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The Economic Implications of Climate Change on Transportation Assets: An analysis framework

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Written by Dave Sawyer

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1.0 Introduction

While economic analysis methods such as cost-benefit and economic impact assessments are well established, their application to climate change impacts on transportation infrastructure is less developed. Generally, there is a need for more clarity on the economic methods to be used, the climate risk and economic data needed and available, and the economic information to be developed. Guidance for practitioners would help better articulate economic methods, data availability and outcome information to be produced.

This guide, developed with support from Transport Canada in partnership with Yukon Research Centre (YRC)[1], focuses on aiding practitioners to better understand how to reveal the economic implications of both the ongoing damages to transport infrastructure and the benefits of investing to improve infrastructure resiliency. It is really an aid to conceptualize how to think about adding economics to your particular adaptation issue. It is not a detailed cookbook about how to perform the actual calculations. A detailed case study that highlights the methods and techniques employed is being developed by IISD, in partnership with EnviroEconomics, YRC and NodelCorp, and will be presented in a subsequent document.

This guide first provides a taxonomy of transportation benefits to communities, business and governments, and highlights the lost opportunities that manifest as climate change impairs infrastructure services. Basic information is then provided on the economic tools that are useful, including cost-benefit and economic impact analysis. This is followed by a step-by-step approach exploring the causal chain linking climate change, asset vulnerability and economic outcomes. Throughout the guide, case examples related to transportation impacts in the North are used, with a focus on permafrost, roads and airports.

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2.0 Economics of Weather-Induced Damages on Northern Infrastructure

Transportation infrastructure is a precondition for strong northern development. Transportation networks increase the flow of people and goods, strengthen regional connections, provide access to key health and social services, and improve economic development opportunities. Moreover, transportation networks contribute to national sovereignty, safety and security. In short, well-functioning and cost-effective transportation networks provide strong social and economic benefits to northern communities, businesses and governments.

Increasingly, climate change is exacerbating the challenge of maintaining northern land-based transportation routes. Ice road networks are a good example, increasingly compromised as a warming climate shortens operations when ice thickness is insufficient to support heavy traffic flows. Indeed, the unseasonably warm conditions of 2006 are likely a sign of things to come, where the operation of the Tibbitt to Contwoyto ice road was cut short by nearly a month. With increased regional mining activity in the Canadian North, greater truck loads can be expected on ice roads, with melting conditions an obvious concern for mining operations.

Highways and airport runways are also facing increasing risks from melting permafrost, including accelerated erosion and instability. The Alaska Highway is a good example, where operating costs are as much as 10 times higher for parts of the highway located over permafrost. Many remote First Nations communities are also finding themselves especially vulnerable to the reduced road access, because of their inland locations and their reliance on roads and trails to maintain their cultural and economic way of life.

Intuitively, these trends are known to trigger economic costs, as the benefits provided by infrastructure services are lost or impaired due to a changing climate. An informal assessment of these costs in the past may have been enough to highlight the risk, but with the need to make investment choices to build resilience, do we know enough to make informed decisions? Can we be more systematic in our approach and move to more formally linking changing climatic variables to economic outcomes?

To better understand what is lost when climate change affects the operations of infrastructure assets, the benefits that are gained from infrastructure must be examined. Transportation infrastructure can provide a variety of implications and beneficial effects. There can be economic benefits to resource extraction companies in the form of reduced operating costs and reliable access to remote areas. For communities, efficient transportation systems reduce the cost of consumer goods, fuel and construction materials in remote communities while providing access to employment opportunities. There are also benefits of a more intrinsic nature, such as shorter commute times. For governments, efficient transport routes facilitate service delivery and minimize costs.

In addition to these types of benefits, there can be positive effects on the economy—the generation of income and employment resulting from increased economic development and activity levels. These benefits then become costs to the extent that climate increases operating and capital costs or reduces the services supplied by transportation infrastructure. In principle, the value of these different types of costs can be estimated in monetary terms and aggregated into two separate measures:

- The value of the positive implications or "outcomes" of the investments in transportation infrastructure can be estimated on the basis of what people and businesses are willing to pay for them.
- The value of the positive and negative impacts on the economy can be estimated on the basis of the incremental impact on employment and other income.

Table 1 provides a taxonomy of costs that can be expected when climate variables stray outside norms.

TABLE 1: TAXONOMY OF COSTS TRIGGERED BY CHANGING CLIMATIC VARIABLES

CHANGING CLIMATE VARIABLES FROM AVERAGE OR SEASONAL NORMS	SOURCE OF COST	MEASURE THE COST
Direct costs Increased maintenance, repair and capital costs	• More frequent and costly activities to maintain service levels • Capital expenditures to prolong life or to build alternatives	• Production costs, where increased capital and operation and maintenance alters the cost of production for businesses decreasing economic surplus.
Accelerated infrastructure replacement costs	• Accelerated degradation of the asset, shortening useful service life	• Asset replacement costs. Accelerated retirement shortens the time between expenditures for asset replacement, thereby increasing total expenditures.
Indirect costs Loss of infrastructure service and activity disruption	• More frequent operational shut downs, such as shortened season for winter ice roads • Slower travel times • Higher cost alternatives required to meet operational needs • Stockpiling output for shipment when transport routes allow	• Production costs. Increased input costs manifest through increased transportation costs, reducing economic surplus. This could include increased labour costs due to limited road access. • Production losses. Where down time due to supply shortages reduces the economic surplus of the operation. • Lost value. Lower value due to market timing when outputs cannot reach market on a timely basis.

