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ADAPTING PAVEMENT INFRASTRUCTURE TO FLOOD RISK UNDER CLIMATE CHANGE — A REVIEW OF ADAPTATION STRATEGIES

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Abstract: Flooding is one of the most common natural hazards in Canada. Climate change is expected to increase flood risk caused by frequent and intense precipitation, and rise of sea level. The implications of climate change influence the planning, design, construction, and management of pavement infrastructure due to flooding risk. In order to live better with the consequence of global warming, appropriate actions should be taken to prevent or minimize pavement damage, and to ensure a satisfactory pavement performance. Climate change adaptation helps to reduce pavement vulnerability to extreme weather events, and thus to offset the effects of global warming. This paper reviews adaptation strategies for managing pavement flooding risk from various aspects. Research literature, current inventories, policies, and adaptation framework and plans from Canada and other developed nations are reviewed. An adaption framework and technical adaptation strategies are developed, which serve as a reference for researchers, pavement managers, and other stakeholders to make better adaptation decisions and to increase pavement system resiliency.

1 INTRODUCTION

Climate adaptation refers to adjustment in natural or human systems to climate change in order to moderate harm. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "*the process of adjustment to actual or expected climate and its effects". "In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities*", while mitigation is "*an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases*" (IPCC, 2014). Climate mitigation is to take actions to permanently eliminate or reduce the long-term risk of climate change. Hence, tackling the causes of climate change is a proactive strategy, while adaptation is to plan to live with the consequences of climate change. They are complementary strategies for managing the risks of climate change. As the impact of climate change is already acting on pavement infrastructure and mitigation is not an immediate measure, for the next several decades, the ability of living with the consequences is critical. This paper will review current practices of the adaptation strategies.

2 IMPACT OF FLOODING ON PAVEMENT INFRASTRUCTURE IN THE CHANGING CLIMATE

2.1 Flooding from Extreme Precipitation

As predicted by IPCC, it is very likely that in the mid-latitude areas, there will be more intense and frequent precipitation events. Most parts of Canada are within the mid-latitude region in the northern hemisphere. This increases the potential of flooding events in the changing climate. Figure 1 shows floodwater on

pavement structure and flood characteristics. When floodwater stands on pavement surface, pavements can be subjected to accelerated deterioration (Willway et al., 2008). In addition, the increase in groundwater level affects the subgrade. When subgrade moisture levels become too high, the structural integrity of pavements could be affected. Acceleration in the degradation of pavement materials increases instability of ground. More frequent extreme downpours cause more landslides disrupting roadways. The debris removal from intense storms will likely become even greater in the future (Peterson *et al.*, 2008). In general, the increased risk of moisture damages leads to greater needs in pavement maintenance, preservation, and rehabilitation. Furthermore, more precipitations or flooding could increase weather-related crashes and traffic disruptions (road closures) leading to safety issues.

