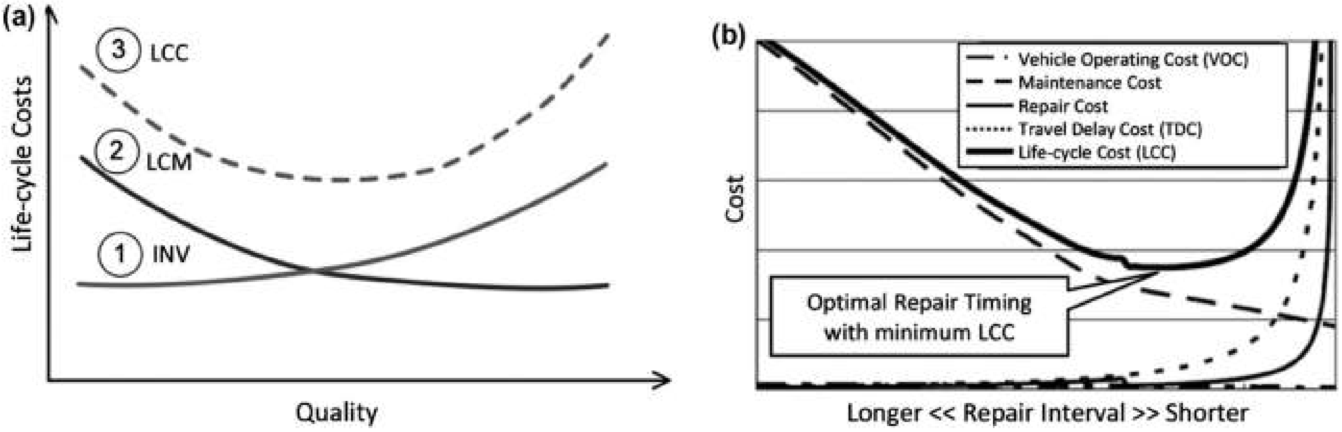


Figure 14. (a and b) Schematic curves showing (a) LCC against quality of the structure (Sundquist, 2011), and (b) the optimal repair timing with minimum LCC, adapted from Nishibayashi et al. (2006).

edge beam is not replaced. The interval which corresponds to the inflection point can be determined to obtain a more efficient solution. Figure 15(b) illustrates the results for intervals of 5, 10, 15, 20, 25 and 30 years, compared with LCS1, for BEBS type I.

LCS-CM becomes less costly from a LCC perspective if the interval is approximately 16–17 years. Obviously, this is limited by the assumption of the equal life span for both the bridge and the BEBS. Other problems such as carbonation or unexpected car impacts may affect the BEBS performance. Even though in Figure 15(b) the LCS-CM tends to have lower LCC, it is important to note that the LCC will start to increase according to Figure 14. The deterioration will be more aggravated, thus requiring more expensive LCMs until reaching the limit at which the interval cannot be extended any further.

6.2.2. Concrete integrated edge beam with stainless steel

Corrosion is one of the main agents governing the deterioration of reinforced concrete structures (The Portland Cement Association – America's Cement Manufacturers [PCA], 2014; Tahershamsi, 2013). In addition, it is the most important problem concerning edge beam performance in Sweden (Pettersson & Sundquist, 2014). Thus, the use of stainless steel is considered as means of life span extension. Although stainless steel is more expensive than regular steel material cost, it may result in a long-term optimal alternative. This might imply that the edge beam would not have to be replaced; only concrete repairs, impregnation and railing LCMs would be carried out. Taking these conditions into account, Figure 16 presents an estimation of the LCC when using stainless steel, compared to the one obtained from LCS1 in type I for BC 1. A recommended design proposal (personal communication with Valbruna Stainless Inc.) has been used, where the steel stirrups of the edge beam are stainless (Figure 17).

As expected, the INV costs are higher for the stainless steel option, approx. 200 SEK/m extra, matching the estimations done on a bridge between Stockholm and Lidingö (Eriksson, 2003). But the total LCC is reduced considerably: it is 15–20% less because of the LCM costs and, more importantly, the user costs. Some bridge experts think, though, that an adequate concrete cover should still be sufficient nowadays (personal communication with 'Trafikverket' bridge managers). In Sweden, new rules have been published regarding the use of stainless steel. More investigation and experience are needed to assure that stainless steel is an optimal solution.