As the table indicates, three costs of infrastructure degradation form the basis of any assessment of the value at risk from changing climate conditions:

1. **Increased maintenance, repair and capital costs**, which may be required to adjust operations given new climate constraints, and which may be transient or may not. Increased wear and tear may also be accelerated due to changes in extreme event characteristics or changes in average conditions. Examples include:
    - Roads that endure multiple freeze-thaw cycles in the winter deteriorate faster and require more maintenance. Hot temperatures cause pavement to soften and form ruts, and cause asphalt to liquefy and bleed out of pavement (Natural Resources Canada [NRCan], 2007).
    - Roads can become soft and rutting and pot holes are more likely to occur, requiring additional maintenance.
    - During times of high runoff or heavy rainfall, increased maintenance includes:
        - Cleaning or repairing drainage and erosion control structures
        - Grading to the road surface to minimize rutting, potholes or channelling of water
        - Hiring more flooding crews to build up the ice earlier
        - Assessing structural integrity of bridges and culverts more regularly

2. **Accelerated infrastructure replacement costs** result when assets must be replaced due to a catastrophic failure or excessive degradation (weathering, etc.) in advance of their projected lifespan. The costs are calculated as the difference between the useful life of the asset (pre-climate impact) and the climate-impaired life of the asset. Alternatively, costs can also be measured as the depreciated value of the asset at time of failure. In time, a series of premature retirements and associated costs by asset category are tracked as a function of the probability of climate-related hazards and the exposure and vulnerability characteristics of the assets. Delays in repairs could also lead to loss of services and business disruptions.

Examples include:

- Regions of discontinuous permafrost must contend with "ground slumping, tilted tree, sinkholes, and other disturbances," which are causing massive problems for all-weather and seasonal roads, rail lines and airport runaways (NRCan, 2007).
- There might be **salvage values lost** where a premature infrastructure failure degrades some residual value that cannot be salvaged. The cost is likely some share of the replacement value of the building that is lower because of the permafrost loss.

3. **Loss of infrastructure service and business disruption**, where the impaired infrastructure decreases the benefits provided by the infrastructure, translating into a loss in economic value to users. Examples could include higher transportation costs or business losses due to road or runway closures. Specific examples where these costs have been observed include:

More frequent shut downs:

- Western Canadian Coal was forced to suspend operations at its Dillon coal mine due to road weight restrictions on public roads caused by an early spring break-up. The temporary suspension began on March 31 and lasted four weeks (Scales, 2006).
- A state of emergency was declared in the Peace River District of northeastern B.C. in July 2011 following torrential rains that caused massive flooding. Major highways in the region were washed out and shut down, causing millions of dollars in damages (CBC News, 2011).

Shortened season for winter roads and ice roads:

- In 2006 operators of the Tibbitt to Contwoyto winter road were forced to suspend the use of the facility temporarily on March 22 and permanently for the season on March 26 as a result of warm weather. The road was deemed no longer safe despite efforts to halt the thinning ice in the face of warm temperatures. No alternate ice routes or other means of stopping the thaw were found. The road operated for only 42 days where past years averaged nearly 70.
- Of the expected 9,000 loads to be dispatched, only 6,841 were shipped, many of which were below maximum weight (Rio Tinto, 2006).
- Tahera Diamonds, which had recently opened its Jericho mine, was affected by the melting ice. Approximately 40 per cent of the loads, including over half the fuel supply, did not reach the site before the end of March. Although Tahera saw no need to cut production levels, the company was forced to defer waste stripping and

capital projects into the next year in order to conserve fuel. The company said if it had to airlift supplies to the mine, it would have cost an extra $3 million or $0.75 per kilogram or litre compared with trucking rates (Robertson, 2006).

- De Beers was in the midst of construction and development of the Snap Lake underground project during the closure, which resulted in significant implications for the project. Of their 2,200 scheduled loads, 600 of them never made it up. Some of the crucial components that got left behind included fuel, the scrubber for the diamond processing plant and a 200-man accommodation complex for the construction workers (Robertson, 2006).

Increase in transportation costs:

- Following the closure of Tibbitt to Contowyto in 2006, Diavik had to airlift hundreds of loads of stranded freight to allow the company to continue its schedule of diamond production and new construction projects, including 15 million litres of fuel. Diavik was forced to reduce diesel fuel consumption on site by 2.6 million litres as a result and did so through an airlift program and employee-driven conservation program (Rio Tinto, 2006).
- To transport large materials Diavik had to use one of Russia's largest most powerful helicopters, the MIL type Mi-26. It took 22 lifts over four weeks to complete the job. The helicopter lift also meant building three separate landing pads, including at Yellowknife Airport, Diavik and the ice road camps halfway up the road for refuelling.
- Many materials had to be assembled and re-welded on the mine site as a result of weight restrictions on the flights, which under normal circumstances would have been done elsewhere.
- Overall, Diavik had to airlift nearly 13,000 tonnes of dry cargo and nearly 11,000 tonnes of fuel as a result of the shorter ice road season. The additional cost was significant—in the tens of millions of dollars (Rio Tinto, 2006).

These costs may be absorbed by businesses, communities and government, indicating a need in the analysis to discuss the distribution of the cost of ongoing climate change and the benefits that adaptation might bring through reducing future risks. The next section introduces and explores the economic tools that help reveal the economic implications of these cost categories.

3.0 Exploring the Economics Toolkit

This section includes a brief overview of the core tools used in applying economics to adaptation: cost-benefit analysis (CBA) and economic impact analysis.

3.1 Cost-Benefit Analysis

CBA evolved based on the need for governments to assess and prioritize projects, and to allocate limited budgets and resources. CBA provides a unifying framework to compare trade-offs and options about investment choices or, in the case of climate change, a choice not to adapt. CBA has a long history of use, is ensconced in policy-making in Canada and abroad, and has well-defined rules to guide project appraisal.

At its core, CBA compares streams of costs and benefits in time so that trade-offs are revealed and investment choices identified that maximize societal returns. It is an approach that makes clear the advantages and disadvantages of a certain decision in terms of its impact on society, recommending projects that maximize social well-being or welfare at minimum cost. It aims to guide decision making and project selection so that scarce resources are used, or allocated efficiently, where they provide the highest increase in social welfare.

Within the CBA frame, as long as the choices made provide increases in satisfaction or welfare greater than the lost opportunity of choosing the next best alternative, then those are efficient choices that maximize well-being. Stated differently, if decisions result in economic benefits that are greater than economic costs, then resources (land, labour and capital) are being used efficiently to improve societal welfare. In the adaptation case, as long as the benefits of investing in improved resilience are greater than the costs needed to build the resilience, social welfare is increased and adaptive action is economically justifiable.

In CBA, costs and benefits are directly linked. Something cannot be used or consumed, and a benefit received, without giving up something or experiencing costs. If, for example, scarce public resources (land, labor and capital) are used to add resilience to a runway, then those resources cannot be used for something else. An opportunity has been lost to use that money on another project that may also improve welfare. The cost of building resilience, therefore, can be defined in terms of what is given up to buy something, or the lost opportunity.