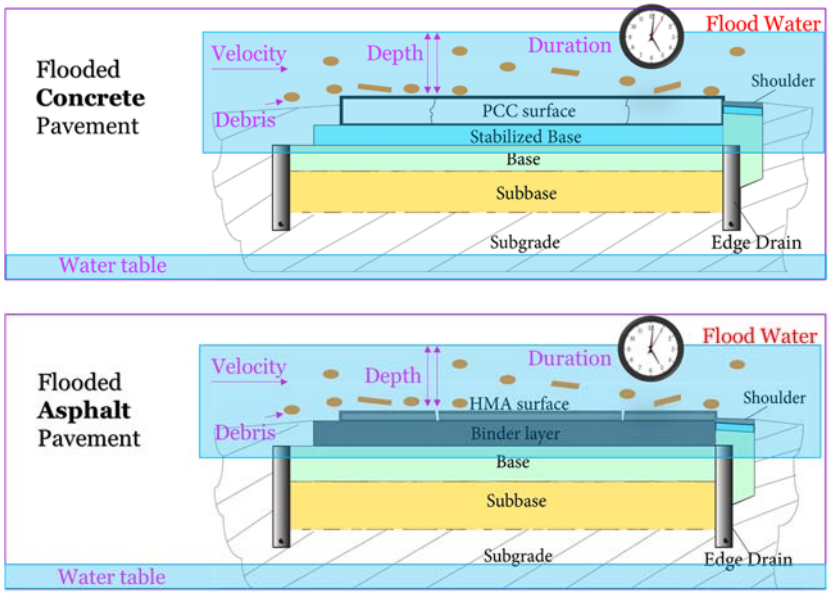

Figure 1: Floodwater on pavement structure and flood characteristics

2.2 Flooding from Sea-level Rise

Pavement infrastructure in coastal communities is vulnerable from the rise of sea level caused by climate change. Low lying pavement infrastructure in coastal areas is especially at risk from flooding. The encroachment of saltwater could result in accelerated pavement degradation. The consequence of coastal flooding could be road closures and increased life cycle cost. Hurricane events are estimated to increase with more intense precipitations. In this case, pavement infrastructure would be subjected to increased flood inundation period. The weakening of pavement from floodwater saturation will lead to accelerated deterioration. Debris removal could increase operation cost and user cost. If groundwater rises with the rise of sea level, groundwater will intersect the subgrade and unbounded layers weakening the pavement structure.

3 CURRENT ADAPTATION POLICIES AND STRATEGIES

The IPCC "*Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation"* gives options on reducing exposure and infrastructure vulnerability, and improving climate resilience (IPCC, 2012). The report also recommends that an iterative process, including monitoring, evaluation, learning, research, and innovation can reduce the risk from climate extremes (IPCC, 2012). Wall and Meyer (2013) presented a review of climate change adaptation strategies that focused on the transportation sector. Some of the important frameworks from different countries are listed in Table 1.

Table 1: Adaptation frameworks used Canada and other countries

Framework	Country	Agency/Organization
Climate Risks And Adaptation Practices For The Canadian Transportation Sector 2016	Canada	Government of Canada (Palko and Lemmen, 2017)
Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate	Canada	Public Infrastructure Engineering Vulnerability Committee (PIEVC) (Engineers Canada, 2015)
Federal Adaptation Policy Framework	Canada	Government of Canada (2011)
Adapting to Climate Change: A Risk Based Guide for Local Governments	Canada	Natural Resources Canada (Black *et al*., 2010)
Adapting to Climate Change: A Risk Based Guide for Ontario Municipalities	Canada	Ontario Ministry of Municipal Affairs and Housing (Bruce *et al*., 2006)
Risk Management for Roads in a Changing Climate: A Guidebook to the RIMAROCC Method	European Union	ERA-NET ROAD (Bles *et al.,* 2010)
Climate Change Effects on the Land Transport Network Volume Two: Approach to Risk Management	New Zealand	NZ Transport Agency (Gardiner *et al.* 2009)
Climate Change Adaptation Strategy and Framework	United Kingdom	Highways Agency (2009)
Climate Change, Extreme Weather Events, and the Highway System Practitioner's Guide and Research Report	United States	National Cooperative Highway Research Program Report 750 (NCHRP, 2014)
Climate Change Risks for Coastal Buildings and Infrastructure: A Supplement to the First Pass National Assessment	Australia	Department of Climate Change and Energy Efficiency (2011)

3.1 Canada

Federal Adaptation Policy Framework was developed in 2011. It guides domestic actions by the Government of Canada to address adaptation to the impacts of climate variability and change. The framework sets out a vision of adaptation, objectives, roles of the federal government, and provides criteria for setting priorities for action. The document notes that the "*costs associated with future climate-related failures in infrastructure could potentially be avoided by changing current infrastructure design protocols to become more resilient to predicted future changes in climate*" (Government of Canada, 2011). An adaptation Platform from Natural Resource Canada was launched in March 2012 bringing together key groups from government, industry, and professional organizations in Canada to collaborate on climate change adaptation priorities. The related investments to be made are to help Canadians adapt to climate change, including protecting the health of Canadians, assessing key vulnerabilities in Northern/Inuit populations, improving predictions of climate changes, and disseminating adaptation tools for regional adaptation. Figure 2 shows the engineering protocol of climate change vulnerability assessment from Public Infrastructure Engineering Vulnerability Committee (PIEVC).