6.2.3. The BEBS today

Edge beams in old bridges were not built for the aggressive environment, they are supposed to stand in contemporary times (Pettersson & Sundquist, 2014). Frost resistant concrete started

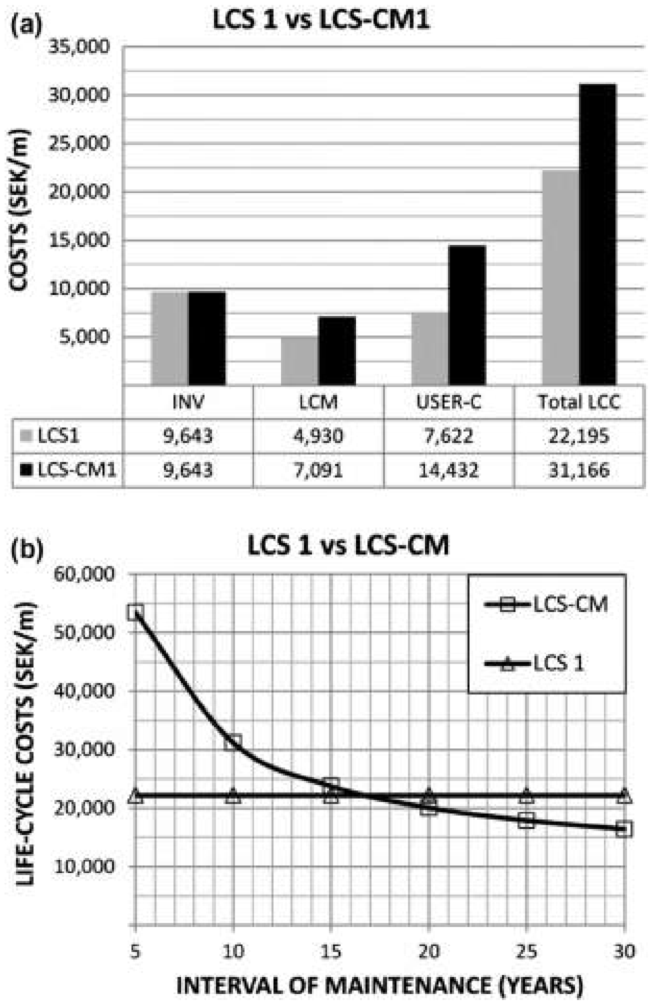


Figure 15. (a and b) LCC comparison between (a) LCS1 and LCS-CM1 with continuous maintenance every 10 years and (b) LCS1 and different LCS-CM with intervals of 5, 10, 15, 20, 25 and 30 years.

to be used in Sweden in the middle of the 1960s. Railings are not attached anymore by embedding them into the edge beam, but through anchoring bolts (ibid.). Edge beams in older bridges with high water–cement ratio concrete are negatively affected by salt water intrusion (Mattson et al., 2007). Hence, edge beams constructed during the 1950s and early 1960s had to be replaced in a shorter period in comparison with newer ones. Since the construction technique and the quality of materials have improved, it is of interest to estimate how these developments have influenced the total LCC.

Three scenarios with different edge beams' life spans and LCP intervals are illustrated (Table 3). Type I, the BEBS design solution normally used in Sweden, for BC 1, is utilised. The savings in terms of LCC due to the more stringent requirements in code regulations are estimated to be approximately 30% (Figure 18), which is a considerable positive influence.

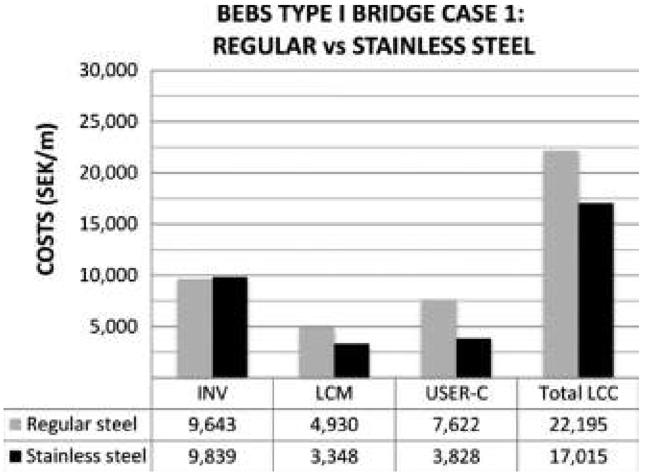


Figure 16. LCC comparison between normal and stainless steel in BEBS type I for BC 1.

