Bridges in a changing climate: A study of the potential impacts of climate change on bridges & their possible adaptations

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Climate change may have multifaceted impacts on the safety and performance of infrastructure. Accounting for the different ways in which potential climate change scenarios can affect our infrastructure is paramount in determining appropriate adaptation and risk management strategies. Despite gaining some attention among researchers in recent years, this research area is still largely uninvestigated. Several studies have indicated bridges to be especially susceptible to the effects of climate change. Noting that a warming higher than the global average is projected for Sweden, this paper identifies the potential impacts of climate change on bridges in Sweden and presents possible adaptation techniques to face these impacts. Although this study focuses on bridges in Sweden, a similar approach can be taken to identify climate change impacts and their adaptations for other infrastructure elements and/or other regions.

Keywords: climate change; risk; bridges; adaptation; infrastructure safety

Introduction

Climate related hazards can have serious impacts on the safety and functionality of infrastructure systems. In its most recent assessment report (AR5), the Intergovernmental Panel on Climate Change (IPCC) maintains that climate change will have substantial impacts on a wide range of infrastructure systems (IPCC, 2014, p. 538). Between the years 1999 and 2007, i.e. a period less than a decade, three damaging storms hit the southern part of Sweden (Wallentin & Nilsson, 2013). The second of these storms, storm Gudrun, was the most consequential storm in centuries (Brodin & Rootzén, 2009; Enander, Hede, & Lajksjö, 2009; Nohrstedt & Parker, 2014). Storm Gudrun, which occurred on the 8th of January 2005, had far-reaching effects including damages to the transportation network, the electricity and telecommunications infrastructure, and water supply infrastructure (Broman, Frisk, & Rönnqvist, 2009; Enander et al., 2009; Nohrstedt & Parker, 2014; Nyberg & Johansson, 2013; Strandén, Krohns, Verho, & Sarsama, 2011). It is estimated that 730000 individuals did not have access to electricity due to this devastating event (Nohrstedt & Parker, 2014; Strandén et al., 2011). These conditions lasted for eight weeks in some areas (Enander et al., 2009) and the total cost inflicted on the society was potentially in the order of 2 billion Euros (The Swedish Civil Contingencies Agency, 2010). Other neighbouring countries were also severely impacted by this event (e.g., Suursaar & Sooäär, 2006).

Noting that some studies suggest a possible increase in storm activity, over e.g.; the North Atlantic (IPCC, 2013); and the North Sea (Lindner, & Rummukainen, 2013), and in wind speeds, over e.g.; the Baltic Sea (Kjellström, Nikulin, Hansson, Strandberg, & Ullerstig, 2011; Lindner, & Rummukainen, 2013), due to a changing climate, it is crucial to ascertain the safety of our infrastructure against the potential impacts of climate change. Furthermore, Nasr et al. (2019a) mentions the usually prolonged process of updating standards and codes of practice (Auld et al., 2010; Meyer, 2008) and the considerable delay associated with the construction of major protection projects (e.g. storm surge barriers) (Hill, 2012), both of which may be necessary as a response to climate change, as two compelling arguments for an expedited consideration of the potential impacts of climate change on infrastructure. With a warming considerably higher than the global average projected at high northern latitudes, (IPCC, 2013; The Swedish Commission on Climate and Vulnerability, 2007), the importance of addressing the potential impacts of climate change in a timely manner is further highlighted for Sweden.

Considering that in the aftermath of storm Gudrun, as in many similar incidents, the blocked road, and railway, network was the root cause of many of the cascading effects impacting other infrastructure systems (e.g., slowed down restoration of electricity supply and disruptions in water supply, sewage, and heating systems)

(Nyberg & Johansson, 2013), this study focuses on one of the main elements of road network infrastructure; bridges. Taking into account their relatively long service life, which in some cases exceed 100 years, bridges are one of the most climate-change relevant elements of the road infrastructure (Meyer & Weigel, 2011; Smith, 2006) and their adaptation responses are not to be delayed (Vicroads, 2015). The aim of this paper is to identify the potential impacts of climate change on bridges in Sweden and their potential adaptation strategies. This is done by reviewing the relevant existing literature and connecting its findings to the projected changes in the Swedish climate. To date, only a small number of studies have addressed the risks imposed on bridges by climate change and their possible adaptations (e.g., Kumar & Imam, 2013; Meyer, 2008; Mondoro, Frangopol, & Liu, 2018; Nasr et al., 2019a; Schwartz, 2010). However, none of these studies considered the specifics of the changes projected for Sweden. Furthermore, the current study is unique in that it provides an extensive list of the possible adaptation techniques in response to the identified risks. This paper starts by discussing the projected future climatic conditions for Sweden. The identified potential risks on bridges in Sweden are then presented. This is followed by a section dedicated for discussing the possible adaptations for managing the potential climate change impacts. Finally, the last section highlights the implications of this research and presents some concluding remarks.