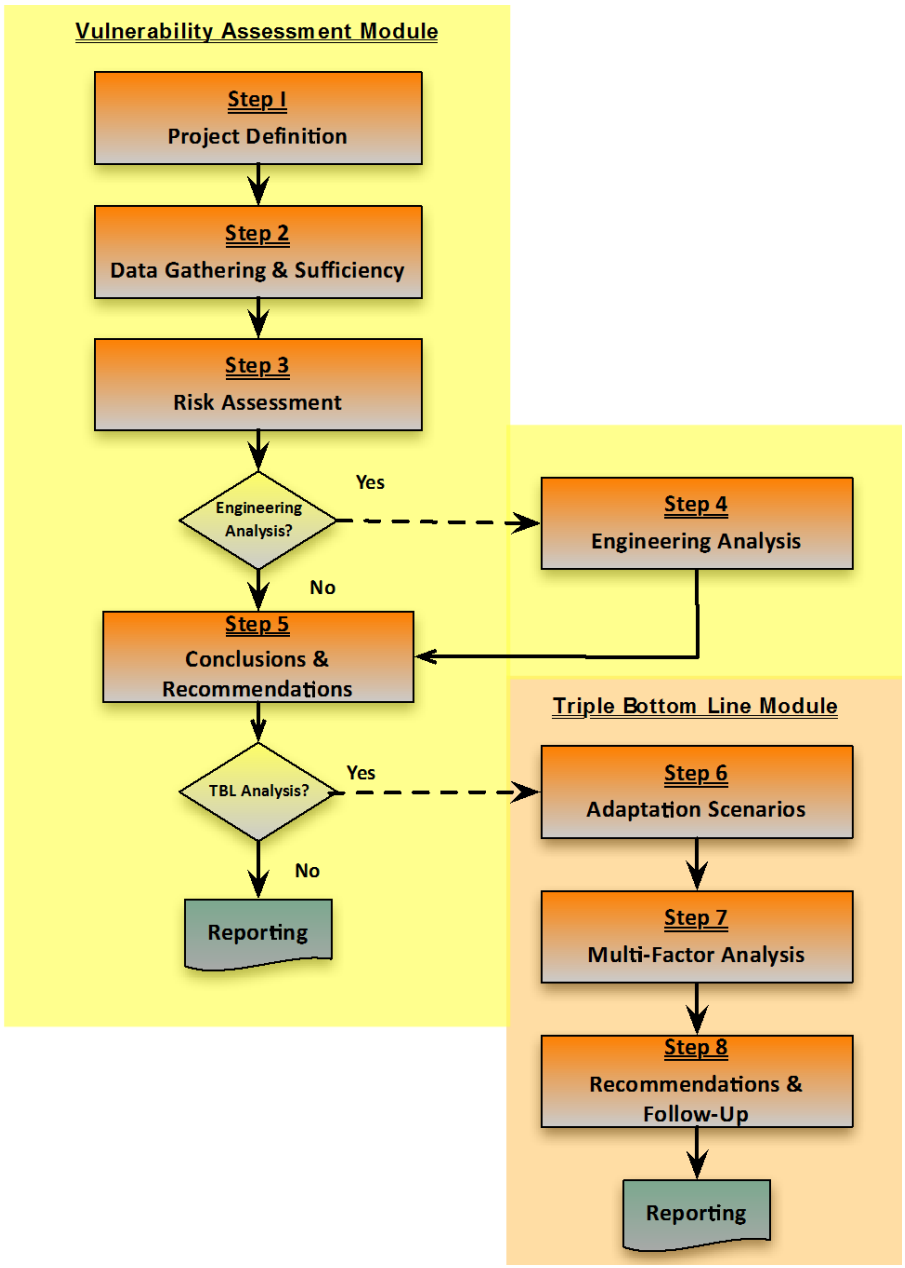

Figure 2: PIEVC Engineering Protocol (Engineers Canada 2015)