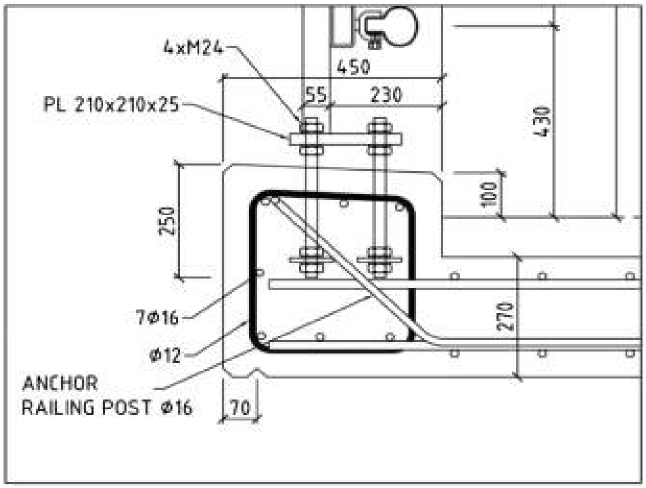


Figure 17. Design proposal with stainless steel in the stirrups (transversal reinforcement) marked in black.

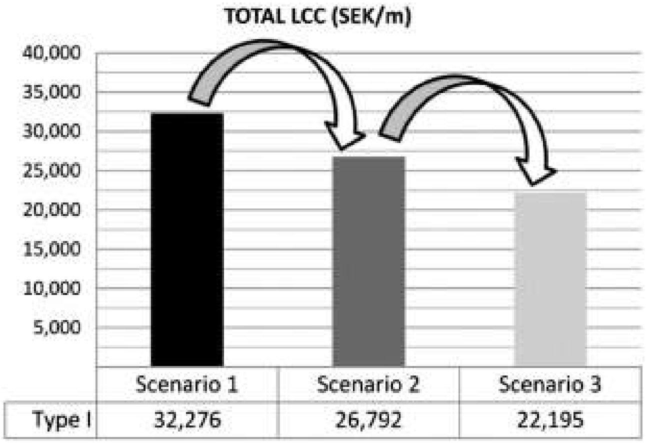


Figure 18. LCC estimation showing a comparison between different scenarios that represent the development of the code requirements.

Table 2. Principal parameters of type II and III for LCS2 and LCS3.

	TYPE II – without an edge beam (year)		Type III – steel edge beam (year)	
	L-steel-profile's life span	Steel support's life span	Repainting	Steel edge beam's life span
Strategy 1	20	60	25	50
Strategy 2	20	80	30	60
Strategy 3	30	60	35	70

Table 3. Assumptions taken regarding the intervals of the LCP for different scenarios.

	Impregnation/concrete repair	Lifespan (years)
Scenario 1	After 15 years	30
Scenario 2	After 20 years	40
Scenario 3	After 20–40 years	60

7. Conclusions

The decision-making process for bridge INV and management is multi-alternative. LCCA may be used as a tool in order to develop solutions that are better for society in terms of cost at a project level during the procurement of a structure. In this context, this article makes use of such a methodology to evaluate and compare four types of BEBS in representative Swedish BC scenarios. A LCC model has been developed for this purpose. The following conclusions can be drawn from this study:

