Climate Change Risk Analysis of Argentina's Land Transport Network

September 2021

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Abstract

Argentina's vast networks of national, provincial, and rural roads, spanning more than 240,000 kilometers, are critical for the country's growth and development. However, climate change–induced hydrological extremes often disrupt road travel and raise logistics costs. Climate projections for Argentina suggest that, by 2050, a temperature increase of between 0.5 and 1°C will lead to an increase in precipitation, exposing the transport network to a significant risk of flooding.

The objective of this study is to quantify the impact of climate change–induced flood risk on the transport network in Argentina. The study analyzes both current and future flooding scenarios, examines the resulting disruptions in the transport network, and estimates the direct and indirect macroeconomic losses. The study uses a system-of-systems approach, where network models are developed to suitably represent the transport system as nodes and links. For each node and link, the study analyzes criticality, vulnerability, and risk, and provides adaptation strategies.

The results show that considerable lengths of road and many point locations are already exposed to extreme fluvial and pluvial flooding (above 50 centimeters of flood depth). This exposure is expected to substantially increase under future climate outlooks. For example, the exposure of national roads to pluvial floods is expected to increase by 10 to 20 percent. Generally, the greatest projected increases in extreme-hazards exposures occur at lower return periods, typically in the range of one-in-five-year to one-in-100-year events, expected to cause frequent disruptions in the future. The criticality analysis indicates that all the major national road freight corridors radiating from Buenos Aires are affected by flooding, with the highest disruptions in flow estimated at approximately 100,000 tons of freight per day. However, it is important to note that if alternative routes are available, the highest disruptions to traffic flow do not necessarily produce the most severe economic impacts.

The risk assessment results show that, under the baseline climate outlooks, and with the assumption that flooding causes disruptions of no more than 10 days at network level, the highest total direct damages and indirect losses due to road failures is estimated to be US$3.8 million. Under future climate conditions, the total damages and losses for these roads is expected to increase by 8.2 percent. Indeed, comparisons between conditions under baseline and future climate outlooks generally indicate widespread increases in flood risks for extreme hazards. Several assets could face an increase in damages and losses of up to 100 percent.

However, targeted adaptation investments can significantly reduce these risks. As the duration of disruptions increases from 10 to 100 days, the number of kilometers of roads with a maximum benefit-cost ratio (BCR) greater than 1 increase by a factor of between 19 and 54, and the corresponding number of kilometers representing robust investments (where minimum and maximum BCR are greater than 1) increases by a factor of between 29 and 60. These results signify that targeted interventions are effective and economical, especially considering potentially prolonged future disruptions.

In summary, the analyses in this study revealed that: (i) major freight transport routes on roads and railways in Argentina face disruptions due to extreme flooding and climate change; and (ii) economic impacts of disruptions can become significant, depending upon the network rerouting capabilities and the duration of disruption. To address these risks, the National Roads Directorate (Dirección Nacional de Vialidad; DNV) and Ministry of Transport (MoT) of Argentina need to be increasingly prepared for extreme flooding events, which will be magnified in the future due to climate change. It will be critical for them to incorporate climate change risks into all long-term planning processes at a national scale to gain a better understanding of the impact. They will also need to go beyond quantifying direct damage and begin to account for macroeconomic losses of climate risk related disruptions. Finally, they must develop their internal capacity to undertake transport risk assessment to inform designs, construction, and maintenance approaches.

[15] Verónica Raffo, Pablo Iribarren Santos, and Yohannes Yemane Kesete, "Transport and Climate Change: Putting Argentina's Resilience to the Test," Transport for Development (blog), World Bank Blogs, September 19, 2018, https://blogs.worldbank.org/transport/transport-and-climate-change-putting-argentina-s-resilience-test.

Abbreviations and Acronyms

AADF	Average Annual Daily Freight
BCR	Benefit-cost ratio
CBA	Cost-benefit analysis
CREMA	Rehabilitation and maintenance contract (Contrato de Rehabilitación y Mantenimiento)
DNV	National Roads Directorate (Dirección Nacional de Vialidad)
EAD	Expected annual damage
EAEL	Expected annual economic loss
GCM	Global Climate Model
GDP	Gross domestic product
IO	Input-output
IPCC	Intergovernmental Panel on Climate Change
MoT	Ministry of Transport
MRIO	Multi-regional economic input-output
OD	Origin-Destination
PFV	Passenger Flow Volumes
RCM	Regional Climate Model
RCP	Representation Concentration Pathway
ROCKS	Roads Cost Knowledge System

1. Introduction

Argentina's land mass, the eighth largest in the world, is interconnected through a network of national, provincial, and rural roads more than 240,000 kilometers in length. The primary network alone comprises approximately 40,000 kilometers of roads, with an estimated asset value of US$45.3 billion. In addition to the roads, a vast network of railways, several airports, and various waterway ports round out Argentina's multi-modal transportation infrastructure. Together, these systems facilitate movement within the country and connect Argentina to its neighbors.

This complex transport sector plays a critical role in economic growth and development by facilitating access to services and markets across the country. However, most transport infrastructure in Argentina underperforms because of its inadequate quality and resulting low capacity to withstand natural disasters. Climate change–induced hydrological extremes exacerbate these challenges by frequently disrupting transportation and increasing transport logistic costs.[16] In addition to their economic and social impact, these disruptions have far-reaching repercussions for the transportation and exportation of goods, ease of communications, and access to services for about 45 million people.

Climate projections suggest that, by 2050, temperatures in Argentina will increase by between 0.5 and 1°C, under both Representation Concentration Pathway (RCP) 4.5 and 8.5 emission scenarios.[17] By the end of the century, temperatures are projected to increase by 1°C under RCP 4.5 and 2°C under RCP 8.5. Warming is expected to be more acute in the northern and western parts of the country, and the northern and central regions will see an increase in precipitation magnitudes. These changes have already begun. In the last 100 years, mean surface temperatures in Argentina have increased by about 0.5°C,[18,19] a trend that became more pronounced in the second half of the twentieth century. Since 1960, annual mean precipitation volume has also risen, at a rate of about 3.5 percent per decade.[20] Similarly, the number of days with extreme precipitation has increased in the last several decades, especially in central and eastern Argentina.

These climatic and meteorologic shifts will make parts of the country more vulnerable to frequent flooding, which already has significant economic impact. Flooding in Argentina has been responsible for about US$22.5 billion in economic losses since 1980, and for 58 percent of all economic losses caused by natural disasters between 1966 and 2015.[21] Such losses are expected to grow, with climate change–related threats projected to impact an estimated 4.5 to 7 percent of Argentina's GDP.[22]

Like many other sectors, transport systems in Argentina are severely affected by widespread flooding, resulting in major economic disruptions. The objective of this study is to quantify the impact of climate change on Argentina's transport sector, specifically focusing on flood-related risks under both current and future flooding scenarios. The study estimates the direct and indirect macroeconomic losses resulting from widespread transport disruptions to sectors that make up the Argentine national economy. The ultimate objective is to provide decision-makers with actionable information that will help them make both short-term maintenance choices and long-term capital investment decisions.

This study includes vulnerability analyses of national, provincial, and rural roads; bridges on national roads; national railways; major waterway ports; and major airports. Vulnerabilities and risks were analyzed in the context of extreme flooding caused by rivers overtopping their banks (fluvial) and flooding caused by extreme local rainfall (pluvial). The outputs of 32 Global Climate Models (GCMs) and two climate emission scenarios (RCP 4.5 and RCP 8.5) were used to sample future rainfall patterns and account for the higher levels of flooding that might be caused by climate change.

[16] Raffo, Santos, and Kesete, "Transport and Climate Change."
[17] Vicente Ricardo Barros, José Armando Boninsegna, Inés Angela Camilloni, Martina Chidiak, Graciela Odilia Magrín, and Matilde Rusticucci, "Climate Change in Argentina: Trends, Projections, Impacts and Adaptation," *WIREs Climate Change* 6, no. 2 (March/April 2015): 151–169, doi:10.1002/wcc.316.
[18] IPCC, *Climate Change 2013: The Physical Science Basis. Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed.* Thomas F. Stocker, Dahe Qin, Gian-Kasper Plattner, Melinda M.B. Tignor, Simon K. Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M. Midgley (Cambridge, UK, and New York, NY: Cambridge University Press, 2014).
[19] José A. J. Hoffmann; Silvia Esther Núnez, and Walter M. Vargas, "Temperature, Humidity and Precipitation Variations in Argentina and the Adjacent Sub-Antarctic Region during the Present Century," *Meteorologische Zeitschrift* 6, no. 1 (1997): 3–11, doi:10.1127/metz/6/1997/3.
[20] World Bank, *Argentina – Análisis Ambiental de País: Serie de informes técnicos* (Washington, DC: World Bank, 2016).
[21] Swiss Re, *Staying Afloat: Flood Risk in Argentina* (Zurich: Swiss Re, 2016), https://reliefweb.int/sites/reliefweb.int/files/resources/Swiss_Re_Argentina_Flood_Risk_Publ_long.PDF.
[22] ECLAC (Economic Commission for Latin America and the Caribbean), *La Economía del Cambio Climático en la Argentina*, Document LC/W.567 (Santiago de Chile: United Nations, 2014).

In addition to the final outputs, the datasets assembled and the analyses conducted under this project can be used in future studies, contributing to the broader objective of considering climate change in development and infrastructure planning. Among the study's technical contributions are its methodology and the detailed spatial evidence of systemic climate risks it presents. Further technical contributions include: (i) the creation of unique datasets and models; (ii) prioritization approaches for transport networks based on criticality; (iii) understanding of the hazard vulnerability of the transport network; (iv) adaptation planning strategies; and (v) uncertainty assessment.

This paper is organized into four sections. Following the methodology and approach laid out in Section 2, the analysis and results are detailed in Section 3. Conclusions and policy recommendations are presented in Section 4.

2. Methodology

2.1 System-of-Systems Approach

The framework used for this study outlines a system-of-systems methodology for transport risk analysis for Argentina. Network models can suitably represent the transport systems for the purposes of this analysis. A network here is defined as a collection of nodes joined by a collection of links. Nodes are point representations of key locations of physical facilities in the transport systems – ports, airports, railway stations, and road junctions. Links are line representations of physical connections between nodes – road sections, railway lines, waterway routes.

Each transport mode (road, railways, ports, and airports) considered in this study is treated as an infrastructure system, which is the collection of all physical facilities that operate in a coordinated way to provide infrastructure service[23] (infrastructure or transport service refers to mobility of freight and passengers between locations). The multi-modal transport infrastructure, which is the interconnection of individual transport systems, is then defined as a system of systems. Figures 2-1 and 2-2 present the process of implementing the systems-of-systems methodology created for this study.