3.2 United States

The Council on Environmental Quality (CEQ) issued "Instructions for Implementing Climate Change Adaptation Planning in Accordance with Executive Order 13514" in 2011. The Order requires US federal agencies to evaluate climate change risks and manage the risks. A climate change adaptation policy was adopted by the U.S. DOT in 2012. The policy also encourages state, regional, and local transportation agencies to consider climate change impacts in the decision-making process. In 2014, "Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report" was released, which comprehensively addressed the strategic issues facing transportation. There are 8 steps in the US transportation adaptation framework (NCHRP, 2014): (1) Identify key goals and performance measures; (2) Define policies on assets, asset types, or locations that will receive adaptation consideration; (3) Identify climate changes and effects on local environmental conditions; (4) Identify the vulnerabilities of

asset(s) to changing environmental conditions; (5) Conduct risk appraisal of asset(s) given vulnerabilities; (6) Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness, and defensibility of options; (7) Coordinate agency functions for adaptation program implementation (and optionally identify agency/public risk tolerance and set trigger thresholds; (8) Conduct site analysis or modify design standards, operating strategies, maintenance strategies, construction practices, etc.

3.3 United Kingdom

The 2008 Climate Change Act in United Kingdom created a framework for building the ability to adapt to climate change. The United Kingdom has also developed the Climate Change Risk Assessment (CCRA) including analysis of climate hazard occurrence, the potential consequences, and the prioritizations.

England developed an adaptation framework named Highway Agency's Climate Change Adaptation Strategy. The framework (Figure 3) includes seven steps for increasing the highway resiliency including methods for prioritizing risk and implementation. These steps are summarized as: (1) Define objectives and decision-making criteria; (2) Identify climate trends that affect the highways agency; (3) Identify highways agency vulnerabilities; (4) Risk appraisal; (5) Options analysis to address vulnerabilities; (6) Develop and implement adaptation action plans; (7) Adaptation program review.

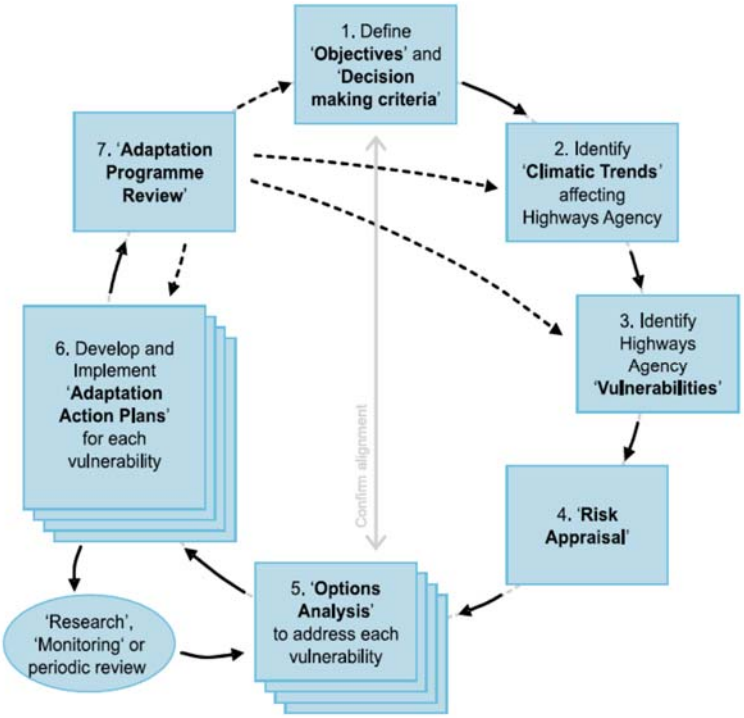

Figure 3: Highway agency adaptation framework model (Highways Agency, 2009)

3.4 Australia

In Australia, climate change adaption is managed under the Department of Climate Change and Energy Efficiency. The policy related to adaptation aims to adapt to the climate change that cannot be avoided. The key goal is to ensure that the infrastructure can provide continued and uninterrupted functioning of these assets, which are critical to support the economy (Commonwealth of Australia, 2010). The Australian Government released a *National Climate Resilience and Adaptation Strategy* in 2015, which outlines how Australia is managing its climate risks for the benefit of the community, economy and environment, now and into the future (Commonwealth of Australia, 2015).