- For short bridges, the prefabricated edge beam (type IV) is recommended as an optimal solution for the society because of the increased quality that the enhanced labour conditions provide, thus extending its life span. Moreover, it is monolithic with the bridge structure. On the other hand, it is not recommended to use for long bridges due to the limitation in the elements length. *In situ* cast joints would be needed, implying an increased risk of deterioration. The concrete integrated edge beam (type I) is the suggested solution in this case.
- There remain uncertainties related to the design solution without an edge beam (type II) and the steel edge beam (type III). For the former, even though the INV costs are considerably lower, the LCM costs become very high due to the maintenance of the L-steel profile and the steel support. The detailing, therefore, needs to be studied further. In contrast, the steel edge beam (type III) requires huge INV costs but lower LCM costs which can become optimal over the long term. A variety of LCSs with different LCP intervals have been proposed to investigate possible optimal outcomes.
- Sensitivity analyses highlight the importance of the influence from three critical factors on the outcome. The assumption of a given interest rate considerably changes the value of the results. The affected roadway length when an edge beam is replaced has a greater influence than the number of days needed for maintenance measures. This can be used as a tool to control the total user costs.
- Further extending edge beam's service life using stainless steel reinforcement may be a design solution used in the future so that less LCMs need to be carried out, thus also considerably reducing the user costs. Its usage in prefabricated edge beams can also be of interest. The possible risk of corrosion in the long term needs to be investigated further.
- More stringent code requirements have significantly diminished the total LCC in the last decades. These enhancements should not only do have a positive influence on new bridges, but be also used to renew existing old structures that were not constructed to withstand the current environment and traffic conditions.
- Finally and most importantly, it is essential to choose a suitable technical BEBS solution for each bridge project. At the same time, the LCS comprising detailed LCPs needs to be known in advance during the preliminary design. This will also result in controlled user costs, and thus, a reduced total LCC.

In continued studies at the department, type II and type III solutions are being further investigated. For type II solutions, a study of the effect of a solution without an edge beam in a cantilever slab – in particular – and in the bridge – in general – from a load–resistance perspective is being carried out. The interest of this solution lies in enhanced construction working conditions, even though other practical aspects need to be sorted out. A type III design alternative will be tested in a real bridge project (south of Stockholm). In order to extend the life span of the edge beam, the use of stainless steel will be investigated in detail. Type IV is planned to be a design solution to be implemented in short frame bridges in Sweden.

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Appendix 1. LCC definitions and contributions

Owner costs

The owner or agency costs are divided into investment (INV) and life-cycle measures (LCM) costs. INV costs refers to the total amount of money paid from the time of signing the construction contract until the infrastructure inauguration, thus including the cost of detailed design, construction material, construction and labour work, transportation, mobilisation, contractor profit, taxes, management, overhead costs and unexpected costs (Troive, 1998). LCM costs comprise inspections, operation and maintenance, repair, replacement and rehabilitation, and recycling and disposal. Since the LCMs are carried out in the future during the life span of the

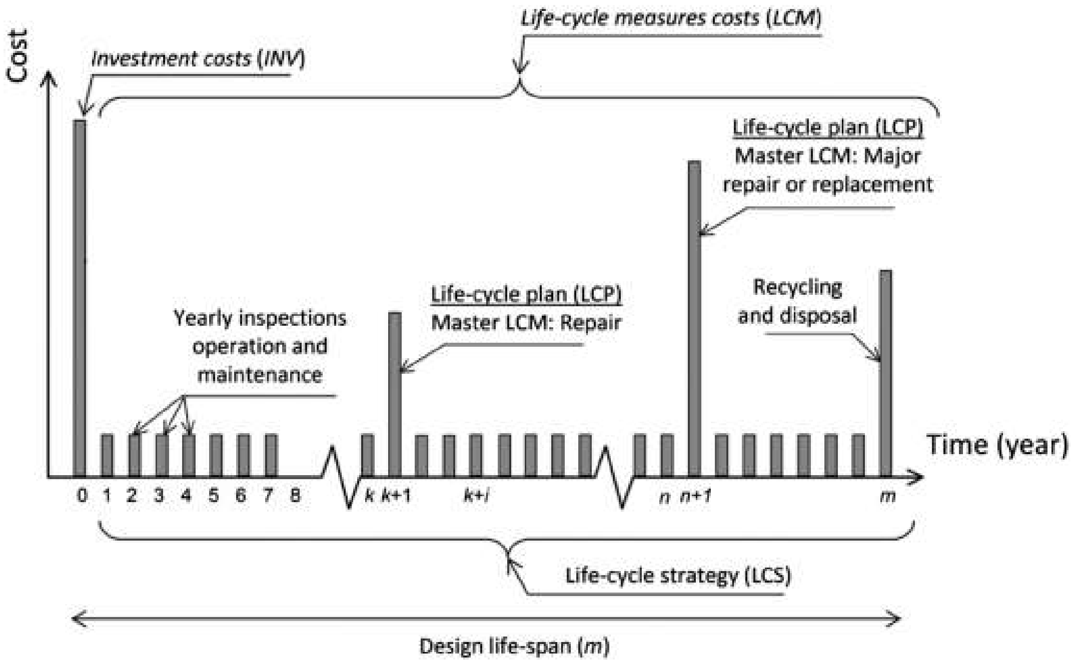

Figure 19. Example of an infrastructure's including the LCS and the owner costs incurred along the design life span, adapted from Sundquist (2011).