CBA adopts a "with" and "without" perspective to avoid double-counting impacts. A baseline view is first articulated of how economic activity will unfold absent a new policy or change in some impact factor like ambient air temperature. Then the new policy or investment is introduced and incremental change from the baseline is identified. For example, a "no climate change" baseline would first identify the normal stock turnover of the infrastructure asset and then the "with climate" scenario would identify the incremental change in accelerated asset failure as permafrost degrades. The CBA would compare the two cost streams in time and the difference would be the incremental cost attributable to the temperature change.

Applied to questions of adaptation and transportation infrastructure, CBA can address two core questions:

1. **What are the costs of current climate-induced damages?** A baseline economic risk scenario is defined to reveal the economic costs (or value lost) of continuing under current infrastructure practices. This is often called a "no new adaptation" scenario—although, in reality, there is always some ongoing adaptation, for example zoning restrictions in flood planes or upgraded foundation types in buildings susceptible to permafrost thaw. For example, due to future threats to ice roads revealed by weather extremes in 2006, adaptive measures have been implemented such as:

- New, lighter-weight and amphibious machinery has been purchased to facilitate road construction earlier in the season; alternative road routings have been developed; and operational efficiencies have been achieved.
- Longer-term alternatives to the ice road are also being explored.
- Construction of a seasonal overland route and utilizing the proposed Bathurst Port and Road Project are just two of the ideas currently being investigated.

2. **What are the benefits of adaptation actions?** Applied to choices about improving the resiliency of transportation infrastructure, CBA starts with vulnerability information on how and when assets might be affected as climatic variables change and impact thresholds are reached. Economic value is then increased through cost-effective risk mitigation actions. The approach is to identify when the value of the risk reduction (benefit) exceeds the incremental adaptation cost for a cost-effective adaptation option.[2]

Helping inform investment choices to build resilience in infrastructure is a major benefit of a CBA. When choices need to be made about how to scale adaptation spending, CBA can also help reveal how the costs of alternative adaptation actions compare to value of benefit when future risks are reduced.

3.2 Economic Impact Analysis

In an economic impact analysis, the cost information developed within the CBA is translated into the known and accepted economic indicators such as gross domestic product (GDP), employment and government revenue. This macroeconomic information is not additive to the cost information above, but rather provides an alternative view of the damages using commonly understood and often sought-after economic indicators.

Economic impacts stem from costs that can be linked to market transactions such as increased operating costs or capital spending. They do not include less tangible non-market costs such as individuals' willingness to pay for better transportation infrastructure. Conceptually, climate-induced weather damages trigger both positive and negative economic impacts, but it is the costs, and therefore negative impacts, that are needed here.

Negative impacts result when production costs rise from spending on maintaining or replacing damaged infrastructure, which raises the costs of production and therefore prices. Increased prices decrease demand for inputs and reduce outputs, having negative ripple effects in the supply chain (Kousky, 2012). Essentially, increased costs lower productivity where it takes more costs per unit of production. This then raises real prices in the economy, thereby lowering economic activity elsewhere.

Negative impacts, or drops in activity, also result from business disruptions as economic activity slows or stops due to a loss in infrastructure service. Any business disruptions lower economic activity for the duration of the climate event directly for businesses as well as for suppliers and other firms using the affected firm's outputs. From the perspective of the whole economy, however, these multiplier effects may well be zero, with positive and negative impacts cancelling out (Kousky, 2012). However, from a distributional perspective, it is most likely that the firm and the region where the firm is located will show an overall economic decline.

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[2] When two options deliver similar levels of risk reduction, the cost-effective option is the one that delivers the reduced risk at least cost or lowest $/units of risk reduced.

Spending to address damages due to the premature asset failure or increased production costs is a curious case in economics. On the surface, it would seem that spending to repair damages and to clean up the climate event-induced mess would increase economic activity. But in reality, this spending has to come from foregoing consumption elsewhere. Again, on aggregate the total economy of a province or Canada may not decline as consumers purchase the good from a different supplier. The net effect of this spending is not so certain, and a macroeconomic model would ideally trace these counteracting forces to produce a net impact measure.

Similarly for government, any expenditures for addressing damages originate from income tax. Government balances are fixed, and taxation must either rise, money must be borrowed or other services forgone. As with industry, the increased spending must be countered with a reduction in consumption elsewhere, and the net effect of the spending is most likely negative.

To estimate these economic impacts, there are really two choices: a regional input-output model (I-O model) and a computable general equilibrium model (CGE model). Both models take business disruption and infrastructure cost information and relate them through known economic structures through the supply chain. In both cases, the severity of the disruption or the cost increase is applied as a cost increase in the production function. The high costs, prices and lower level of economic activity are captured in the I-O model or the CGE model as it traces its way through the economy, identifying the change in macroeconomic impacts that arise.

4.0 Climate Risk Assessment and Revealing Economic Outcomes

In this section, the economic analysis is nestled more tightly in a typical climate risk assessment process to demonstrate how economic analysis using a CBA or economic impact model could complement a typical climate damage or adaptation assessment. As mentioned above, the focus will continue on the example of permafrost thawing and ice road impacts linked to northern temperature increases under future climate change scenarios.

4.1 Overview of Approach

A key issue for decision-makers is how and when to adapt to a changing climate. Understanding climate hazards and asset vulnerability is the necessary first step, but so too is identifying cost-effective and weather-resilient choices that minimize long-term risks and costs. At the root of understanding the costs of a warming climate and the benefits of adaptation choices is an analysis linking accelerated asset decay and increased costs with ambient air temperature and permafrost and ice thawing in a climate scenario.

Clearly this causal chain is complex and, not surprisingly, so too is the methodology. In this guide, the methodology has been simplified with an eye on creating a replicable approach that others can follow. An important objective of the framework, therefore, is to support the development of credible analytics, but also to present a method that can be adopted by others.