3.5 Pavement Flood Adaptation Framework in the Changing Climate

In general, most of the adaptation frameworks include: (1) define objectives; (2) identify climate stressors; (3) identify vulnerabilities; (4) risk assessment; (5) adaptation alternative appraisal; (6) develop implementation plans; (7) monitoring. Based on the review of frameworks, a new framework is established in this paper. Pavement flood risk management framework includes risk assessment and risk adaptation, which is illustrated in Figure 4. From the aspect of asset management, setting goals and policies is the first step in the management procedure. Flood hazard analysis and pavement vulnerability analysis are the integral components of risk assessment. The potential impact of hazard on pavement asset, including pavement asset value loss and future deterioration trend, can then be identified. Identification of "needs" is the next step which is the basis for risk adaptation. Prioritization is for optimization of resource allocation in the short-term and long-term. Budgeting, project design, and implementation are required for achieving adaptation goals. Monitoring and evaluation involve collecting feedbacks and verifying good practices for pavement flooding risk management. These steps ensure that vulnerability can be reduced, and resiliency can be built.

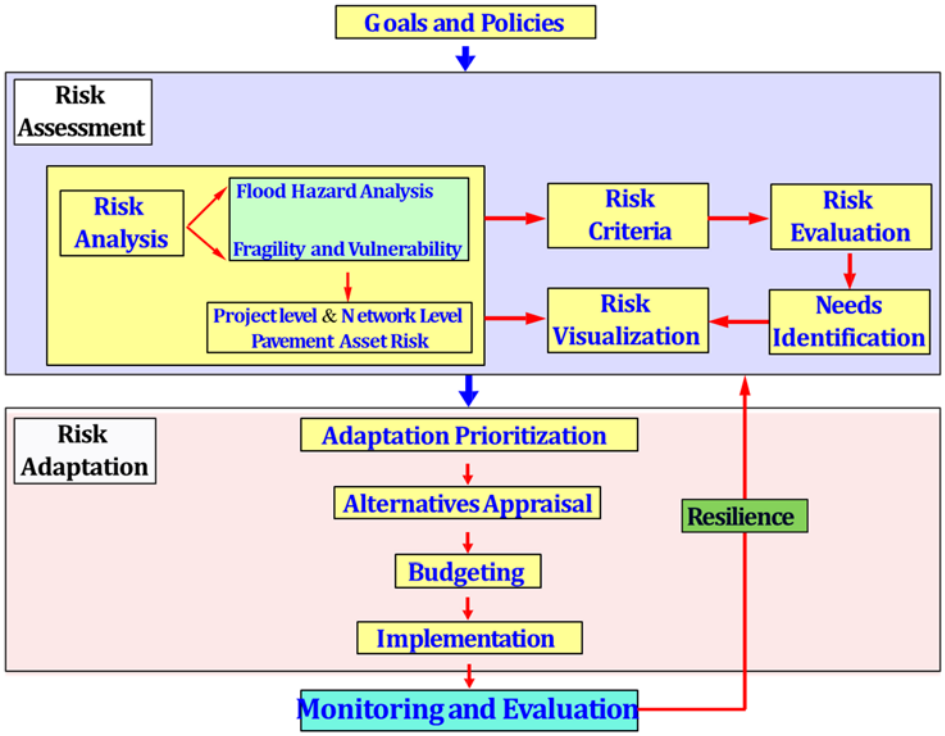

Figure 4: Adaptation Framework

4 PAVEMENT FLOODING ADAPTATION

Flooding events can result in inundation of pavement infrastructure, leading to reduction of pavement performance. The flooding magnitude can be reduced through different ways (Silva and Costa, 2016):

Infiltrate: measures to 'infiltrate' excessive water includes trenches, basins or permeable pavements to reduce the inundation of pavement structure.

Convey: 'convey' is related to the process of transporting rainwater through channels. These channels may vary in size and nature. The sizes of these channels can be upgraded according to extent of climate change and risk.

Store: the storage capacity to collect rainwater before distributing to storm water runoff. This capacity can compensate the capacity of convey system, especially when there is heavy downpour of rain in a short time.