infrastructure, the net present value technique to discount the value of the money should be used. The owner costs are calculated according to:

$$\mathrm{LCC}_{\mathrm{owner}} = \mathrm{INV} + \mathrm{LCM} = \mathrm{INV} + \sum_{t=0}^{L} \frac{C_t}{(1+p)^t} \quad (2)$$

where

- C_t is the total cost of a certain LCM performed at a time t.
- p is the real interest rate.
- L is the life span of the infrastructure.

Life-cycle is the group of processes that are required for a certain structure to fulfil its performance requirements. Figure 19 displays an example of the life-cycle of an infrastructure with a timeline of the total owner costs incurred along its design life span, given a certain life-cycle strategy (LCS). The design life span is defined as the time period 'from cradle to grave' of a certain structure for which it must fulfil its performance requirements (in Figure 19, m). The life-cycle strategy (LCS), apart from including yearly inspections, operation and maintenance, comprises a set of life-cycle plans (LCPs) that have to be carried out at a several specific points in time throughout the design life span of the bridge (in Figure 19, k + *1, n* + *1*). Each LCP is composed of a package of LCMs. A 'Master-Slave' approach can be used to define the LCP. The LCP is thus governed by a 'Master' LCM, which refers to that which is relevant for the performance of the structure and takes more time to carry out. The rest of the LCMs – denoted 'Slaves' – are performed simultaneously. This analysis can be done for an infrastructure in general or for a structural member in particular. For the BEBS, an example of a 'Master' LCM is the edge beam replacement, and an example of a 'Slave LCM' is the railing replacement (see Figure 7).

User costs

The user costs refer to impact on the infrastructure users that are affected by the construction works when the bridge is built and the LCMs performed along the life span. In road bridges, the most important contributions are generally the traffic delay costs (TDC) and the vehicle operation costs (VOC), as follows:

$$\mathrm{LCC}_{\mathrm{user}} = \mathrm{VOC} + \mathrm{TDC} \quad (3)$$

while VOC and TDC can be computed using Equations (4) and (5), respectively:

$$\mathrm{VOC} = \sum_{t=0}^{L} T \cdot \mathrm{ADT}_t \cdot N_t \cdot \left(r_t w_t + (1-r_t) w_{\mathrm{p}}\right) \frac{1}{(1+p)^t} \quad (4)$$

$$\mathrm{TDC} = \sum_{t=0}^{L} T \cdot \mathrm{ADT}_t \cdot N_t \cdot \left(r_t O_t + (1-r_t) O_{\mathrm{p}}\right) \frac{1}{(1+p)^t} \quad (5)$$

where

- T is the expected travel delay time in case of a roadway work measured in h.
- ADT_t is the average daily traffic at a time t measured in vehicles/day.
- N_t is the total amount of days that are needed to carry out a certain *LCM.*
- r_t is the percentage of heavy vehicles out of the ADT_t.
- w_t is the hourly time value for a heavy vehicle measured in SEK/h.
- w_p is the hourly time value for a passenger car in SEK/h.
- O_t is the average operating cost in SEK/h for a heavy vehicle including transported goods.
- O_p is the average operating cost in SEK/h for a passenger car.

Society costs

Society costs may comprise accidents, environmental impact, use of non-renewable materials and other related issues. In this work, only accident costs (ACC) are taken into account. ACC are calculated according to

$$\mathrm{LCC}_{\mathrm{society}} = \mathrm{ACC} = \sum_{t=0}^{L} L_t \cdot \mathrm{ADT}_t \cdot N_t \cdot C_{\mathrm{acc}} \cdot (A_{\mathrm{r}} - A_{\mathrm{n}}) \frac{1}{(1+p)^t} \quad (6)$$

where

- L_t is the affected roadway length in m.
- C_{acc} is the cost of an accident for the society in SEK.
- A_r is the accident frequency during a road work in accident/vehicle-km.
- A_n is the accident frequency during normal conditions in accident/vehicle-km.