The framework consists of seven core elements, as outlined below, with additional detail in the following section:

1. Screening Hazard, Vulnerability and Infrastructure Assets at Risk

   For the geographic study area, identify, categorize and prioritize key climate hazards and economic asset categories for analysis. An initial scoping exercise can provide a screening-level assessment of the climate hazards, asset inventory and likely vulnerabilities for the infrastructure assets at risk. The scoping studies can be completed through key informant interviews, preliminary compilation and review of available data for the study area, and targeted stakeholder engagement (facilitated workshops).

2. Data Collection, Economic Assets and Forecasts

   Baseline economic assets are identified reflecting economic growth and decline with detailed profiles of important assets and economic uses now and in the future. This then forms the basis of a forecast of assets for time frames from which to estimate economic indicators.

3. Assessment Scenarios Identified

   This step identifies scenarios that typically form the basis of economic analysis such as a base case "pre-climate impact" scenario, a "no adaptation" scenario and a "with adaptation" scenario. Essentially, the scenario is the core question that needs to be addressed; for example: Does the risk mitigation measure deliver avoided future costs (benefits) greater than the costs to implement the measures?

4. Climate Risk and Economic Value Assessment

   Forecast the probable magnitude and frequency of climate hazard-driven damage for each asset category under climate change, as well as any secondary or cascading effects of potential economic consequence (e.g., service disruptions and property damages).

Climate risk refers to the probability of harmful consequences or expected losses resulting from interactions between climate hazards and vulnerable economic assets and activities in the context of climate variability and change. The assessment should first identify the range of possible climate impacts (hazard types) and asset vulnerabilities for the study area now and in the future. It should then estimate the probability of occurrence of each climate-related hazard type at frequencies and/or magnitudes corresponding with specified damage- or loss-related thresholds for each asset type, under alternative climate futures. Risks related to the interaction of each climate-related hazard with each relevant category of economic asset will be expressed probabilistically (reflecting uncertainty) and reflect analyses of key constituent elements (e.g., sensitivity and adaptive capacity) of economic asset- and activity-related vulnerability.

With hazards and vulnerabilities known, economic approaches can then be used to:

5. Develop Climate Risk Value Model

   The objective is to reveal the probable economic outcomes of each climate risk (hazard-asset *category*-value at risk) for each climate change scenario to be assessed. To accomplish this, a climate risk and economic value model (CR-EVm) provides the conceptual framework to combine climate-related hazards, economic assets *and* asset vulnerability, and economic value at risk.

   The CR-EVm estimates the magnitude of potential climate risk losses associated with a single baseline scenario as well as multiple climate change and adaptation scenarios. Economic value is calculated using welfare economic principles and a total economic value framework to monetize economic damages under alternative climate scenarios. A best practice is probabilistic analysis, where uncertainty information on key paramters is defined as probability density functions so that ranges of outcomes are available to reveal key uncertainties. Uncertainties are then made explicit as a range of probable outcomes that combine climate risks and economic and social assets at risk.

6. Monetize Climate Induced-Damages on Assets and/or Adaptation Benefits

   Costs can be expected as climate-induced vulnerabilities manifest, including direct expenditures made for prolonging infrastructure life or to replace infrastructure more frequently. Indirect effects include any loss in services for those that use the impaired infrastructure. A distinction can be made between impacts on current assets and future “greenfield” assets that may be built with a higher degree of climate resilience relative to current assets.

   Adaptation benefits can accrue to the extent that expenditures reduce asset vulnerability and hence future costs. A net benefit is present, signifying the investment is socially desirable, when actions to reduce future costs are outweighed by the dollar value of the benefit of avoided damages.

7. Economic impacts on regional economies.

   The climate-induced weather damages trigger both positive and negative economic impacts. Negative impacts result from business disruptions as economic activity slows or stops due to a loss in infrastructure service. Any business disruptions lower economic activity for the duration of the climate event directly for businesses as well as for suppliers and other firms using the affected firm’s outputs. Countering this is an increase in activity from any spending on adaptation actions that then ripples through the economy.

Items 3 and 4 can be implemented within the unifying frame of a CBA while item five falls squarely under an economic impact methodology. While both approaches use dollar values as the reporting metric, they are not comparable given that alternative assumptions and methods are employed. As such, one can think of the economic analysis supporting climate risk assessments as two separate reporting accounts:

- The CBA is about options analysis where outcomes are identified that maximize benefits and minimize costs, highlighting the trade-offs of alternative adaptation options and indicating actions that maximize social benefits (i.e., are the benefits of the option greater than the costs?).
- The economic impacts analysis highlights changes in activity levels and other macroeconomic indicators in the economy.

With this analytical chain, a range of indicators can be developed, including the dollar value of the cost of inaction in terms of increased expenditures as, for example, assets fail prematurely, as well as the benefits gained when adaptive asset design reduces future asset vulnerability.

4.2 Steps in Methodology

Step 1: Screening of Hazard, Vulnerability and Assets at Risk

This task is focused on a screening exercise to identify, categorize and prioritize key climate hazards and economic asset categories for analysis and eventual inclusion in the economic modelling.

Estimating the economic implications of climate change on transportation infrastructure requires the collection and processing of substantial amounts of climate data, asset data and economic value data. The first step is to identify, categorize and prioritize key climate hazards and economic asset categories for analysis. An initial scoping exercise can provide a first pass, screening-level assessment of the climate hazards, asset inventory and likely vulnerabilities. The preliminary screen can be completed through, for example, desktop analyses, key informant interviews or a series of expert workshops, enabling a first, rapid survey and characterization of:

- Significant economic assets damaged in the past by climate-related hazards.
- Climate-related hazards that have damaged important economic assets or caused pronounced service disruptions.
- Hazard thresholds associated with past damage to important economic assets or pronounced service disruptions (e.g., thresholds of precipitation above which roadway flooding is typically experienced in specific areas).
- Climate-related hazards that have yet to result in significant damage to important economic assets or pronounced disruptions in services, but that may increasingly pose a risk as the result of climate change.
- Non-climate-related factors known or suspected to have contributed to past climate-related damages to important economic assets, or pronounced disruptions to services (i.e., vulnerability factors).
- Level and type of remedial actions taken to enhance the resilience of important economic assets in the community (e.g., after experiencing past climate hazard-related damages or pronounced reductions in service levels).

- Planned actions to enhance the resilience of important economic assets.
- Significant trends/changes in the local climate, based upon observed data and available climate projections.