Projected climatic changes in Sweden

Potential risks on bridges

The main aim of this section is to identify the potential impacts of the climatic changes presented in the previous section on bridges in Sweden as the first step of risk analysis; see, e.g., Kaplan & Garrick (1981). As stated in Kaplan, Haimes, & Garrick (2001) the risk scenarios identified during this risk identification process should be “complete”.

Providing an as complete as possible list of risks at this stage of risk analysis has been highlighted by several researchers (e.g., Chapman, 2001; Raspotnig & Opdahl, 2013). For instance, Chapman (2001) mentions that this stage should aim at “identifying as exhaustively as practicable” risks. The aim of this completeness criterion is to avoid leaving out risks that may be of significance. For example, Kaplan & Garrick (1981) cites the criticism that has been made to a Reactor Safety Study as a result of not meeting this criterion.

Possible adaptation techniques

As has been discussed in the previous section, climate change may impose considerable impacts on bridges. Nevertheless, measures to reduce the probability and/or consequences associated with such impacts can, and should, be taken. The risk of such impacts can be represented as shown in Figure X (Nasr et al., 2019b). As presented in Figure (XX), climate change impacts can be controlled in two general ways; mitigation and adaptation. Firstly, mitigating GHG emissions, by e.g. reducing vehicle miles travelled (VMT) through land use and urban planning strategies (e.g., Hamin & Gurran, 2009), can significantly decrease the potential impacts of climate change. However, Füssel (2007) gives several arguments why mitigation alone is insufficient and prompt adaptation actions are, in many cases, necessary. For instance, as a result of the inertia of the climate system, the coming decades are projected to exhibit a substantial increase in the rate of climate change regardless of the emissions scenario (Füssel, 2007). Furthermore, unlike mitigation, adaptation measures are not contingent on the actions of others and can induce direct benefits on the regional and local scale.

In Sweden, the Swedish Transport Administration has already developed a climate adaptation strategy which provides a list of general activities for adapting to a changing climate. These activities, for instance, include adapting new and existing infrastructure, and developing methods for determining when and where such adaptations would be cost-effective (Liljegren, 2016). Several cases where adaptation measures have already been implemented exist. For instance, in the wake of storm Gudrun tree-free zones were established on high priority parts of the railway network to prevent the blockage of railways with fallen trees during future storms (Lindgren, Jonsson, & Carlsson-Kanyama, 2009). Other cases of climate change adaptation in Sweden can be found on the Swedish climate adaptation portal (http://www.klimatanpassning.se).

Future bridges can be adapted to climate change in several ways. For instance, Auld et al. (2010); Connor, Niall, Cummings, and Papillo (2013); Gibbs (2012); Mondoro, Frangopol, and Liu (2018); and Pietro et al. (2016) among many other studies emphasize the need for regularly updating codes and standards to accommodate a changing climate. Examples of updating codes and standards in response to climate change already exist; e.g. including adjustment factors for design floods and design rainfalls in several European guidelines (Madsen, Lawrence, Lang, Martinkova, & Kjeldsen, 2014), and introducing a cyclone uncertainty factor in Australian standards (Connor et al., 2013). It is worth noting that this adaptation measure has been categorized as a no regret adaptation strategy (Auld, Maclver, & Klaassen, 2006) which is considered robust irrespective of the future climate scenario and therefore should be implemented without delay. Restrictive land use planning, by e.g. increasing insurance rates in hazardous coastal zones (FHWA, 2009; NRC, 2008), has also been identified as a no regret adaptation strategy (Hallegatte, 2009). Furthermore, the development of new materials and/or technologies that are more resistant to the impacts of climate change (e.g., the development of new heat-resistant paving materials (FHWA, 2009; NRC,

2008) has been mentioned in literature as a possible adaptation technique. Another important aspect for adapting future bridges to climate change is opting for designs which are flexible to any adaptations that may be needed in the future.