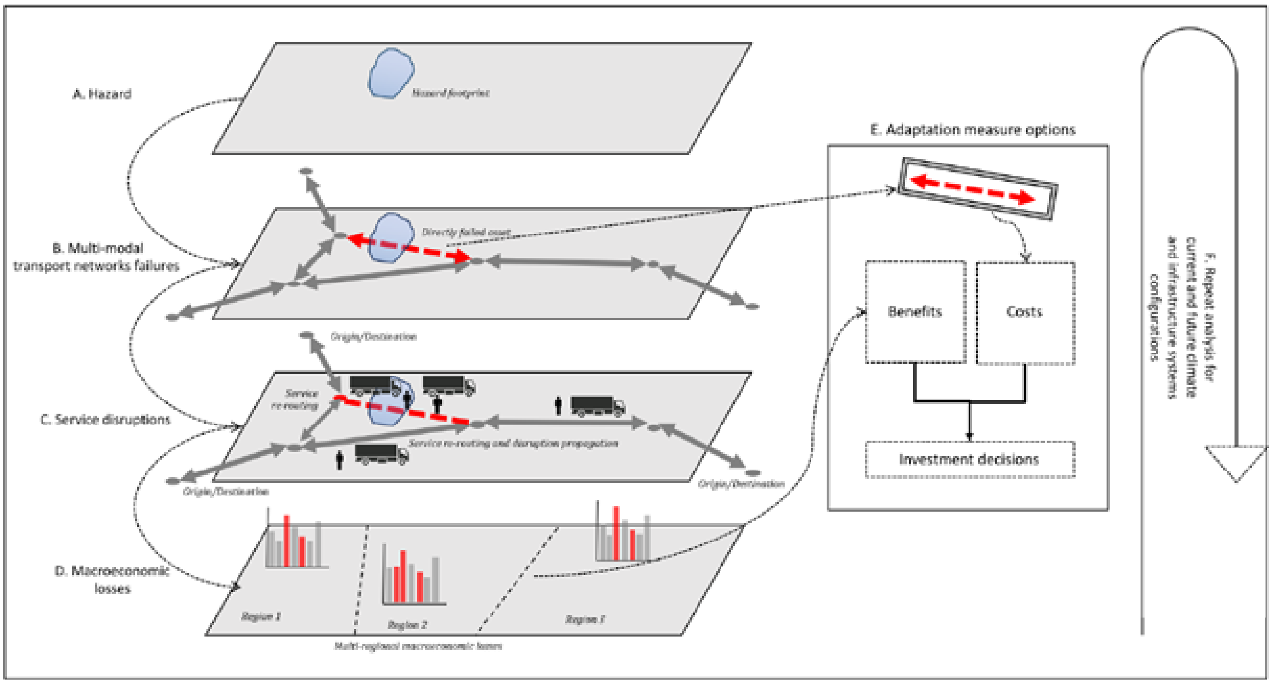
This methodological framework has been employed in similar spatial system modelling studies, including in Tanzania,[24] Vietnam,[25] and the United Kingdom,[26] to inform infrastructure vulnerability and extreme hazard risk assessments at regional[27] and national[28] scales. These studies informed adaptation measures by identifying hotspots in the transport network, analyzing both current and future scenarios. This Argentina land transport risk analysis builds on these studies, contributing novel approaches to quantifying the macroeconomic impact of transport disruptions to help decision-makers understand the cascading effects of climate change in the economy. The framework used in this study presents different types of system-of-systems assessments useful for decision-making, including:

- Criticality assessment. Criticality is defined as a measure of a transport link's importance and disruptive impact on the rest of the transport infrastructure.[29] Criticality assessment ranks network elements according to their relative impact on the serviceability of the transport networks.[30]

[23] Jim W. Hall, Martino Tran, Adrian J. Hickford, and Robert J. Nicholls, eds., The Future of National Infrastructure: A System-of-Systems Approach (Cambridge, UK: Cambridge University Press, 2016).
[24] Raghav Pant, Elco E. Koks, Tom Russell, and Jim W. Hall, Transport Risk Analysis for The United Republic of Tanzania: Systemic Vulnerability Assessment of Multi-Modal Transport Networks, Final Report Draft (Oxford, UK: Oxford Infrastructure Analytics Ltd., 2018), doi:10.13140/RG.2.2.25497.26722.
[25] Raghav Pant, Elco E. Koks, Tom Russell, Roald Schoenmakers, and Jim W. Hall, Analysis and Development of Model for Addressing Climate Change/Disaster Risks in Multi-Modal Transport Networks in Vietnam, Final Report Draft (Oxford, UK: Oxford Infrastructure Analytics Ltd., 2018).
[26] Scott Thacker, Raghav Pant, and Jim W. Hall, "System-of-Systems Formulation and Disruption Analysis for Multi-Scale Critical National Infrastructures," Reliability Engineering & System Safety 167 (November 2017): 30–41.
[27] Raghav Pant, Scott Thacker, and Jim W. Hall, David Alderson, and Stuart Barr, "Critical Infrastructure Impact Assessment due to Dlood Exposure," Journal of Flood Risk Management (December 2016): 22–33, doi:10.1111/jfr3.12288.
[28] Scott Thacker, Stuart Barr, Raghav Pant, Jim W. Hall, and David Alderson, "Geographical Hotspots of Critical National Infrastructure," Risk Analysis 27, no. 12 (December 2017): 2490–2505, doi:10.1111/risa.12840.
[29] Raghav Pant, Jim W. Hall, S. P. Blainey, and J.M. Preston, "Assessing Single Point Criticality of Multi-Modal Transport Networks at the National-Scale," paper presented at the 25th European Safety and Reliability Conference, Zurich, Switzerland, September 7–10, 2015.
[30] Bramka Arga Jafino, "Measuring Freight Transport Network Criticality: A Case Study in Bangladesh" (master's thesis, Delft University of Technology, 2017).

- Vulnerability assessment. Vulnerability is defined as the measure of the negative consequences of transport link failures caused by external shock events.[31] Vulnerability is assessed in the context of natural hazards and elucidates the relative impacts of hazards on continued transport availability.
- Risk assessment. Risk is defined as the product of the likelihood of a hazard and the consequences of transport link failures. Risk assessments quantify the comparative impacts of different hazard frequencies.
- Adaptation planning. Adaptation refers to measures taken to reduce risks. In the context of climate change,[32] adaptation planning seeks to capitalize on the opportunities associated with climate change. For transport systems, adaptation planning seeks to identify the assets and locations that could be prioritized for targeted investments to most effectively minimize risk.

Figure 2-1: Infrastructure System-of-Systems Risk and Adaptation Assessment Framework



Source: *Original figure for this publication.*

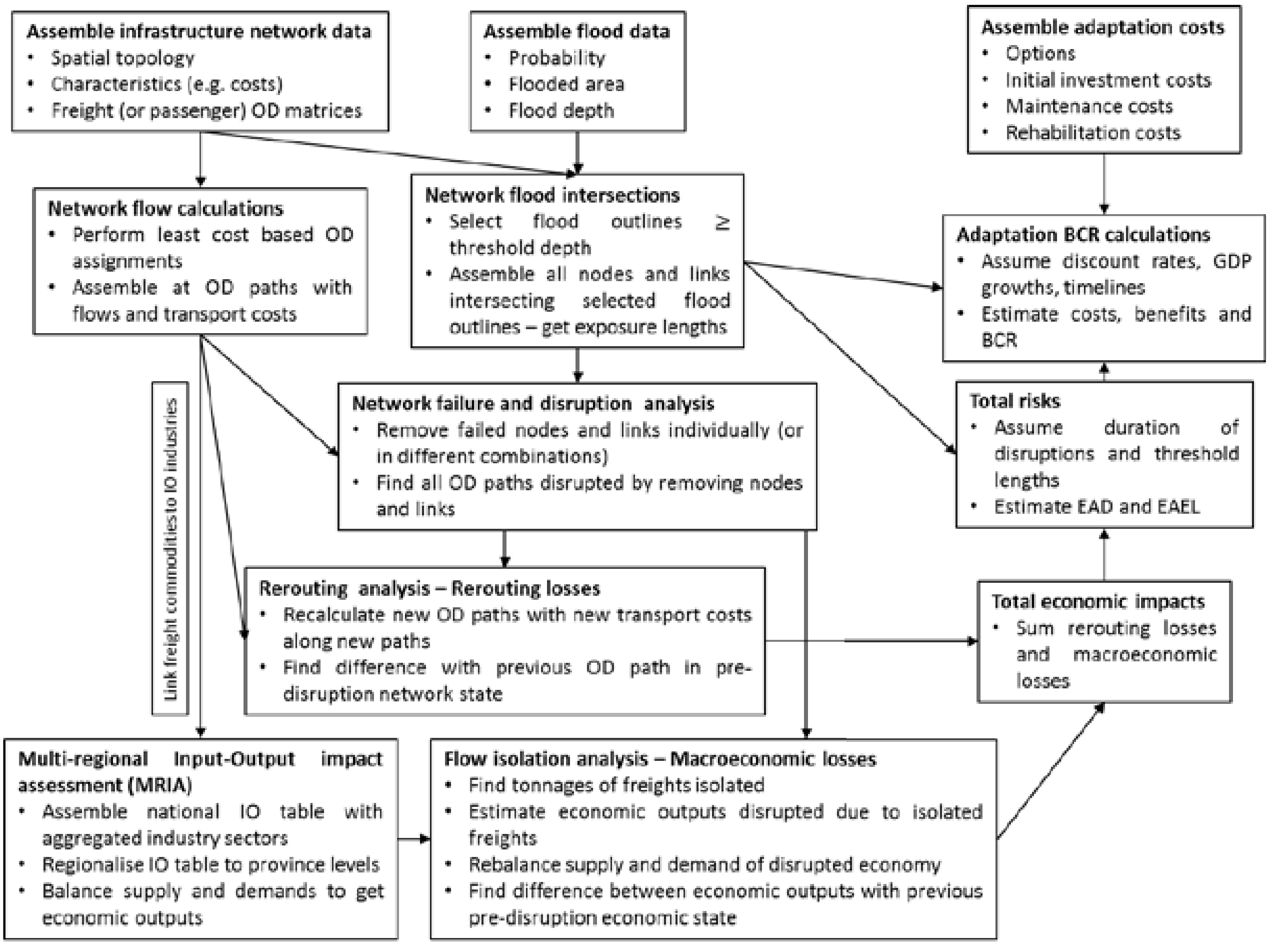
2.2 Defining Network Flow, Flood Vulnerability, Criticality, and Risk Analysis

In this study, network flows are modelled and measured in terms of volumes of mobility between network locations (origin-destination pairs) over a suitable time frame. The study focuses on freight flow analysis for roads, railways, and waterways, and on passenger flow analysis for air transportation. Network flows are hence modelled and measured based on Average Annual Daily Freight (AADF) volumes and Passenger Flow Volumes (PFV). AADF is the estimated tonnage of freight moving between different network locations on an average day; PFV is the estimated number of passengers using airports annually. These measures are assembled from usage statistics provided by several authorities in Argentina. Figure 2-2 shows the process of implementing the system-of-systems analysis, with types of information for, and outcomes of, each component.

[31] Raghav Pant, Jim W. Hall, and Simon P. Blainey. "Vulnerability Assessment Framework for Interdependent Critical Infrastructures: Case Study for Great Britain's Rail Network," *European Journal of Transport and Infrastructure Research* 16, no. 1 (2016): 174–194, doi:10.18757/ejtir.2016.16.1.3120.

[32] H.-M. Füssel, "Adaptation Planning for Climate Change: Concepts, Assessment Approaches, and Key Lessons," *Sustainability Science* 2, no. 2 (2007): 265–275.