Step 2: Data Collection: Climate, Economic Assets and Forecasts

This task is focused on compiling baseline data such as:

- Historic climate data and downscaled modelling where available.
- Climate data, economic baselines and asset inventories reflecting location-specific data on commercial activity and other local activity linked to assets at risk, current and future.
- Forecast growth and decline in economic assets of significance.
- Baseline inventory of important infrastructure assets.

Baseline data needs to be compiled and analyzed for each infrastructure asset or class of assets to support development of:

- Economic baselines and asset inventories and forecasts reflecting commercial activity and other drivers such as demographic trends.
- Forecast growth and decline in economic assets of significance.

Table 2 summarizes the data sources typically required for the analysis.

TABLE 2: DATA SOURCES, AVAILABILITY AND ACCESS

DATA TYPE	DATA REQUIREMENTS
Climate Data	Historic climate data for site
	Climate scenario projections
	Climate change downscale data
Asset Data	Road, rail, marine transport infrastructure
	Average age and replacement schedule
	Current weather impacts on replacement life
	Infrastructure vulnerabilities to climate hazards
Economic Data	Replacement costs
	Activity data
	Economic sector forecasts (GDP, employment etc.)
	Demographic forecasts
	Historical estimates of damages associated with extreme weather events

Step 3: Identify Scenarios for Estimating Climate Risk Economic Outcomes

There are three core scenarios that typically form the basis of economic analysis: a base case "pre-climate impact" scenario; a "no adaptation" scenario; and a "with adaptation" scenario. This is the basis of the "no" and "with" comparisons that enable incremental changes to be identified for the economic analysis.

Pre-Climate Impact Base Case

This scenario is the base case from which the costs of climate change ("with" climate change case) on transportation assets is compared. In this scenario, transportation assets come to the end of their useful life and are replaced absent of any climate change impact. The present value of the stream of replacement costs is estimated in this pre-climate impact scenario. There are no service disruption costs and no incremental production costs, given that all infrastructure is operating as designed.

To define the scenario, first identify a profile in time of asset replacement under a no-climate-change future. In time zero, the remaining useful life of the transport asset sets the scheduled future replacement year and then the asset replacement costs are assigned to the year after retirement (assuming useful life ends and new capital is then immediately deployed).

Ideally, asset replacement costs are not annualized, and instead are accounted as lump sum costs accrued in the year after the asset's end-of-life year. Replacement costs are also scaled up or down to reflect expected growth in transport demand as indicated by population or economic growth projections.

With a stream of no climate impacts estimated, comparisons can then be made with a climate change scenario with rising temperatures and associated cost increases such as accelerated asset replacement.

Costs of Climate Change Scenario (No Adaptation Scenario)

In this scenario, the incremental costs that occur as a result of climate change are estimated. The climate impact on infrastructure is triggered when an increase in ambient air temperature triggers a threshold resulting in impairment to or a failure of the transportation asset. Existing and planned adaptation actions are also included so that these actions become unavailable in the other scenarios given they are already deployed.

The susceptibility to failure of each type of asset in a region is ideally expressed as a probability of asset failure, such as the probability that ambient air temperature (and hence ground temperature) will lead to a performance threshold reached for a road.

With a credible link made between ambient air temperature changes and the degradation of transportation assets, the costs identified in Table 1 can be examined, including:

- Loss of infrastructure service and activity disruption
- Increased maintenance, repair and capital costs
- Accelerated infrastructure replacement costs

The Benefits of Adaptation (With Adaptation Scenario)

This scenario identifies and monetizes the benefits of remedial measures that avoid premature retirement and ongoing costs identified in the no adaptation scenario. The "active adaptation" scenario introduces adaptation measures that prolong the life of existing transportation assets, but also deploys climate-resilient measures to avoid ongoing costs. This then avoids a series of costs that were identified in the no adaption scenario.

The important outcome is the net benefits of the scenario, where the expenditures to mitigate future risks are less than the benefits of avoided costs identified in the no adaptation scenario.

For each asset type, ideally there are a number of discrete adaptation measures that reduce future risk, with higher costs to reduce higher levels of risk. In effect, a marginal risk reduction curve is developed that plots cost and risk reduction trade-offs. This allows for the identification of the change in the likelihood that the normal functioning of the asset will be impaired or the asset will fail for an identified adaptation measure.

An optimization routine can then be used to determine if there is a combination of measures that can maximize the net benefit (benefits minus costs), where minimal costs are needed to maximize the benefits (or future costs avoided).

Step 4: Climate Risk and Economic Value Assessment

This task focuses on combining assessments of climate hazard, asset vulnerability and changes in economic value in a unified framework or climate risk and economic value model (CR-EVm). The goal is to monetize future damages for specified climate scenarios under alternative adaptation action and climate scenarios.

Key efforts in this task include:

- Refine and validate hazard variables and asset category threshold response values for each relevant climate hazard-asset category pairing.
- Identify the severity of the impacts on the economic assets, including exposure and vulnerability assessment estimates that link the likely sensitivity of the asset categories to changes in the frequency of hazards of defined magnitudes and durations (i.e., probabilistic vulnerability curves that pair climate hazard with infrastructure impact).
- Quantify and monetize the expected magnitude of damage, loss or disrupted services under climate scenarios in relation to each relevant climate hazard-asset category pairing.