Several measures to adapt existing bridges to climate change have been cited in literature. Stewart, Wang, and Nguyen (2012) mentions increasing the concrete cover thickness, the use of protective surface coatings and barriers, galvanized reinforcement, corrosion inhibitors, electrochemical chloride extraction, or cathodic protection as possible adaptation techniques for controlling the potential increase in the corrosion of concrete infrastructure as a result of climate change. Mondoro et al. (2018) suggests the use of riprap, concrete bock systems, and gabion mattresses as possible adaptations against an increased scour rate and the use of anchorage bars, concrete shear tabs, and increasing continuity as adaptations against deck unseating during storms. Table X presents an extensive list of the measures presented in literature as possible adaptations against climate-change imposed risks. In addition, adaptations that have not been previously identified as climate change responses but are judged as suitable measures to decrease climate change related impacts are also presented. For the sake of completeness, the presented adaptation techniques are not limited to the risks discussed in the previous section but also include climate change relevant risks identified in other studies (e.g., Nasr et al., 2019a).

Considering the large number of possible adaptations (as demonstrated by Table X), a crucial question that needs to be considered is which adaptation option to choose. It has been repeatedly suggested that a cost-benefit, risk-based, life cycle analysis is most suitable for answering such a question (e.g., ATSE, 2008; CEN, 2016; Gibbs, 2012; Stewart, Val, Bastidas-Arteaga, O'Connor, & Wang, 2014). For this purpose, Stewart et al. (2014) identifies three criteria that may be used for such analysis, namely, the Net Present Value (NPV); the probability of cost effectiveness; and the Benefit-to-Cost Ratio (BCR), and demonstrates the procedure for a number of case studies.

Discussion & conclusions

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Swedish Transport Administration and the strategic innovation program InfraSweden2030, a joint effort of Sweden's Innovation Agency (Vinnova), the Swedish Research Council (Formas) and the Swedish Energy Agency (Energimyndigheten). Any opinions, findings, or conclusions stated herein are those of the authors and do not necessarily reflect the opinions of the financiers.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Swedish Transport Administration and the strategic innovation program InfraSweden2030.

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Table X. Potential climate change risks and their possible adaptations

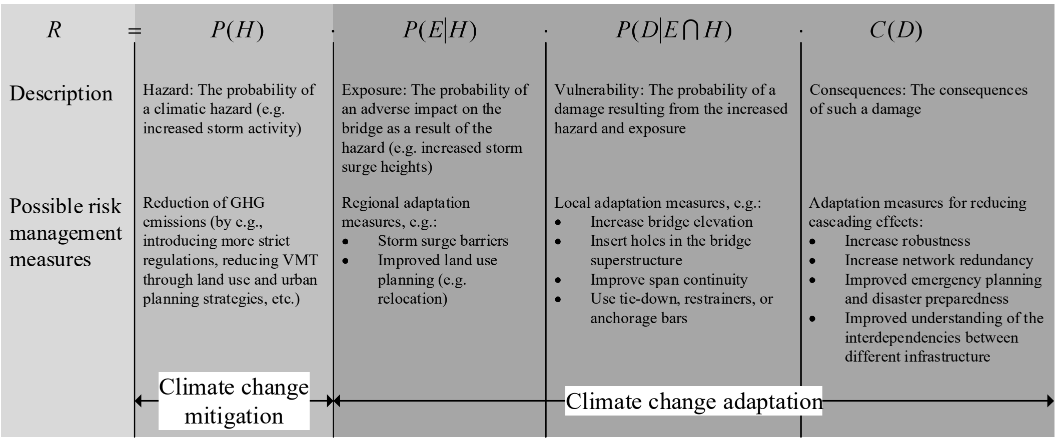
Potential impact	Adaptation
Accelerated degradation of material	Cathodic protection (Stewart et al., 2012; Vicroads, 2015); Increase in concrete cover thickness, improve quality of concrete (strength grade), protective surface coatings and barriers, use of stainless steel, galvanized reinforcement, corrosion inhibitors, electrochemical chloride extraction (Stewart et al., 2012); Protection by design, preservative treatment and the use of modified wood for timber bridges (Mahnert & Hundhausen, 2017); More frequent inspection and maintenance
Heat-induced damage to pavements and rails	Use of polymer modified binders (Vicroads, 2015); Development of new heat resistant paving materials (FHWA, 2009; NRC, 2008); More frequent maintenance(ATSE, 2008; FHWA, 2009; FHWA, 2013; Lindgren et al., 2009); Use of concrete railroad ties instead of wood ties (Delgado & Aktas, 2016); More expansion joints in pavements and rails (Meyer & Weigel, 2011); Introducing speed restrictions (Mehrotra et al., 2011)
Increased long-term deformations	Improved monitoring and inspection of bridges (Mahnert & Hundhausen, 2017)
Increased scour rate	Use of riprap (FHWA, 2009; Mondoro et al., 2018; Nemry & Demirel, 2012; NRC, 2008); Partially grouted riprap, concrete block systems, gabion mattresses, grout-filled mattresses; Upstream walls and obstructions, collars, etc. (Mondoro et al., 2018; NRC, 2008); Use of sacrificial embankments (Brand, Dewoolkar, & Rizzo, 2017); Increased use of sonars to monitor streambed flow and bridge scour (FHWA, 2009; NRC, 2008); For further scour protection measures see e.g., Arneson, Zevenbergen, Lagasse, & Clopper (2012); and Chen & Duan (2014).
Side-slope failure & Landslides	Adequate slope stabilization measures, river bank protection works (FHWA, 2009; NRC, 2008; Regmi & Hanaoka, 2011); Relocation, modification of slope geometry, drainage, retaining structures, internal slope reinforcement (see, e.g., Chen & Duan, 2014, p. 337)
Foundation settlement	Relocate facilities to more stable ground (Meyer & Weigel, 2011); Incorporate increased ground subsidence in the design of infrastructure (Meyer & Weigel, 2011); Remove permafrost before construction, crushed rock cooling systems, insulation/ground refrigeration systems (CCSP, 2008; Mehrotra et al., 2011; Meyer & Weigel, 2011); Use of