Figure 2-2: Implementation Steps in the Infrastructure System-of-Systems Risk and Adaptation Assessment Framework



Source: *Original figure for this publication.*

Note: *BCR = Benefit-cost ratio; EAD = expected annual damage; EAEL = expected annual economic loss; IO = input-output; OD = Origin-Destination.*

Since the main objective of the vulnerability analysis is to understand the criticality of specific elements of the network, the analysis only considers complete loss of network functionality. Given that the vulnerability analysis is at the national level, various simplifications are adopted to manage its complexity. Usually, analyzing asset failures due to hazards requires the use of detailed, physical process–based models, which quantify the fragility of assets for given hazard magnitudes. For example, the flood fragility of a road will depend on its physical dimensions (for example, height), construction standards (for example, design return periods of its drainage systems), material types, exposure to flooding, flooding severity levels (for example., depths and river flows at road locations), and the different damage states determined for different levels of flooding. Given the complexity of assembling such a database at the national level, this analysis adopts a simplified failure criterion that is based solely on the flood depth levels. The analysis assumes that flood levels above a certain depth threshold (dtr) represent extreme flood hazards that cause flow disruptions leading to failures. Only areas of (d_tr)≥50 cm were considered to present extreme hazard scenarios,[34] and therefore those network locations that intersected such areas were considered to have failed. Hence, all subsequent analysis presented in this report shows results for network assets exposed to ≥ 50 cm of flooding only.

Argentina-specific flood outputs were created by the FATHOM Global Flood Hazard models.[35] These datasets provided gridded pixels at 90-meter resolution that show the flood extents and maximum expected water depth in meters at 10

[33] Fragility refers to the conditional probability of an asset's failure for a given level of hazard. Fragility is quantified through fragility curves, which are derived from statistical analysis of historical failure data that record the condition of an asset and its level of hazard exposure. They can also be created by simulating the physical properties of a system based on its design standards, and stress-testing it under different hazard levels.

[34] The choice of 50 centimeters as a minimum threshold was based on discussions with stakeholders in Argentina and can be adjusted as necessary in the model.

[35] FATHOM is a UK-based company that models flood hazards (http://www.fathom.global/).

different return periods: 1 in 5, 1 in 10, 1 in 20, 1 in 50, 1 in 75, 1 in 100, 1 in 200, 1 in 250, 1 in 500, and 1 in 1,000 years. Two types of flood hazard outputs were produced: fluvial (flooding caused by rivers overtopping their banks) and pluvial (flooding caused by extreme local rainfall).

The flood maps were produced over three different climate outlooks to capture current and future flooding hazards. Conventionally, future climate-driven flood outcomes are produced by generating future rainfall patterns for different Global Climate Models (GCMs) under specific climate scenarios (for example, RCP 4.5 or RCP 8.5, or 1.5°C or 2°C). This is a "scenario-led" approach, which propagates uncertainties in scenario and model selection and is very computationally intensive because of the huge ensemble of rainfall patterns and resulting flood maps that must be calculated when multiple GCMs and climate scenarios are considered.

This study instead adopts a "scenario-neutral" and pragmatic approach for country-level evaluations. Here, the selected changes in the five-day rainfall were sampled from a distribution of changes predicted across all GCMs and climate emission scenarios. The median and 90th percentiles of the distribution were then selected to represent the most likely and extreme rainfall change scenarios based on the range of climate outputs. In the end, the flood maps were generated for one current and two future climate outlooks:

1. Baseline. The estimated flood depths representing the 2016 flooding outlook, informed by the 1986–2005 baseline precipitation (sourced from historical rainfall records).
2. Future median. The estimated flood depths and flooded areas in 2050, informed by the median value of the change in five-day maximum precipitation with respect to the 1986–2005 baseline precipitation. This median value is approximately +6 percent, recorded across 32 GCMs and across RCP 4.5 and RCP 8.5 climate emission scenarios.
3. Future high. The estimated flood depths and flooded areas in 2050, informed by the 90th percentile value of the change in five-day maximum precipitation with respect to the 1986–2005 baseline precipitation. This value is a pproximately +12 percent, recorded across 32 GCMs and across RCP 4.5 and RCP 8.5 climate emission scenarios.

The +6 percent and +12 percent rainfall perturbations for the future climate outlooks were applied universally across all return periods and were found to be within predicted changes given by the global Intergovernmental Panel on Climate Change (IPCC) approaches.[36] The approach used here was found to represent a good metric of extreme rainfall change across several catchment sizes.[37]

Criticality assessment is carried out to rank network assets based on the relative impact their failure would have (in monetary terms) on the serviceability of the transport networks.[38] An exhaustive "what if" failure analysis of all individual network elements (nodes and links) is performed. The analysis is a useful first step toward exploring and evaluating the system's performance in a generalized context, independent of the likelihood and severity of the external shock event.

Network disruption for the criticality assessment is determined by spatially intersecting the extent of flooding with a given network. Relevant stakeholders were also actively engaged to refine and validate historical disruption locations. To estimate network disruption, the freight assignment must first be calculated. This is a composite performance measure of the monetary value (in US dollars) of transport, expressed as a function of travel time and transport tariff prices; it is based on both the existing spatial patterns of freight transport in the country and a generalized cost. Estimating network disruptions involves three steps. First, the freight assignment is calculated, and failed links are removed from the network. The next step is to simulate rerouting freight movement to the next route option with the least generalized cost estimate. Finally, the redistributed flows and performance measures are compared with the pre-disruption values. When there are no alternative routes, the freight disruptions may further result in significant macroeconomic flow losses.

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[36] IPCC, *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Vicente R. Barros, Christopher B. Field, David Jon Dokken, Michael D. Mastrandrea, Katharine J. Mach, T. Eren Bilir, Monalisa Chatterjee, Kristie L. Ebi, Yuka Otsuki Estrada, Robert C. Genova, Betelhem Girma, Eric S. Kissel, Andrew N. Levy, Sandy MacCracken, Patricia R. Mastrandrea, and Leslie L. White (Cambridge, UK, and New York, NY: Cambridge University Press, 2014).

[37] Andrew Smith, Paul Bates, Jim Freer, and Fredrik Wetterhall, "Investigating the Application of Climate Models in Flood Projection across the UK," *Hydrological Processes* 28, no. 5 (February 2014): 2810–2823, doi:10.1002/hyp.9815.

[38] Jafino, "Measuring Freight Transport Network Criticality."

Macroeconomic losses are estimated through multi-regional economic input-output (MRIO) models.[39] Disruptions to the transport network cause AADF flow losses, which in turn result in economic losses. By tracking the flow type and industry type of each disrupted Origin-Destination (OD) route, these losses – both direct and indirect – can be calculated. Direct economic flow losses consist of: (i) macroeconomic supply losses, which occur when the production capacities of industries are diminished due to unavailability of commodities required for production; and (ii) macroeconomic demand losses, which occur when the final demand for goods produced by the disrupted industries are diminished as they cannot reach the markets. Indirect economic flow losses are knock-on effects, caused by impacts to the ability of those sectors directly affected by the network disruption to trade with other sectors; these effects disrupt the multi-regional macroeconomic system. Trade relationships between sectors are known as backward (supply) and forward (demand) linkages. The ripple effect of the original direct economic flow losses through these linkages is what leads to indirect (output) losses.[40]

Once the criticality of network links has been assessed, the risks of extreme-hazard failures at individual network nodes and links can be estimated by combining hazards and impacts into one metric. Network risks at the level of individual network elements are estimated in terms of:

Expected Annual Economic Loss (EAEL), which signifies the indirect risks of failures. Theoretically, if the transport links are exposed to hazard events sampled from a joint multi-variate probability density function p(x), and the economic losses for the events are given by l(x), then the EAEL = $\int p(x)l(x)$. More realistically, the losses (in US dollars) are estimated for discrete events with increasing exceedance probabilities $p_1,\ldots,p_n$, and losses $L_1,\ldots,L_n$, for which the EAEL is estimated as below. The losses here equate to the daily economic impacts (estimated in the criticality assessment), multiplied by a certain duration of disruption, which is the period during which the affected network link is assumed to be out of operation.

$$EAEL = \frac{1}{2}\sum_{i=1}^{n}(P_{i+1} - P_i)(L_i + L_{i+1}) \qquad (1)$$

Expected Annual Damage (EAD), which signifies the direct risks of failures. Similar to the EAEL, EAD = $\int p(x)d(x)$, and is estimated for discrete events with increasing exceedance probabilities $p_1,\ldots,p_n$, and damages $D_1,\ldots,D_n$, as below. The damages here are estimated by multiplying the exposure lengths of transport links by an estimated cost (in US dollars) per kilometer, which is generally sourced from compiled data in the country.

$$EAD = \frac{1}{2}\sum_{i=1}^{n}(P_{i+1} - P_i)(D_i + D_{i+1}) \qquad (2)$$

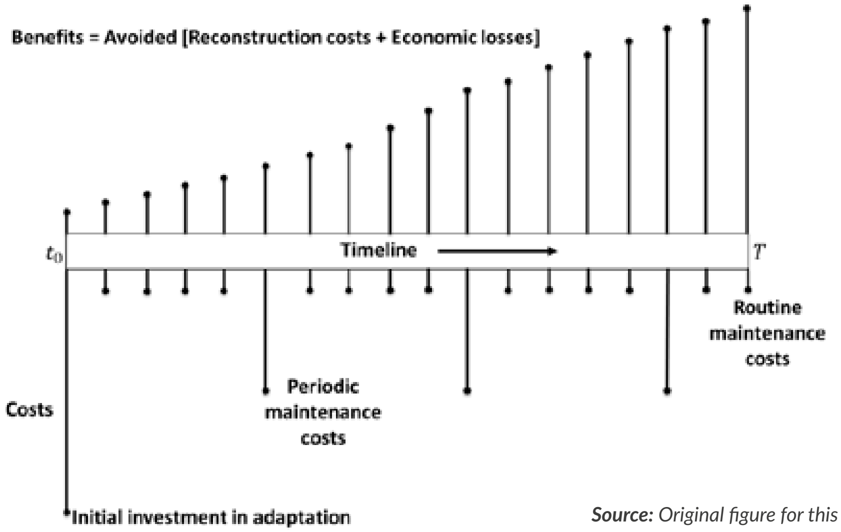
The total risks of flooding for a link or node are estimated by adding the direct risks (EAD) and the indirect risks (EAEL) from all flooding, which means that each flooding event is assumed to be independent.

2.3 Adaptation Planning

Adaptation actions are defined as structural improvements carried out on a transport network (node or link) to climate-proof or upgrade it over its lifetime. The effectiveness of different adaptation options is evaluated and compared through a cost-benefit analysis (CBA), which is a well-established technique for comparing the costs of an action with its benefits. Figure 2-3 shows a schematic diagram of how adaptation actions are analyzed in this study. It is important to note that adaptation strategies can be very broad, encompassing both physical and organizational aspects, and their implementation may depend upon the objectives of various government organizations and available funding. However, given the size of Argentina's transport network and the national scale of this study, this analysis limits the adaptation actions under consideration to those that involve the standardized, uniform physical improvement of infrastructure.