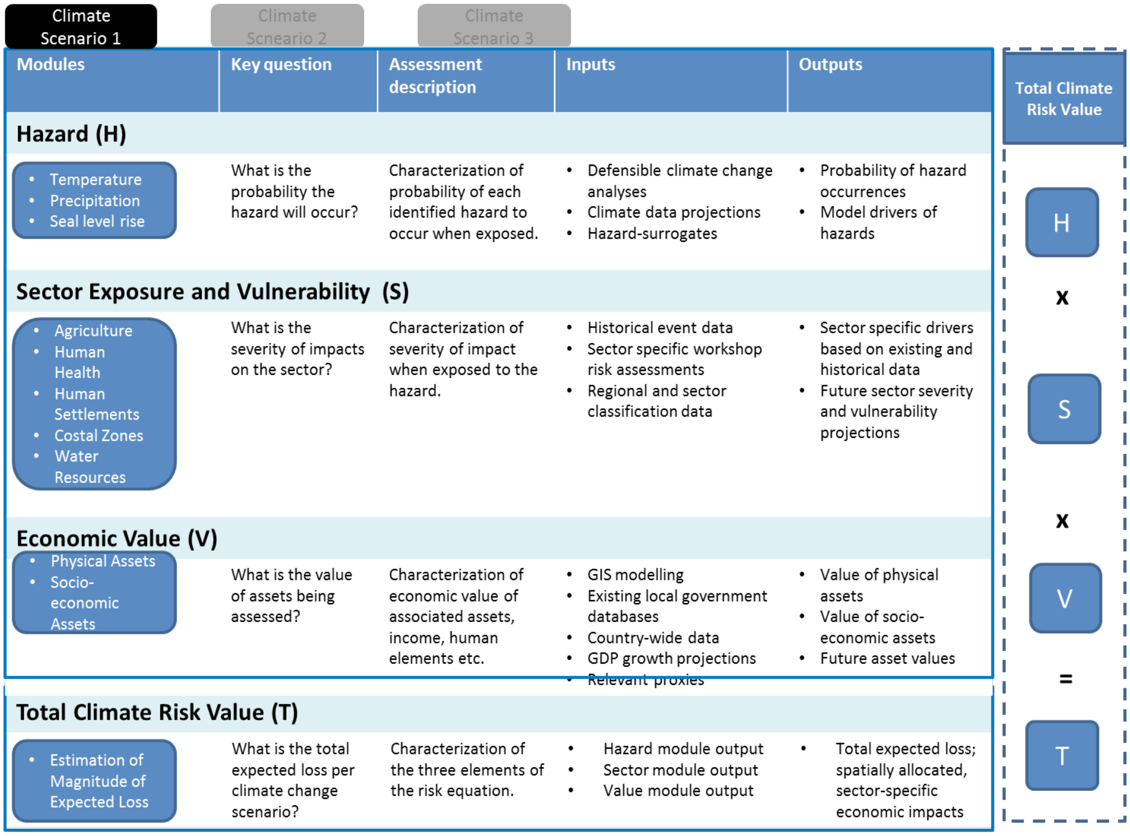
Key task outputs include:

- Climate hazard analysis (historical and future)
- Asset exposure and vulnerability
- Probabilistic functions that link changes in hazard to asset damages
- "Marginal vulnerability curves" linking climate-induced hazards with asset damages

To populate the CR-EVm, probabilistic damage functions or marginal vulnerability curves by economic asset category need to be developed that pair climate hazards and asset vulnerability. Step 1 in the process is therefore a climate hazard assessment, while Step 2 requires vulnerability of each of the respective asset categories to be established. These are then combined by economic asset category and unit dollar values (e.g., output per hour for service disruptions) are added to represent a range of expected damage types for given changes in climate outcomes.

When all are combined, the economic damages on infrastructure and service disruptions for a given climate scenario are calculated, and can then be coupled with adaptation actions that reduce expected damages and hence future costs. For the adaptation scenario, the costs of the adaptation measures are compared with the benefits of the avoided future damages.

Figure 1 below provides an overview of the CR-EVm followed by the methodological detail for each of the subtasks, including the assessment of the climate hazards, vulnerabilities and economic value at risk. It is the last metrics of economic value at risk that then informs the economic impact component.



Modules	Key question	Assessment description	Inputs	Outputs
Hazard (H)				
Temperature Precipitation Seal level rise	What is the probability the hazard will occur?	Characterization of probability of each identified hazard to occur when exposed.	Defensible climate change analyses Climate data projections Hazard-surrogates	Probability of hazard occurrences Model drivers of hazards
Sector Exposure and Vulnerability (S)				
Agriculture Human Health Human Settlements Costal Zones Water Resources	What is the severity of impacts on the sector?	Characterization of severity of impact when exposed to the hazard.	Historical event data Sector specific workshop risk assessments Regional and sector classification data	Sector specific drivers based on existing and historical data Future sector severity and vulnerability projections
Economic Value (V)				
Physical Assets Socio-economic Assets	What is the value of assets being assessed?	Characterization of economic value of associated assets, income, human elements etc.	GIS modelling Existing local government databases Country-wide data GDP growth projections Relevant proxies	Value of physical assets Value of socio-economic assets Future asset values
Total Climate Risk Value (T)				
Estimation of Magnitude of Expected Loss	What is the total expected loss per climate change scenario?	Characterization of the three elements of the risk equation.	Hazard module output Sector module output Value module output	Total expected loss; spatially allocated, sector-specific economic impacts

FIGURE 1: CLIMATE RISK-ECONOMIC VALUE FRAMEWORK

Climate Hazard Assessment

The assessment of the climate hazard is the first of three steps required to quantify the expected magnitude of damage, loss or disrupted services under either adaptation or future climate scenarios. First, however, further consideration is given to refining and validating hazard variables and asset category threshold response values identified in the screening step (Task 1) for each relevant climate hazard-asset category pairing, as elaborated for demonstration purposes in Table 3.

Information can be collected through focused reviews of the literature (by asset category) as follows:

- Peer-reviewed literature in the areas of engineering meteorology, engineering risk assessment, critical infrastructure performance and protection.
- Grey literature in the form of government (e.g., Public Works), research bodies (National Research Council Canada) and other published works (e.g., over 26 PIEVC vulnerability assessments) documenting the performance of specific asset classes when exposed to climate hazard conditions (whether acute or long term) of relevance to one or both of the case studies.
- Codes, standards and related instruments (e.g., design specifications) known to be used in the planning, design, construction or management of one or more of the assets (categories).

For each case study, once all climate hazard variables have been refined and performance threshold values defined for each related asset category, a draft final set of asset category-hazard variable-performance threshold listings should be developed.

Note that methodologies to quantify climate hazard probabilities will be fundamentally shaped by the time frames of the economic analyses. This time frame is usually aligned either to the life of the asset, or some long-term time frame associated with a climate scenario (out to 2050 for example).