	different types of passive refrigeration schemes, e.g., thermosiphons, rock galleries, and "cold culverts", to prevent settlement due to permafrost melt(NRC, 2008); Replacement of ice-rich soils with gravel (Bastedo, 2007)
Rockfalls	Energy dissipating protective structures for bridge piers (He, Yan, Deng, & Liu, 2018); Attenuator fence system and combined wire mesh and cable net drapery, soil berm to provide protection for piers (Graham, Turner & Axtell, 2016); Embankments and ditches, rockfall protection galleries (cushion layer, structural elevation), flexible protection systems (Volkwein et al., 2011)
Snow avalanches	Relocation, early warning systems, flow deflection (e.g., earthfill deflectors) and deceleration methods, structural protection measures (e.g., avalanche sheds), artificial release by explosives, afforestation (Decaulne, 2007; Ganju & Dimiri, 2004; Höller, 2007; Rheinberger, Bründl, & Rhyner, 2009)
Debris flows	Terrain alteration, soil bioengineering, debris flow breakers, debris flow deflectors, etc. (see e.g., Huebl & Fiebiger, 2005)
Liquefaction	Stone columns (Adalier, Elgamal, Meneses, & Baez, 2003; Adalier & Elgamal, 2004); Gravel and rubber drainage columns (Bahadori, Farzalizadeh, Barghi, & Hasheminezhad, 2018); Chemical grouting, passive site remediation techniques (Gallagher, 2000); Ground improvement methods (grouting), Vibro systems, buttresses and surcharge fills, containment and reinforcement, drains, underpinning with mini-piles, deep dynamic compaction and deep blasting (Cooke & Mitchell, 1999)
Additional loads on piles	For negative skin friction: Treatment of subsiding soils, removal of subsiding soils, sleeve liner to allow the soil to settle without causing downdrag, bitumen coating of piles (Davisson, 1993)
Clay shrinkage and swelling	Wet compaction and lime stabilization (Kasangaki & Towhata, 2009); Geofiber reinforcement (Viswanadham, Phanikumar, & Mukherjee, 2009)
Higher wave impact	Surface coatings, pile wraps, pile jackets, etc. (Mondoro et al., 2018)
Wind-induced loads	Use of guide vanes (Larsen, Esdahl, Andersen, & Vejrum, 2000; Larsen & Larose, 2015); Streamlinig the bridge deck cross section for suppressing vortex shedding excitations (Larsen & Larose, 2015); Use of damping devices (e.g., tuned mass dampers, tuned liquid dampers) (Chen et al.,