[39] Elco E. Koks and Mark Thissen, "A Multiregional Impact Assessment Model for Disaster Analysis," *Economic Systems Research* 28, no. 4 (2016), 429–449.
[40] Yasuhide Okuyama and Joost R. Santos, "Disaster Impact and Input–Output Analysis," *Economic Systems Research* 26, no. 1 (2014), 1–12.
[41] David Pearce, Giles Atkinson, and Susana Mourato, Cost-Benefit Analysis and the Environment: Recent Developments (Paris: OECD Publishing, 2006).
[42] Jane Olga Ebinger and Nancy Vandycke, Moving Toward Climate-Resilient Transport: The World Bank's Experience from Building Adaptation into Programs (Washington DC: World Bank, 2015).

Figure 2 3: Schematic Representation of Types of Adaptation Costs and Benefits Considered in the Benefit-Cost Ratio Calculations



Source: *Original figure for this publication.*

The analysis of an adaptation action is performed on an annual timescale $t_0,\ldots,t_T$, starting at the time t_0 when the action is implemented and continuing over its planned time horizon T. Assuming r is the rate for discounting over time (as a percentage), and j is the number of years over which the value of the adaptation is evaluated, the effectiveness of a given adaptation option is quantified as follows:

Costs include the initial cost of investment (CI_{t_0}) of implementing the adaptation action at the start year t_0, and the costs of (periodic and routine) investments needed to maintain (CP_{t_j}) the adaptation action over the time horizon. The total net present value of the investment cost of an adaptation action over the project timeline is therefore given by Equation (3).

$$\text{Cost} = CI_{t_0} + \sum_{j=0}^{j=T} \frac{CP_{t_j}}{\left(1+\frac{r}{100}\right)^j} \qquad (3)$$

Benefits include avoided losses both in terms of the direct damage risks (EAD) and the indirect economic risks (EAELs) incurred by the network assets' failure due to flooding. Over time, the EAELs are assumed to grow (or decline) based on annual percentage GDP growth rates GDP_j. The total net present value of the benefits over the project timeline is therefore given by Equation (4).

$$\text{Benefit} = \sum_{j=0}^{j=T} \left(\frac{EAD_{t_j} + \left(1+\frac{GDP_j}{100}\right)^j EAEL_{t_j}}{\left(1+\frac{r}{100}\right)^j} \right) \qquad (4)$$

The benefit-cost ratio (BCR) of adaptation is given as:

$$BCR = \frac{\text{Benefit}}{\text{Cost}} \qquad (5)$$

While this study conducts a network analysis for all modes of transportation, the adaptation planning analysis is limited to road links and bridges on national roads. This is because of the complexity of providing a simplified adaptation strategy for all modes of transportation at a national level. The Roads Cost Knowledge System (ROCKS) database developed by the World Bank[43] was used to estimate the unit cost of various road infrastructure. The database provided information on the costs of different national roads and highway projects implemented in Argentina from 2006 to 2017.

Table 2-1 summarizes the adaptation actions and costs considered in this study based on the ROCKS database. For simplification, three adaptation options – climate-resilient bituminous 2L, climate-resilient concrete 2L, and climate-resilient concrete 4L – were used.

[43] ROCKS Database – https://collaboration.worldbank.org/content/sites/collaboration-for-development/en/groups/world-bank-road-software-tools/files.asset.html/content/usergenerated/asi/cloud/content/sites/collaboration-for-development/en/groups/world-bank-road-software-tools/files/jcr:content/content/primary/library1/rocks_version_2_3zi-wy4Y.html.

Table 2-1: Consolidated Costs of Actions for Building and Maintaining Climate-Resilient Roads in Argentina

Climate-resilient action	Description of action	Number of projects	Cost/km (US$, millions)	Increased cost/km due to climate change (US$, millions)	Percent increase in cost due to climate change	Cost/km of climate-resilient design (US$, millions)	Design road width (m)
Road costs							
Initial investment	Upgrading to climate-resilient bituminous 2L	26	1.11	0.18	16.0%	1.29	7.3
	Upgrading to climate-resilient concrete 2L	4	1.32	0.21	16.0%	1.53	7.3
	Upgrading to climate-resilient concrete 4L	11	3.03	0.55	18.0%	3.58	14.6
Routine maintenance	CREMA: Rehabilitation and routine maintenance	11	0.270	0.024	9.0%	0.294	7.3
Periodic maintenance	Asphalt mix resurfacing / surface treatment resurfacing	9	0.322	0.026	8.0%	0.346	7.3
Reconstruction	Reconstruction	19	0.782	0.122	15.6%	0.904	7.3
Costs for bridges on national roads (derived from road costs)							
Initial investment	Upgrading to climate-resilient bridge	–	–	–	–	3.58*	–
Routine maintenance	CREMA: Rehabilitation and routine maintenance	–	–	–	–	0.294	7.3
Periodic maintenance	Asphalt mix resurfacing / surface treatment resurfacing	–	–	–	–	0.346	7.3
Reconstruction	Reconstruction	–	–	–	–	0.904*	–

Source: *World Bank ROCKS database.*

Note: *CREMA = Rehabilitation and maintenance contract (Contrato de Rehabilitación y Mantenimiento).*
***Cost is in millions of USD per bridge.*

3. Analysis and Results

This section first presents the results of a detailed network flow analysis, followed by hazard exposure results. Next, failure analysis is conducted for an exhaustive set of individual network links, and their impacts are assessed. The risks of network failures are then presented, followed by an analysis of adaptation actions. Throughout, the section presents results for both current and future flooding conditions, illustrating how climate change affects disruption risks.

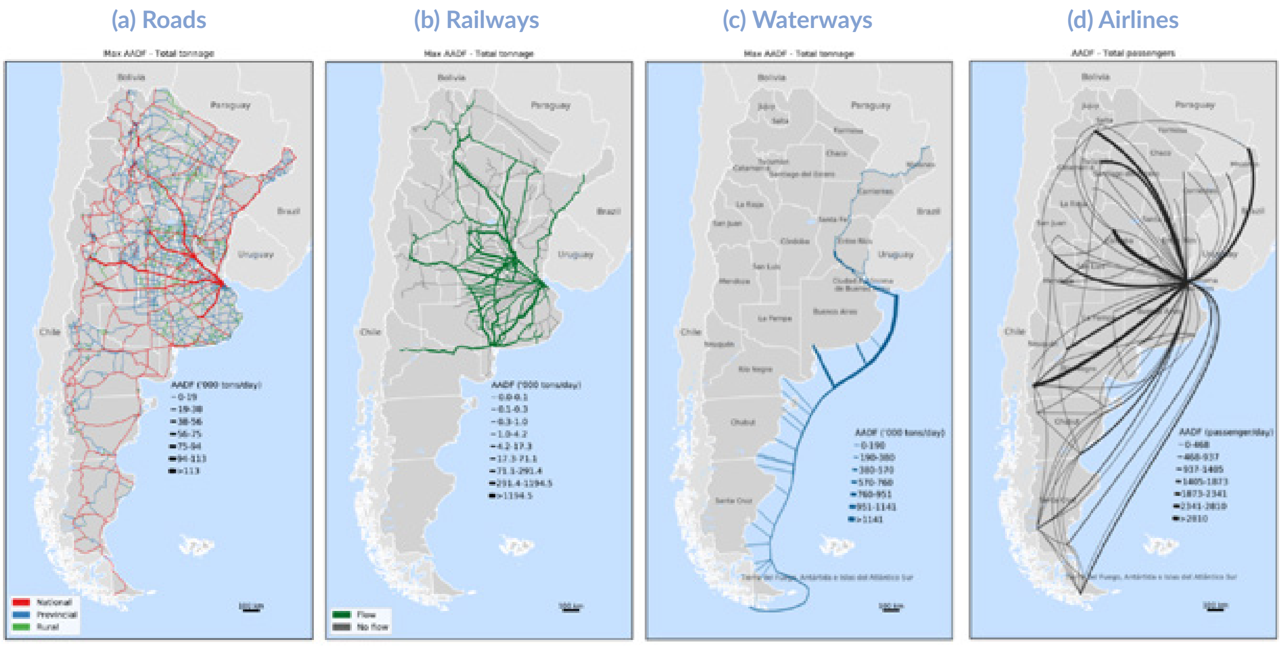
3.1 Network Analysis Results

Figures 3-1(a)-(d) geospatially represent the maximum AADF estimates on Argentina's road, railway, waterway, and airline networks. The highest volumes of daily flow on the roads are along main national routes – A008 around the port of Rosario, and Routes 9, A001, 3, 7, 8, and 1V09 radiating from the city of Buenos Aires.

Figure 3-1(b) clearly illustrates that the full extent of the railway network is not used, with the analysis confirming that only an estimated 19,367 kilometers of the total 38,500-kilometer network (approximately 50 percent) is currently in use. Most of the railway network in Argentina exists as legacy infrastructure, built and used extensively in the early 1900s. Since that time, the network in operation has shrunk. The reliability of railways in Argentina is very poor due to low levels of service and declining speeds.[44] Freight usage has also declined, from about 25 million tons in 2007 to 19 million tons in 2015, although it was once as high as 41 million tons in 1936.[45] These results are in line with the Ministry of Transport's 2016 estimations of the lengths and spatial distribution of operational and non-operational parts of the railway network.

The waterway network flows of Figure 3-1(c) show the highest volumes of flows due to international cargoes from and toward clusters of ports around Bahia Blanca in Buenos Aires, and around Rosario in Santa Fe. These flows only capture bulk commodity tonnage; containerized cargoes were not included in this study because of lack of data. Figure 3-1(d) visualizes annual domestic passenger statistics (assumed to be uniformly distributed throughout the year to produce daily averages). They show that most domestic travel takes place to and from the Buenos Aires airport.

Figure 3-1: Maximum AADF Flows on Argentina's Roads, Railways, Waterways, and Airlines



Source: *Original figure for this publication.*
Note: *AADF for roads, railways, and waterways in thousands of tons per day; airline network AADF in passengers per day.*

[44] Bain and Company, *Restructuración del Sistema Ferroviario de Carga de Argentina* (2018).
[45] Ministry of Transport, *Operación abierta de los trenes de cargas: Nuevo Sistema para bajar los costos logísticos.* (Buenos Aires, 2018). https://tradenews.com.ar/operacion-abierta-de-trenes-de-carga-nuevo-sistema-para-bajar-costos-logisticos/

3.2 Flood Exposure Analysis

Considerable lengths and many point locations of importance to Argentina's transport networks are exposed to extreme fluvial and pluvial flooding (≥50cm flood depth). These lengths are summarized in Table 3-1 for the flood events that are most frequent (5-year return period), those that are most severe (1,000-year return period), and those with middling frequency and severity (100-year return period).

Under future climate outlooks, transport networks will be substantially more exposed to extreme flooding. For example, compared to their current exposure, national roads are expected to be 10 percent and 20 percent more exposed to pluvial floods under medium and high climate-change projections, respectively. Generally, the greatest projected increases in extreme hazard exposures occur at lower return periods, typically in the range of the one in 5-to-100-year events. This range is similar to the design ranges for flood-protection standards of most transport assets – meaning there is a high possibility that transport disruptions might be more frequent in the future.