TABLE 3: EXAMPLES OF HAZARD VARIABLES AND ASSET CATEGORY THRESHOLD RESPONSE VALUES

ASSET CATEGORY	CLIMATE HAZARD	SPECIFIC VARIABLE	THRESHOLD RESPONSE VALUE(S)	RESPONSE
Storm water conveyance systems	Severe rainfall	Total 1-hour rainfall	>25 mm rain / hour	Moderate overland flooding 8 times out of 10
			>35mm rain / hour	Moderate overland flooding 9 times out of 10, extreme flooding 4 times out of 10
Roads and Airports	Air temperature	Mean annual, mean daily minimum winter/ summer	Heat index (KJ/m2)	Accelerate decay in infrastructure age
				Performance thresholds reached much sooner (e.g., low Bituminous Condition Index (BCI)score)

Assessment of Vulnerability

In this step, the purpose is to identify the potential severity of the impacts on the economic assets. The vulnerability assessment estimates the extent to which each class of infrastructure asset is sensitive to changes in the defined climate hazards. The task seeks to probabilistically assess the future vulnerability of the asset based on its future exposure and sensitivity to specific climate hazards.

"Vulnerability" refers to the potential for an asset category to be harmed by a climate hazard. Of concern are the vulnerabilities of classes of economic assets to a specific climate hazard (the stressor). The two elements of vulnerability for which data and information need to be collected include:

- The sensitivity of infrastructure assets to climate hazards is the degree to which infrastructure assets are affected, positively or negatively, by climate variability or change. Sensitivity needs to be "measured" through impact studies such as engineering studies, actual observed data and studies on the impact of climate hazards on economic outcomes.
- The adaptive capacity of institutions and people to climate hazards refers to the ability of institutions, systems and individuals to take advantage of opportunities or to cope with the consequences of potential damages. For all scenarios, some assumptions need to be made about levels of autonomous adaptation absent of new policy. For example, changes in building practices in areas prone to flooding may naturally occur as part of industry-driven loss management. The risks of assuming no new adaptation is a significant overstatement of the economic cost should current and future practices be realigning towards adaptation.

The economic asset vulnerability can be linked to climate hazard conditions to define the severity of impacts through various methods. Potential risk severity characterization approaches include:

- Use of regional severity and economic asset classification data, based on regional norms and historical occurrences
- Conduct facilitated sector-specific vulnerability and risk assessment workshops with local stakeholders, including municipal engineers
- Development of engineering estimates based on design standards and engineering judgement
- Validate with local stakeholders to "ground truth" or verify results

Understanding the climate hazard-exposure-vulnerability relationship provides the basis for defining the future severity of the risk and impact, based on projections of changes in these three elements over time.

The following types of data and information may need to be collected or generated to support the assessment of **economic asset exposure**:

- Spatial distribution of significant transportation assets
- Spatial distribution of other key economic assets (e.g., commercial, industrial activity)
- Locations of geographic features that may contribute to or result in exposures (e.g., permafrost zones)

The following types of data and information can be collected or generated to support the assessment of **vulnerability** by economic asset category and/or economic activity:

- Historical business losses or costs
- Government-held data on losses associated with climate change
- Key performance threshold values at which a defined hazard will generate damage or interrupt service (through reference to design specifications, specific codes or standards, interviews with key informants, or other means as possible and necessary)
- Service level and reliability requirements of key economic activities with respect to key assets
- Institutional capacities to minimize loss and damage

Estimate Economic Value at Risk

With baseline economic assets (including activities) identified in previous sub-tasks and marginal vulnerability curves developed (pairing of risks reduced and costs of adaptive measures), the value at risk now needs to be calculated for each asset class.

Planned adaptive measures or practices need to be included in the baseline given they will happen under current expectations of climate change. Expenditures to include would be increased operating and maintenance costs as well as any capital expenditures to avoid future damages.

The valuation of asset categories at risk should use standard valuation methods focusing primarily on market value but using surrogate valuation techniques where needed. Intrinsic values, such as the willingness to pay for improved transport infrastructure, can be collected and included in the estimate of economic value but not in the economic impact section (below).

Asset values are expressed in unit values, such as costs per kilometre (km) travelled on ice roads or permafrost operating cost increase per km of highways, and need to be estimated. These are then multiplied by activity levels to provide an estimate of cost. Where data gaps exist for local data, unit asset values can be estimated from country-wide data and downscaled to the regional entities using relevant proxies (i.e., value-added per-unit operating hour for disrupted or reduced services for industry).

Key data to assemble include:

- Value of important economic assets using market prices for infrastructure replacement, material costs and changes in productivity.
- Surrogate valuation techniques where needed.
- Costs and benefits by economic assets (and economic activities) likely affected by climate hazards.

With data collected, the total CR-EVm needs to be constructed to monetize damages to each of the economic assets and determine the value at risk to the extent climate risk probabilities are relevant (sum of hazard, exposure and vulnerability). Essentially, monetize the total net loss for each allocated asset class in the climate change scenarios. To do this, one must combine within a CR-EVm numerical model the hazard and vulnerability curves (or points) with the corresponding economic asset value for the defined climate change or adaptation scenarios.

At this point in the analysis, the practitioner needs to have developed the critical information required to develop a numerical CR-EVm. The analyst needs to populate the numerical model, conduct some preliminary testing, then run the scenarios. Central to the process is to validate the results to ensure that the key outputs meet expectations and then adjust and refine as needed.

Step 5: Estimate Net Costs of Climate-Induced Weather Pattern

In this task, the economic value at risk is mapped into a macroeconomic model to provide estimates of the economic costs of the climate change or adaption scenario. Economic risks (net costs) are mapped into an economic impact model to estimate changes in core economic indicators such as regional GDP, industry output, employment and municipal taxes. To estimate the economic impacts, the asset value at risk from the CR-EVm is mapped into the appropriate economic sectors as either increases or decreases in costs. With this change in cost, a macroeconomic model is run to reveal changes in the core economic indicators.

The key objectives for this task include:

- Disaggregate the expected losses and expenditures per asset class calculated in the CR-EVm into final demand categories for use in the regional I-O model.
- For each scenario and time slice, run the macroeconomic model to estimate the current and future climate risk losses (climate-adjusted economic baselines with no new adaptation).
- Produce estimates of expected climate risk losses to investment, GDP, government balances, trade effects and structural change in the economy.
- Test assumptions and outputs to ensure results conform to expectations.
- Report on key indicators of net economic costs for the different scenarios and time slices.