	2004; Dieng, Helbert, Chirani, Lecompte, & Pilvin, 2013; Larsen & Larose, 2015; Main & Jones, 2001)
Additional snow load	See the general strengthening and retrofitting measures at the end of the table
Higher risk of thermally-induced stresses	Increased ongoing maintenance (CCSP, 2008); Design for higher maximum temperatures in replacement or new construction (NRC, 2008); Greater use of expansion joints (Meyer & Weigel, 2011; Regmi & Hanaoka, 2011); Paint the bridge white to introduce an albedo effect and reduce overheating (Delgado & Aktas, 2016)
Additional demand on drainage capacity	Upgrading drainage systems (Karl, Melillo, & Peterson, 2009; NRC, 2008); Increases in the standards for drainage capacity for bridges (FHWA, 2009, NRC, 2008); Increase in pavement sloping and grooving (FHWA, 2009); Increase in monitoring of drainage systems (Mehrotra et al., 2011; NRC, 2008)
Higher hydrostatic pressure behind abutments	The use of anchors to stabilize abutments (e.g., Truong-Hong, Laefer, & Ba, 2013; and Wade & Davies, 1993); Enlargement of abutment components (Truong-Hong, Laefer, & Ba, 2013)
Increased loads on bridges with control sluice gates	See the general strengthening and retrofitting measures at the end of the table
Loss of prestressing	More frequent inspection maintenance and retensioning
Ice-induced loads	Scour protection measures to prevent scour damage; Pier protection against the impact from ice flues; Strengthened connections, improved span continuity, and increased elevation to prevent the damage of superstructure from ice accumulation
Water vessel collisions	Fender systems, pile-supported systems, Dolphin protection systems, island protection systems, floating protection systems (see, e.g., Chen & Duan, 2014)
Vehicle-pier collisions	Speed control (Mehrotra et al., 2011), Pier protection (e.g., Williamson & Winget, 2005), Pier strengthening

Vehicle accidents	Speed control (Mehrotra et al., 2011)
Train-pier collisions	Speed control (Mehrotra et al., 2011); Pier protection (e.g., Williamson & Winget, 2005); More frequent wheel truing and maintenance of rails (Delgado & Aktas, 2016)
Floods	Relocation or flood-proofing (Mehrotra et al., 2011; Meyer & Weigel, 2011); Flood control seawalls, dikes, and levees (Stewart & Deng, 2015); Elevation of bridges, strengthening and heightening of existing levees, increase in real-time monitoring of flood levels, restriction of most vulnerable coastal areas from further development, increase insurance rates to help restrict development (NRC, 2008); Channel alteration and stabilization, diversion and storage of floodwaters (e.g., Dunne, 1988); Regulate the flow of water through dams (Batchabani, Sormain, & Fuamba, 2016)
Storms	Elevate critical infrastructures, insert holes, tie-down, restrainers, anchorage bars, etc., concrete shear tabs etc., connect adjacent spans, cladding (e.g., toe nails, hurricane straps, etc.) (Mondoro et al., 2018); Strengthened connections, improved span continuity, modified bridge shape, increased elevation (Cleary, Webb, Douglass, Buhring, & Steward, 2018); Relocation and restriction of development in vulnerable regions (Meyer & Weigel, 2011; NRC, 2008); Strengthening and heightening existing storm surge barriers and building new ones (NRC, 2008)
Wildfires	Vulnerability assessments incorporated into infrastructure location decisions, use of fire-resistant materials and landscaping (Meyer & Weigel, 2011); Installing monitoring systems, installing on site firefighting equipment, implementing structural fire design for bridges, fire proofing main structural elements (Naser & Kodur, 2015); Vegetation management strategies (i.e. control operating situation around the structure by regularly removing vegetation in the vicinity of bridges) (NRC, 2008; Wright, Lattimer, Woodworth, Nahid, & Sotelino, 2013); Bigger expansion gaps, passive fire protection, active fire suppression (e.g., wet pipe water systems, dry pipe water systems, total flooding agents, foam deluge systems) (Wright et al., 2013)
General strengthening and retrofitting measures	

Addition of steel cover plates, shear reinforcement (e.g., external, epoxy injection and rebar insertion), jacketing of timber or concrete piles & pier columns (modification jacketing), post-tensioning various bridge components, developing additional bridge continuity, use of CFRP (Carbon Fiber Reinforced Polymers) strips (see, e.g., Chen & Duan, 2003)



$R =$	$P(H) \cdot$	$P(E\vert H) \cdot$	$P(D\vert E \cap H) \cdot$	$C(D)$
Description	Hazard: The probability of a climatic hazard (e.g. increased storm activity)	Exposure: The probability of an adverse impact on the bridge as a result of the hazard (e.g. increased storm surge heights)	Vulnerability: The probability of a damage resulting from the increased hazard and exposure	Consequences: The consequences of such a damage
Possible risk management measures	Reduction of GHG emissions (by e.g., introducing more strict regulations, reducing VMT through land use and urban planning strategies, etc.)	Regional adaptation measures, e.g.: • Storm surge barriers • Improved land use planning (e.g. relocation)	Local adaptation measures, e.g.: • Increase bridge elevation • Insert holes in the bridge superstructure • Improve span continuity • Use tie-down, restrainers, or anchorage bars	Adaptation measures for reducing cascading effects: • Increase robustness • Increase network redundancy • Improved emergency planning and disaster preparedness • Improved understanding of the interdependencies between different infrastructure
	Climate change mitigation	Climate change adaptation		

Figure X. Different ways for managing climate change risks.