Table 3-1: Summary Results – Transport Asset Exposures to Fluvial and Pluvial Flooding in Argentina

Return period (years)	Fluvial flooding					Pluvial flooding				
	Baseline	Future median outlook	% change	Future high outlook	% change	Baseline	Future median outlook	% change	Future high outlook	% change
Roads (exposure lengths, km)										
1,000	22,430	23,080	2.90%	24,328	8.46%	23,001	25,065	8.97%	26,973	17.27%
100	12,508	13,202	5.55%	13,955	11.57%	10,202	11,270	10.47%	12,273	20.30%
5	3,161	3,502	10.81%	3,735	18.17%	1,829	2,008	9.78%	2,178	19.09%
Railways (exposure lengths, km)										
1,000	827	842	1.70%	882	6.60%	941	1,032	9.58%	1,118	18.72%
100	430	468	8.86%	479	11.46%	391	432	10.58%	478	22.25%
5	87	97	10.92%	107	22.61%	76	83	9.63%	89	17.44%
National-road bridges (number of bridges exposed)										
1,000	818	817	-0.12%	861	5.26%	1,188	1,206	1.52%	1,261	6.14%
100	595	608	2.18%	657	10.42%	805	865	7.45%	907	12.67%
5	213	238	11.74%	252	18.31%	248	267	7.66%	280	12.90%
Maritime and inland waterway ports (number of ports exposed)										
1,000	41	57	39.02%	48	17.07%	18	22	22.22%	23	27.78%
100	28	30	7.14%	31	10.71%	11	13	18.18%	14	27.27%
5	18	19	5.56%	20	11.11%	2	2	0.00%	2	0.00%
Airports (number of airports exposed)										
1,000	7	8	14.29%	9	28.57%	6	8	33.33%	10	66.67%
100	1	2	100.00%	3	200.00%	2	2	0.00%	2	0.00%
5	1	2	100.00%	3	200.00%	2	2	0.00%	2	0.00%

Note: *Highest changes in each column are highlighted in grey.*

Our analysis of specific ports and airports shows that climate change might induce vulnerabilities at such locations, with increasing frequencies in the future. Table 3-2 lists the five ports and airports with the highest maximum tonnages per day and annual passenger numbers, respectively, along with their hazard and climate outlook–specific extreme flood exposures. These exposures are interpreted in terms of the minimum return period at which the location is exposed to extreme flooding, which implies it will be flooded for subsequent flooding events of greater return periods. For example, the Quequén port is exposed to floods with a 1,000-year or higher return period in the baseline climate outlook, but in the future climate outlooks, it is exposed to floods with a 500-year or higher return period. Similarly, the San Carlos de Bariloche airport in the Río Negro province, with annual passenger flows in excess of 870,000, is 1.5 times more prone to pluvial flooding in the future median climate outlook than in the baseline, moving from a 75-year to a 50-year return period.

Table 3-2: Hazard Exposure of Top Five Waterway Ports and Airports in terms of Minimum Return Periods

Ports

Name	Port cluster	Minimum flow (tons/day)	Maximum flow (tons/day)	Hazard type	Climate scenario	Return period (minimum)
Terminal 6	San Martín, Dto. San Lorenzo	235,532	528,861	Fluvial flooding	Future High	1,000
					Future Med	1,000
Quequén	Quequen	206,258	494,272	Fluvial flooding	Baseline	1,000
					Future High	500
					Future Med	500
San Lorenzo - San Martín - Muelle YPF	San Lorenzo	133,403	339,119	Fluvial flooding	Future Med	1,000
ACA (San Lorenzo)	San Lorenzo	73,495	164,531	Fluvial flooding	Future Med	1,000
Bunge (Dempa y Pampa)	San Martín, Dto. San Lorenzo	124,711	147,261	Fluvial flooding	Baseline	50
					Future High	20
					Future Med	20

Airports

Name	Passenger flow (passengers/year)	Hazard type	Climate scenario	Return period (minimum)
SALTA/GENERAL D. MARTÍN MIGUEL DE GÜEMES	890,432	Pluvial flooding	Future High	1,000
			Future Med	1,000
SAN CARLOS DE BARILOCHE	871,372	Pluvial flooding	Baseline	75
			Future High	50
			Future Med	75
MENDOZA/EL PLUMERILLO	779,814	Pluvial flooding	Baseline	200
			Future High	200
			Future Med	200
COMODORO RIVADAVIA/GRAL. E. MOSCONI	559,526	Pluvial flooding	Future High	1,000
JUJUY/GOBERNADOR GUZMÁN	213,452	Pluvial flooding	Future High	500
			Future Med	1,000

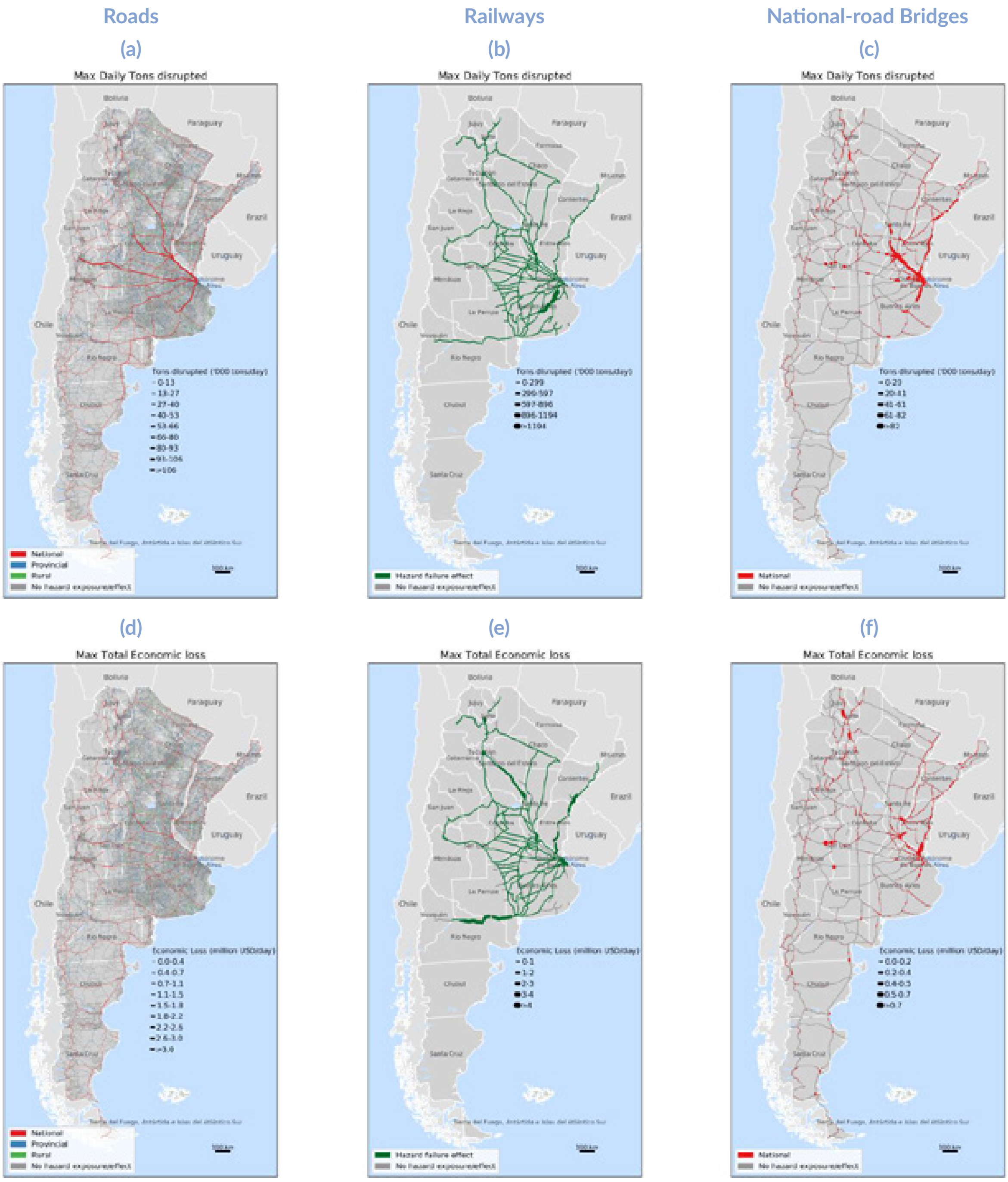
3.3 Criticality Analysis

The criticality analysis shows that all the major freight corridors on national roads radiating from Buenos Aires are affected by flooding, with the highest disruptions in flow estimated at approximately 100,000 tons per day. Almost all railway freight routes are expected to be affected by flooding, and in the worst-case scenario, potential disruptions could be as high as 1.2 million tons per day. Assuming that flood hazards cause individual road and railway links to fail, the resulting economic impacts for road, railway, and bridge failures could reach US$3.0 million per day for roads, US$4.2 million per day for railways, and US$700,000 per day for bridges. Figure 3-2 highlights the maximum daily tonnages on roads, railways, and bridges that could be disrupted due to exposure to at least one extreme flooding event, and the maximum economic impacts that could result.

The highest disruptions to traffic flow do not necessarily result in the highest economic impacts. If the network has rerouting options, then much of the disrupted traffic flow can be rerouted. Although this lengthens journeys, the overall economic loss could be relatively low if alternative routes do not require very long detours.

The greatest losses due to road failures are macroeconomic losses resulting from the very few cases of flow isolation. This situation is more common in the railway network, which has relatively fewer rerouting options. Failures along sections of lines in Entre Ríos, Corrientes Salta, and Río Negro provinces would result in highest economic impacts. Table 3-3 ranks the top five roads, railways, and national-road bridges by the maximum economic impacts their failure could incur.