To estimate the economic impacts, there are really two modelling choices: a regional input-output model and a general equilibrium model. Both models require business disruption and infrastructure costs to be expressed similarly. The incremental cost of running either approach is likely to be similar, although a general equilibrium model requires highly specialized consulting support. On the other hand, the general equilibrium model also provides better information as it provides a more dynamic economic view of the macroeconomic outcomes.

As mentioned in Section 3.2 above, the macroeconomic analysis starts with an accounting of the business disruptions and increased spending to address damages. For an adaptation scenario, any spending to avoid damages is accounted for first as a cost for the expenditures to the sector and then later as an avoided cost (or benefit) as future risks are avoided.

For the I-O model approach, expenditures by asset class identified in the previous task are mapped into impact type, such as the following final demand categories included in Canada's input-output tables:[3]

- "Construction, local, municipal and regional public administration" for government infrastructure spending
- "Construction, housing construction, non-government sector" for residential spending
- "Machinery and equipment, utilities" for impacts on utility infrastructure
- "Machinery and equipment, chemical manufacturing" for impacts in the chemicals sector

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[3] Statistics Canada, National Input-Output Tables (15F0041X). http://www5.statcan.gc.ca/olc-cel/olc.action?ObjId=15F0041X&ObjType=2&lang=en&limit=1

In a good regional I-O model, local impact multipliers will be available for most regions of the country, including the North. The table below highlights a simple run completed using a regional I-O model for a $1 million climate impact on municipal infrastructure in Mississauga. This scenario indicates that the weather event would result in $1.34 million in lost economic output (GDP), reduce wages by $940,000 and decrease tax revenue by $380,000. Based on this hypothetical scenario, it is clear that the capacity exists to estimate a range of economic impact outcomes for a diverse set of climate impacts on both infrastructure and businesses.

TABLE 4: COST IMPACT OF $1 MILLION PUBLIC INFRASTRUCTURE DAMAGES IN MISSISSAUGA RESULTS IN $1.34 MILLION IN ECONOMIC DAMAGES (GDP)

REGION	ECONOMIC INDICATOR	DIRECT EFFECTS	INDIRECT EFFECTS	INDUCED EFFECTS	TOTAL IMPACT
Mississauga	GDP	$650,094	$158,550	$319,453	**$1,128,097**
Rest of Canada (CDN)		$4,267	$53,122	$189,586	**$246,975**
Mississauga	Employment (FTE)	$11	$2	$4	**$17**
Rest of CDN		$0	$1	$2	**$3**
Mississauga	Wages, salaries, and supplementary income	$584,497	$90,346	$142,630	**$817,473**
Rest of CDN		$3,077	$26,113	$96,827	**$126,017**
Mississauga	Tax Revenue	$146,438	$78,653	$93,387	**$318,479**
Rest of CDN		$1,157	$12,986	$49,153	**$63,296**

Source: Canadian Input-Output Model, Regional Economic Impact Policy Model (http://www.policymodels.com/)

Step 6: Reporting

There are many deliverables that could be developed for the analysis outlined in this document. A preliminary list and their contents include:

- **Climate scenarios to be used**, how these are defined and a justification for inclusion.
- **Hazards and weather changes**, which include the climate-induced hazards that trigger impacts on economic assets, including a justification for their inclusion.
- **Vulnerability assessment** linking classes of economic assets to climate-induced hazards with justification for their inclusion.
- Description of the methodological approaches that will be utilized to:
  - Forecast economic activity in a given area
  - Quantify the costs and benefits of climate-induced hazards on the major asset classes
  - Estimate ultimate net economic impacts, including elements of direct and indirect impacts on major macroeconomic indicators

5.0 Recommendations for Future Work

The CBA guidance document provides a general framework to conceptualize adding an economic lens to a particular climate change or adaptation issue. There is further work that can be done to improve the tools and information available to practitioners and decision-makers interested in including the economic implications of climate change in their planning. The following list of recommendations includes priority areas for future work that arose from the development of the CBA guide.

1. Develop an in-depth user guide that provides a directive approach

   Given budget and resource constraints, it was not possible to develop a guidebook that walks practitioners through the detailed steps and calculations to conduct an economic analysis. In the future, a companion document could be developed that is more detailed and more of a cookbook of methods.

2. Develop a number of case studies for demonstration

   Given the lack of available information identified in the literature search, there is a real need for concrete examples to showcase both ongoing costs and adaptive benefits. Ideally, these would be selected to reflect a range of climate hazards and infrastructure types.

3. Develop general rules of thumb for economic impact

   Using the case studies as an information base, it would be possible to develop general impact measures for infrastructure by climate hazard. This could be thought of as a complement to the PIEVC engineering protocols.

4. Communicate more broadly

   There is a really need for more communication on economic approaches to adaptation in Canada. As a result, a series of webinars and other outreach activities could be developed to help disseminate the guidebook and open a dialogue on how to conduct an economic analysis applied to adaptation. Ideally, these would showcase the approach contained in this document, a companion "cookbook" and a series of transportation infrastructure case studies.

6.0 Conclusion

This document provides a general framework for practitioners to think about adding an economic lens to a particular climate change or adaptation issue. The guide is not a cookbook with detailed calculations, but instead was designed to help the practitioner to conceptualize how economics might complement existing climate risk assessment approaches. A companion document will eventually provide more detailed calculations using a case study to highlight the method.

It is clear that the analytical chain to link climate change to economic outcomes is complex, requires specialized expertise and has a great deal of inherent uncertainty. This should not be cause for concern, because it is not always necessary to fully monetize the economic outcomes. Instead, it may be useful to identify the types of costs and benefits that can be expected and to craft a communications story that highlights this full range. To the extent that some of these can be quantified using available information, the story is then bolstered by numerical evidence. Finally, it will not always be possible to monetize all of the outcomes. Still, some can be easily monetized, such as increased operating costs. Again these monetary values can be added to the overall economics story to reveal a broad picture that identifies the scope and scale of economic outcomes while being supported by some monetized information.

A key point is that the economic information should complement existing climate risk information that is already being used to highlight current and future risks. Taken together, the climate risk information and the economic story then present a unified picture of the impacts of climate change on infrastructure and the benefits that might stem from adaptation investments that build infrastructure resilience.

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