Avoid: measures to prevent water from contacting pavement structure. Increased elevation of pavement can potentially prevent the ingress of water from getting into pavement structures. Relocation is a more expensive way to avoid flood hazards. In addition, upgrade or maintain great culverts so that flood water can pass through under pavement can alleviate the issues.

Considering pavement structure design, the adaptation in terms of design and construction improvement in the changing climate is summarized in Table 2.

Table 2: Extreme precipitation adaptation and pavement design (NCHRP, 2014)

Climate Change Impact	Affected Components and Strategies
More Extreme Rainfall Events	• Increased need for surface friction (Maintain positive cross slope to facilitate flow of water from surface; Increase resistance to rutting; Reduce splashing/spray through porous surface mixtures; Increased need for functioning sub drainage) • Need to improve visibility and pavement marking demarcation • High levels of precipitation may threaten embankment stability • Develop a better understanding of how submergence affects pavement layer structural capacity and strategies to address it
Higher Average Annual Precipitation	• Reduce moisture susceptibility of unbound base/subgrade materials through stabilization • Ensure resistance to moisture susceptibility of asphalt mixes • Investigate better construction processes

4.1 **Pavement Flooding Adaptation Measures**

Figure 5 shows measures to reduce flood risk with strategies emphasizing flood adaptation (on the left) and strategies emphasizing pavement design and construction (on the right).

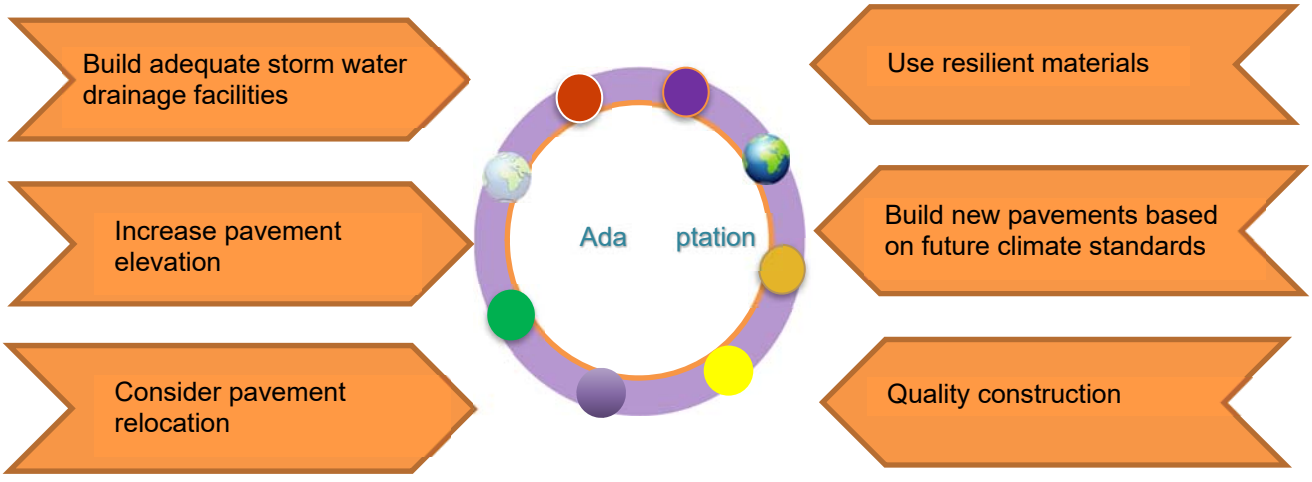

Figure 5 Summary of pavement flooding adaptation measures

For different climate regions and budget reality, different strategies should be utilized. When evaluating adaptation options, cost-effectiveness adaptation designs should be the preferred program.

5 SUMMARIES AND CONCLUSIONS

This paper reviews adaptation strategies for managing pavement flooding risk from various aspects. Research literature, current inventories, policies, and adaptation framework and plans from Canada and other developed nations are reviewed. Pavement flooding risk adaptation framework and adaptation measures are reviewed and summarized. This study can provide a reference for researchers, pavement managers, and other stakeholders to make better adaptation decisions and increase pavement system resiliency for flood hazard in the changing climate.

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