Figure 3-2: Maps of Maximum Potential Tonnage Disruptions and Estimated Economic Impacts for Single-Link Failures due to Extreme Flooding



Source: *Original figure for this publication.*

Table 3-3: Top Five Roads, Railways, and National-Road Bridges, Ranked by Maximum Daily Economic Impacts

Roads

Road name	Road type	Province name	Tons disrupted (thousands of tons/day)		Rerouting losses (US$, millions/day)		Macroeconomic losses (US$, millions/day)		Total economic impacts (US$, millions/day)	
			Min	Max	Min	Max	Min	Max	Min	Max
14 – 49	Provincial	Buenos Aires	46.6	49.7	0.0	0.0	2.7	3.0	2.7	3.0
4	Provincial	Buenos Aires	88.5	105.6	0.5	0.8	0.0	0.0	0.5	0.8
0003	National	Río Negro	12.7	14.2	0.7	0.8	0.0	0.0	0.7	0.8
18	Provincial	Santa Fe	28.5	28.5	0.0	0.0	0.7	0.7	0.7	0.7
0007	National	Mendoza San Luis	44.2	44.9	0.6	0.7	0.0	0.0	0.6	0.7

Railways

Operator	Line	Province name	Tons disrupted (thousands of tons/day)		Rerouting losses (US$, millions/day)		Macroeconomic losses (US$, millions/day)		Total economic impacts (US$, millions/day)	
			Min	Max	Min	Max	Min	Max	Min	Max
SOFSE	Roca	Buenos Aires	3.5	48.8	0.0	0.0	1.1	4.2	1.1	4.2
Trenes Argentinos Cargas	Belgrano	Santa Fe	132.9	275.9	1.3	4.1	0.0	0.0	1.3	4.1
SOFSE	Mitre	CABA	12.7	22.4	0.0	0.0	3.2	3.9	3.2	3.9
NCA	Mitre	Santa Fe	102.8	184.3	1.9	3.8	0.0	0.0	1.9	3.8
Trenes Argentinos Cargas	Belgrano	Tucumán	2.5	8.4	0.0	0.0	1.5	3.2	1.5	3.2
	Urquiza	Entre Ríos	8.1	19.1	0.0	0.0	0.0	2.7	0.0	2.7
		Corrientes	7.2	18.8	0.0	0.0	0.0	2.7	0.0	2.7
			6.5	17.3	0.0	0.0	2.1	2.7	2.1	2.7

National-road bridges

Road name	Bridge type	Province name	Tons disrupted (thousands of tons/day)		Rerouting losses (US$, millions/day)		Macroeconomic losses (US$, millions/day)		Total economic impacts (US$, millions/day)	
			Min	Max	Min	Max	Min	Max	Min	Max
0007	Large over waterway	Mendoza	44.2	44.9	0.6	0.7	0.0	0.0	0.6	0.7
0007, 15		San Luis	44.5	44.9	0.6	0.7	0.0	0.0	0.6	0.7
		Entre Ríos	21.2	21.6	0.6	0.6	0.0	0.0	0.6	0.6
0012		Buenos Aires	21.2	21.6	0.6	0.6	0.0	0.0	0.6	0.6
0143, 0188		San Luis	24.8	25.3	0.6	0.6	0.0	0.0	0.6	0.6

Note: *Highest value in each column is highlighted in grey.*

3.4 Risk Analysis

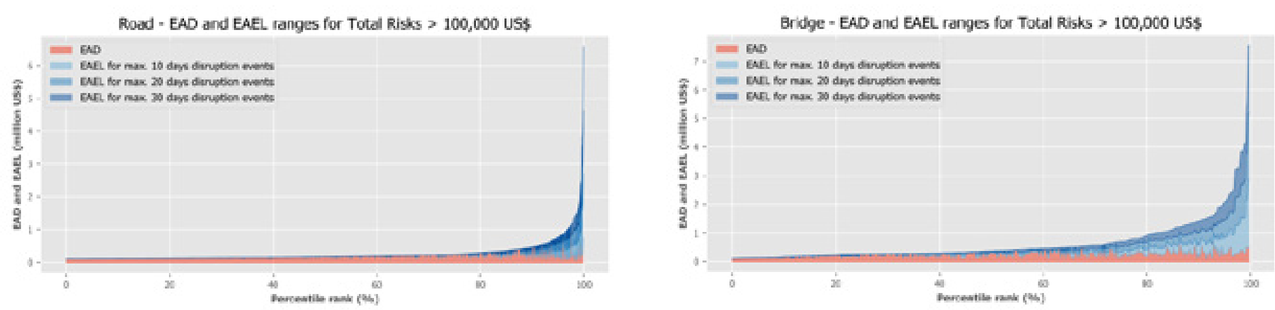
The flooding of transport network links in Argentina creates significant systemic risks. Under the baseline climate outlooks, and assuming that disruptions at network locations last a maximum of 10 days, road failures due to flooding can result in direct damages (EAD) and indirect losses (EAEL) as high as US$3.8 million every year; for bridges on national roads, damages and losses are estimated at US$2.8 million. These damages and losses can grow to over US$6.5 million for roads and US$7.5 million for bridges if the maximum disruption duration is raised to 30 days. For railway failures causing 10-day disruptions at most, the indirect economic risks alone are estimated to be as high as US$11 million.

Based on the daily economic impacts of network asset failures (calculated in the previous section), the EAEL from flooding were estimated for roads, railways, and national-road bridges. EAEL here were estimated by assuming duration of flooding disruptions of maximum t days (t = 10, 20, 30, …), materialized in the most severe cases when more than 500 meters of individual roads and railways links were flooded; for bridges, the length threshold was much smaller, at 5 meters. Figure 3-3 demonstrates that the indirect economic risks (of freight disruptions) become dominant as the duration of the disruption increases.

Figure 3-3: EADs and EAELs for Roads and Bridges, Ranked by their Total Damages and Losses above US$100,000

(a) Roads

(b) National-road Bridges



Source: *Original figure for this publication.*

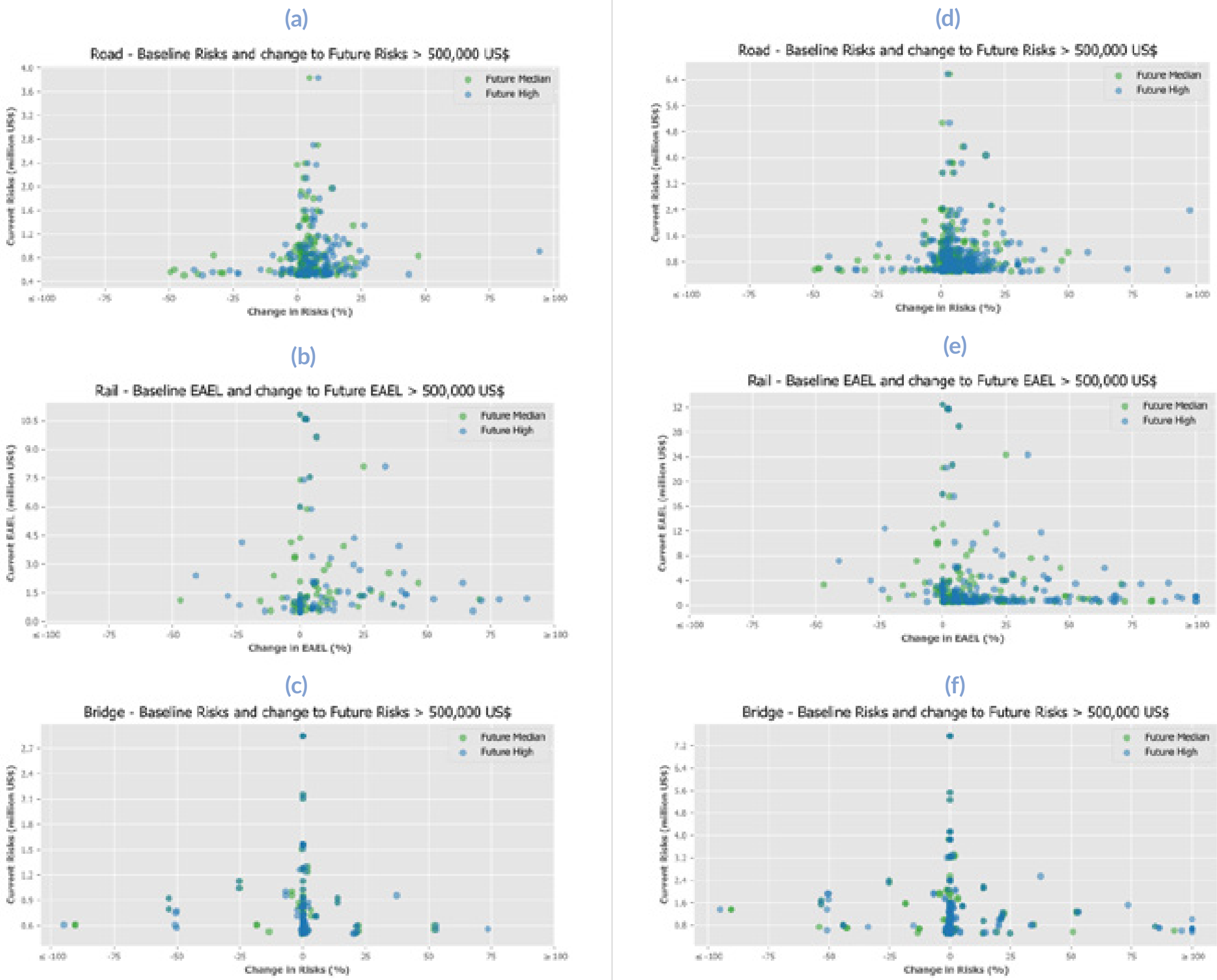
Widespread increases in extreme-hazard risks across transport networks in Argentina can be expected in a changing climate. Figure 3-4 shows how the failure risks of the individual roads, railways, and national-road bridges with some of the highest damage and loss values (more than US$500,000) under the baseline climate outlook change under future climate outlooks. The distributions are skewed toward increasing risks under future climate outlooks. While the highest economic risks due to asset failures in all these networks do not significantly change, there are several assets for which the damages and losses are expected to increase by almost 100 percent. This means that current economic risks of at least US$500,000 could rise to over US$1 million in the future.

As the maximum disruption duration increases from 10 to 30 days, the distribution shifts further toward greater increases in risks. Figure 3-4(d) shows a road link for which baseline damages and losses of US$2.4 million increase by almost 100 percent to reach around US$4.8 million in the future. Several baseline risks for railways – Figures 3-4(b) and (e) – are already over US$1.5 million for 10-day disruptions and US$3 million for 30-day disruptions, so an increase of about 50 percent for these locations under future climate outlooks becomes significant.

Table 3-4 ranks roads, railways, and national-road bridges by the maximum damages and losses their failure would incur in the baseline and future climate outlooks (for disruptions of 10 days or fewer). A comparison with the table 3-3 results reveals that the locations with the highest potential damages and losses are not necessarily those with the highest daily economic impacts, though that might become the case if the duration of disruptions begins to increase.

Figure 3-4: Baseline Economic Risks (Damages and Losses) and Changes in Risks under Future Climate Outlooks for Road, Railway, and Bridge Failures

Disruptions of 10 Days or Fewer | Disruptions of 30 Days or Fewer



Source: *Original figure for this publication.*

Photo Credit: *istock.com/Andrés Ruffo*

Table 3-4: Top Roads, Railways, and Bridges by Maximum Damages and Losses for Disruptions of 10 Days of Fewer

Roads – Total Damages and Losses ≥ US$2 million							
Road name	Road type	Province name	Baseline	Future med	% change	Future high	% change
0051	National	Salta	3.8	4.0	4.8%	4.2	8.2%
0012	National	Buenos Aires Entre Ríos	2.7	2.9	8.0%	2.9	6.4%
4	Provincial	Catamarca	2.4	2.5	3.1%	2.5	4.1%
0040	National	Chubut Río Negro	2.4	2.4	0.0%	2.5	7.5%
0060	National	La Rioja Catamarca	2.1	2.2	2.7%	2.2	3.5%
0168, 168	National	Santa Fe	2.0	2.2	13.4%	2.2	13.8%
0143, 0188	National	San Luis Mendoza	1.9	2.0	1.5%	2.0	4.5%
0007	National	Mendoza	1.8	1.9	6.4%	2.0	8.6%

Railways – Total EAEL ≥ US$6 million							
Operator	Line	Province name	Baseline	Future med	% change	Future high	% change
Trenes Argentinos Cargas	FFCC Urquiza	Entre Ríos	10.8	10.8	0.0%	10.8	0.0%
		Corrientes	10.6	10.8	2.0%	10.8	2.2%
Ferrosur	FFCC Roca	Buenos Aires	9.6	10.3	6.6%	10.3	6.6%
Trenes Argentinos Cargas	FFCC Urquiza	Corrientes	8.1	10.1	25.0%	10.8	33.6%
Ferrosur	FFCC Roca	Río Negro	7.6	7.8	3.8%	7.8	3.8%
Trenes Argentinos Cargas	FFCC Urquiza	Corrientes	7.4	7.4	0.1%	7.5	1.5%
	FFCC Belgrano	Jujuy	5.9	6.0	2.7%	6.1	4.5%
	FFCC Urquiza	Entre Ríos Buenos Aires	6.0	6.0	0.0%	6.0	0.0%

National-Road Bridges – Total Risks ≥ US$1 million							
Road name	Structure type	Province name	Baseline	Future med	% change	Future high	% change
0012	MAYOR SOBRE VIA DE AGUA	Buenos Aires	2.8	2.8	0.0%	2.8	0.0%
0009, 0034		Salta	2.2	2.2	0.0%	2.2	0.0%
0009, 1		Jujuy	2.1	2.1	0.0%	2.1	0.0%
0012		Buenos Aires	1.6	1.6	0.0%	1.6	0.0%
0014, 16		Entre Ríos	1.6	1.6	0.0%	1.6	0.0%
0012		Buenos Aires	1.5	1.5	-0.5%	1.5	0.0%
0168, 168		Santa Fe	1.3	1.3	2.0%	1.3	1.0%
0003, 55		Santa Cruz	1.3	1.3	-0.1%	1.2	-1.4%
0168, 168		Santa Fe	1.2	1.3	2.0%	1.3	1.0%
0009, 0034		Salta	1.1	1.1	0.0%	1.1	0.0%
			1.0	1.0	0.0%	1.0	0.0%
0007, 27B		San Luis	0.9	1.1	13.8%	1.1	13.8%
0143, 0188		San Luis	1.0	0.0	0.0%	1.3	37.3%

3.5 Adaptation Analysis

This section evaluates the benefit-cost ratios (BCRs) of adaptation options across all climate outlooks for each disrupted road link and national-road bridge. The analysis examined the overall sensitivities of the adaptation actions' effectiveness over changing disruption durations. GDP growth projections of +2.8 percent was assumed over the lifetime of the investment (assumed to be 35 years from 2016 to 2050).

The BCR of an adaptation action is estimated for all failed transport links, following which all BCR estimates can be ranked. The links with the highest BCR values (≥1) should be prioritized for investments. They offer the highest justification for the cost, since investments in these assets will be the most beneficial in maintaining network service reliability. The BCRs across all assets and all adaptation actions could therefore be compared, selecting those with the highest values selected for investment. When considering climate change, the effectiveness of the same set of adaptation actions can be further compared between current hazards and future climate change–driven hazards. Tables 3-5 and 3-6 show detailed results of adaptation actions, costs, benefits for 20 specific roads and bridges on national roads ranked in descending order of BCR values, considering maximum 10-day disruptions.

The investment needs – both initial investments and ongoing periodic and routine maintenance needs – for upgrading roads and bridges to climate-resilient standards increase by a factor of 6.2 and 1.8 respectively as the disruption durations increase threefold. Figure 3-5 shows the scale of investment needs as the duration of disruptions increases. The figure shows the favorable investments (those with a BCR greater than 1), comparing their cumulative benefits (avoided risks) with their cumulative initial and cumulative total investment needs, for varying durations of disruption.

Photo Credit: Istock.com/Andrés Ruffo

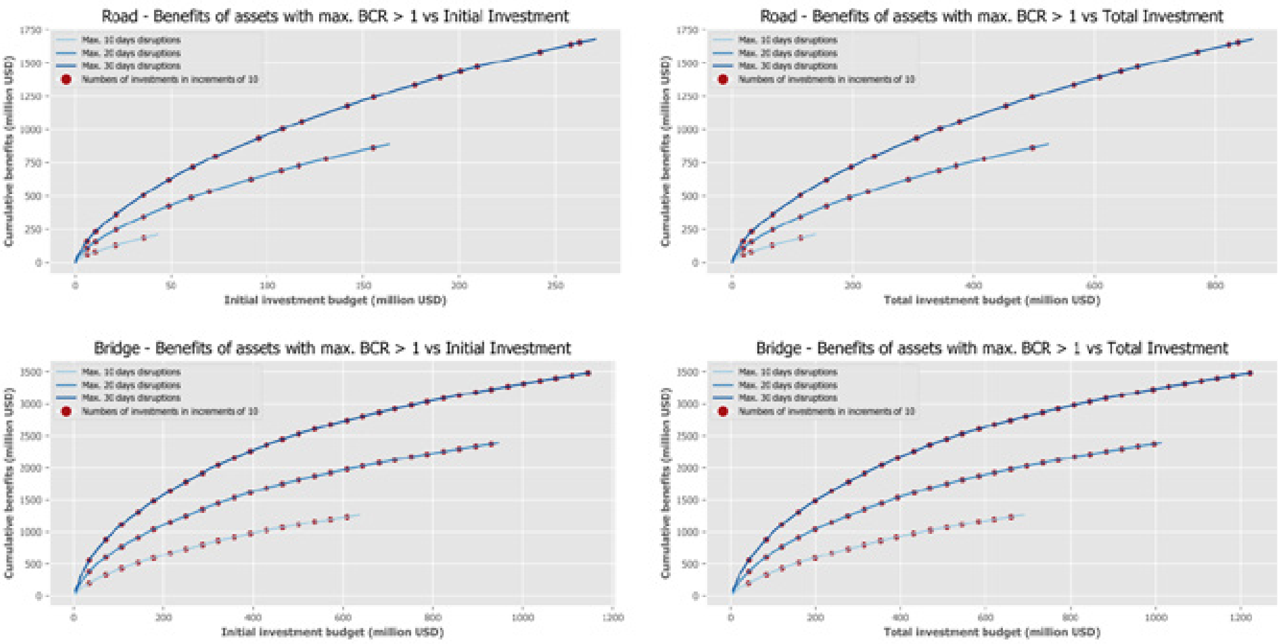
Table 3-5: List of Top Twenty Roads Ranked in Descending Order of BCR Values of Adaptation for Maximum 10 Days disruptions

Road name	Province name	Existing Surface	Width (m)	Adaptation actions (Upgrading to climate resilient)	Max exposure length (m)	NPVs in US$				BCR	
						Initial investments	Total investments over 35 years	Benefits over 35 years			
								Min	Max	Min	Max
0009, 0034	Salta	Asphalt	10.5	Bituminous 3L	34.6	64,147	209,515	1,422,156	1,510,614	6.8	7.2
		Asphalt	10.5	Bituminous 3L	142.0	263,171	859,555	5,257,161	5,584,158	6.1	6.5
		Asphalt	10.5	Bituminous 3L	165.2	306,268	1,000,316	5,424,222	5,761,611	5.4	5.8
		Asphalt	10.5	Bituminous 3L	115.1	213,318	696,728	2,407,900	2,559,682	3.5	3.7
		Asphalt	10.5	Bituminous 3L	92.3	171,150	559,001	1,897,206	2,015,214	3.4	3.6
		Asphalt	10.5	Bituminous 3L	180.1	333,866	1,090,455	3,194,043	3,395,379	2.9	3.1
0007, 15	San Luis	Concrete	14.6	Concrete 4L	706.5	2,527,617	6,654,654	19,224,925	19,327,955	2.9	2.9
0009, 0034	Salta	Asphalt	10.5	Bituminous 3L	126.1	233,811	763,663	2,001,790	2,126,303	2.6	2.8
168	Entre Ríos	Asphalt	15	Bituminous > 4L	748.7	1,982,711	6,475,832	12,684,998	14,906,499	2.0	2.3
0009, 0034	Salta	Asphalt	10.5	Bituminous 3L	140.1	259,704	848,232	1,783,670	1,896,103	2.1	2.2
1*	Catamarca	Consolidated	7.3	Bituminous 2L	289.0	372,511	1,216,678	2,474,049	2,636,028	2.0	2.2
0009, 0034	Salta	Asphalt	10.5	Bituminous 3L	104.2	193,203	631,031	1,231,544	1,366,127	2.0	2.2
1*	Catamarca	Paved	7.3	Bituminous 2L	141.2	181,928	594,205	1,199,242	1,199,242	2.0	2.0
7*	Neuquén	Dirt road	7.3	Bituminous 2L	766.6	988,025	3,227,040	6,281,632	6,281,632	1.9	1.9
1*	Catamarca	Paved	7.3	Bituminous 2L	223.0	287,390	938,660	1,771,736	1,771,736	1.9	1.9
0009, 0034	Salta	Asphalt	10.5	Bituminous 3L	91.2	169,114	552,352	953,899	1,014,028	1.7	1.8
0007	San Luis	Concrete	7.3	Concrete 2L	890.6	1,364,122	3,965,365	6,455,580	6,981,157	1.6	1.8
0009, 0034	Salta	Asphalt	10.5	Bituminous 3L	111.3	206,319	673,869	1,103,965	1,172,632	1.6	1.7
307*	Tucumán	Paved	7.3	Bituminous 2L	109.8	141,522	462,233	666,874	781,237	1.4	1.7
0009, 0034	Salta	Asphalt	10.5	Bituminous 3L	119.2	220,895	721,477	1,061,507	1,177,509	1.5	1.6
Total						**10,480,793**	**32,140,861**	**78,498,098**	**83,464,847**		

Table 3-6: List of Top Twenty Bridges in National Roads Ranked in Descending Order of BCR Values of Adaptation for maximum 10-days disruptions

Road name	Structure type	Province name	Width (m)	Max exposure length (m)	NPVs in US$				BCR	
					Initial investment	Total investment over 35 years	Benefits over 35 years			
							Min	Max	Min	Max
9	Major over waterway	Salta	9.4	30.0	3,577,607	3,690,427	22,417,670	23,695,872	6.1	6.4
12		Entre Ríos	10.1	344.1		4,968,037	29,915,693	31,617,187	6.0	6.4
9		Jujuy	10.8	59.6		3,834,969	20,816,314	23,022,719	5.4	6.0
12		Entre Ríos	10.1	564.1		5,856,937	29,915,693	31,617,187	5.1	5.4
		Buenos Aires	13.4	8.0		3,620,441	15,700,524	16,551,271	4.3	4.6
14		Entre Ríos	8.4	209.6		4,282,180	16,313,116	16,968,534	3.8	4.0
			8.3	209.6		4,273,793	16,268,106	16,923,523	3.8	4.0
188		San Luis	9.3	61.7		3,807,105	14,479,468	14,633,270	3.8	3.8
3		Santa Cruz	9.9	47.9		3,767,322	12,533,489	13,867,470	3.3	3.7
12		Buenos Aires	10.1	284.4		4,726,987	16,385,983	17,317,957	3.5	3.7
			10.1	284.4		4,727,026	16,385,983	17,317,957	3.5	3.7
168		Santa Fe	12	83.0		3,976,098	12,061,028	14,024,970	3.0	3.5
			11.8	83.0		3,969,457	12,016,017	13,979,960	3.0	3.5
			11.7	169.8		4,372,350	12,475,663	14,518,558	2.9	3.3
			9.4			4,216,118	11,937,230	13,980,125	2.8	3.3
34		Salta	10.3	66.5		3,851,758	11,334,370	11,790,981	2.9	3.1
14		Entre Ríos	10	107.7		4,008,709	10,965,540	11,830,937	2.7	3.0
7		San Luis	9.4	36.3		3,714,161	9,591,215	10,871,484	2.6	2.9
14		Entre Ríos	8.3	81.8		3,849,281	10,200,357	11,065,754	2.6	2.9
7		San Luis	11.3	90.0		3,984,383	10,792,177	11,322,715	2.7	2.8
Total					67,974,538	83,497,538	312,505,635	336,918,429		

Figure 3-5: Cumulative Benefits vs. Initial Investment and Total Investment Budgets for Roads and Bridges



Source: Original figure for this publication. *Note:* Assumes a GDP growth rate of +2.8% for Argentina.

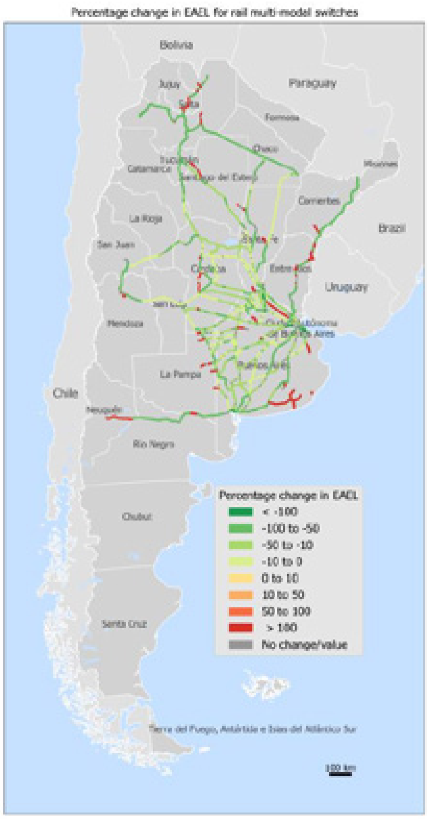
Finally, given the high economic cost of flow interruptions in some railway links, multi-modal transport options were examined. Roads and waterway networks were explored as viable alternatives to railways. For sections of railway routes in Entre Ríos, Corrientes, Buenos Aires, La Pampa, and Río Negro provinces, for which the risks were in excess of US$6 million, the damages and losses could be reduced by about 99 percent by switching to road transports.

Figure 3-6(a) shows the spatial distributions of the EAELs for a maximum-10-day disruption scenario; the maximum economic risks of railway failure are reduced from US$11 million to US$2.4 million by switching to road transport. Figure 3-6(b) shows that, for most routes where multi-modal options exist, damages and losses are at least 50 percent lower than routes for which there are no multi-modal alternatives.

Figure 3-6: The Impact of Multi-Modal Adaptation Options on Expected Damages and Losses due to Extreme Flooding

(a) Maximum EAELs with multi-modal adaptation options

(b) Changes with respect to a scenario without multi-modal options



(c) Comparison of EAELs for rail locations (with the highest EAELs for individual railway network link failure) with EAELs when multi-modal options on roads and waterways are available

Photo Credit: *istock.com/Grafissimo*

4. Conclusion

This study contributes to growing literature and a range of methodologies for integrating climate change projections into transport risk analysis and investment planning. It makes the first attempt to aggregate all the transport infrastructure and logistics data of Argentina into one platform, and to use a system-of-systems modelling approach to conduct vulnerability, risk, and adaptation assessments at a national scale in a country with vast networks. The study offers an organized dataset and an adaptable model for use and continued improvement by relevant agencies such as the National Roads Directorate (Dirección Nacional de Vialidad; DNV) and the Ministry of Transport (MoT) of Argentina, and provides these agencies with a better understanding of the impact of climate change on the transport network.

The study's engagement with government agencies and universities has also initiated an interest in thinking critically about how to account for climate change in transport planning. Currently, DNV and MoT are not considering climate change impacts in their planning process in a systematic way. This study is a first step toward integrating climatic risks into long-term planning.

This shift will be critical to building the resilience of Argentina's transport networks and minimizing damages and losses. The analysis conducted under this study demonstrates that: (i) major freight transport routes on Argentina's roads, national-road bridges, and railway networks face disruptions due to extreme flooding and climate change; and (ii) economic impacts of disruptions can become quite significant, depending upon the network rerouting capabilities and the duration of disruption. To address these risks, DNV and MoT need to be increasingly prepared for extreme flooding events, which will become more severe due to climate change. By incorporating climate change risks into all long-term planning processes at a national scale, DNV and MoT can gain a better understanding of the impact. The next crucial step is to go beyond quantifying direct damage and begin to account for macroeconomic losses from climate-related disruptions. Finally, DNV and MoT must develop their internal capacity to undertake transport risk assessment to inform designs, construction, and maintenance approaches.

While building resilient infrastructure might incur a marginal additional cost, this study clearly demonstrates that, for many assets, the benefits of avoiding flood damages and disruption losses outweigh the investment costs. Given that disruptions and macroeconomic losses make up significant proportion of the total losses, DNV and MoT should prioritize maintaining or upgrading roads that will lead to significant economic losses if disrupted. Furthermore, DNV and MoT should ensure that these are not one-off analyses and investments. Availability of data, modeling approaches, and computational capabilities continue to improve every year. DNV and MoT should continuously assess climate risks and the robustness of adaptations across a range of climate outlooks, and proactively invest in building climate-resilient roads and bridges. All future analysis should also consider previous adaptation measures so that the benefits of adaptation investments are accounted for continuously.

While this study provides several key insights, it is important to acknowledge the limitations of the analysis and potential improvements for the future:

- The FATHOM flood maps used in the analysis have coarse resolution. As the resolution of global flood models continues to improve, it will be critical to update the flood hazard input data. For selected high-impact areas, the use of a localized flood hazard model might also be warranted.
- The climate change outlooks are created from Global Climate Models (GCMs) downscaled for Argentina. The analysis could be improved by replacing or complementing these models with Regional Climate Models (RCMs).
- Given the size of the network and the available resolution of the data, various assumptions and oversimplifications have been used to manage the complexity of the task. For example, the assumptions of uniform +6 percent and +12 percent rainfall changes across the country are an oversimplification and could be improved based on realistic regional variations.
- The model accounted for variation in road quality, but only for national roads and bridges for which data was

provided by Argentina's national roads agency. The elevation of the roads was also not readily available. For national roads that are built to high standards, the model most likely overpredicts the flooding impacts. Incorporating road heights and design standards could significantly improve the accuracy of the results.

- Several data-quality challenges were tackled during this study. Based on lessons learned from this analysis, it is important to continue to improve the data quality of: (i) network topology and attributes information; (ii) transport OD datasets at the network level; (iii) macroeconomic datasets; and (iv) an adaptation actions database for all transport assets, including other types of adaptation options (e.g., grey and green infrastructure interventions) most relevant to Argentina. It is also important to have a consistent standard of collecting and storing data across various government agencies.

Despite the data challenges and the broad scale of the analysis, these findings and accompanying recommendations provide crucial, actionable conclusions. This study builds the foundation upon which DNV and MoT can begin incorporating climate change risk into their planning processes.

Photo Credit: *Ministry of Transport*

Appendix – Review on Systems-of-Systems Approaches for Infrastructure Risk Analysis and Recent Hazards and Impacts in Argentina

System of Systems Approach: The system-of-systems approach proposed in this report adds to a rich literature of large-scale integrated modelling frameworks adopted for local and global scale analysis of infrastructures. Extensive reviews of infrastructure modelling approaches for risk and resilience analysis are provided by Ouyang(2014)[46], Hosseini et al. (2016)[47], and Saidi et al. (2018)[48]. Network science-based modelling approaches have gained wide popularity over the years[49], because they require less data than complexity science-based models[50] and agent-based models[51] while also representing infrastructure connectivity at sufficient detail. With the availability of geospatial network data on point and line assets several real-world studies of road and rail networks have been possible. Some of these include analysis of Swedish rail networks[52], Vietnam transport networks[53], UK rail network[54], European road networks[55], and global road and rail networks.[56]

Using network data, different kinds of criticality analysis approaches have been adopted. Some studies used network centrality metrics, which quantify the most critical nodes and edges based only on the topological characteristics of networks[57,58]. A better understanding of network criticalities is possible by quantifying flows on the physical networks and assessing how those flows are disrupted. Several studies have applied this approach on roads[59] and rails[60]. Further assessments of wider network criticalities have been quantified by combining macroeconomic loss estimation models with transport networks[61], which this study employs. At the national scale, such analysis is useful for identifying the importance of key transport corridors that are critical for maintaining connectivity of prominent supply chain corridors for the country.

There are very few large-scale climate vulnerability and risk assessments of transport networks that combine hazards with network criticality measures. A global scale multi-hazard risk assessment of road and rail network was done by Koks et al.[48], but it only quantified risks due to the direct damages to physical assets intersecting hazards. The indirect climate risk assessments of transport networks, which are caused by flow disruptions and wider economic impacts, have only been done in few studies. Previous studies in Vietnam[45] and Tanzania[17], which quantified macroeconomic impacts of transport disruption are similar to the study in Argentina.

Recent Hazards and Impacts: To better understand the scale of the climate risk impacts, and to ensure all relevant data were used, this study included a review of existing hazards (meteorological, hydrological, and climatological) and vulnerabilities in Argentina. Historically, Argentina has been subject to various convective and local storms as well as thunderstorms,

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[60] Espinet Alegre, X., Rozenberg, J., Rao, K. S., & Ogita, S. (2018). "Piloting the use of network analysis and decision-making under uncertainty in transport operations: preparation and appraisal of a rural roads project in Mozambique under changing flood risk and other deep uncertainties." *World Bank Policy Research Working Paper*, (8490).
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particularly in the north and west of the country. For example, hailstorms impacted multiple cities in the province of Córdoba in October 2017.[62] Similarly, one of the world's most intense deep convective storms occurs regularly near the Sierras de Córdoba, peaking during the austral summer months.[63]

Hydrological hazards such as flooding represent over 60 percent of natural disasters in any given year.[64] According to Munich Re's NatCatSERVICE[65] statistics on the impact of natural hazards on Argentina between 2000 and 2017, hydrometeorological hazards are the most frequently occurring, and as a result have caused substantial economic and human losses. For example, floods in 2013 and 2016 caused losses of approximately US$3 billion, and in 2013 alone, more than 50 people died because of hydrological hazards.

A review of the impact of flood events on roads shows extensive and widespread damages. Table A-1 lists examples of events in Argentina from 2015 to 2018 and summarizes their impacts.

Photo Credit: *istock.com/Andrés Ruffo*

[62] Jason Samenow, "Two Argentine towns were bombarded with hail storms, one like a cannon, the other like a shotgun," Capital Weather Gang, *Washington Post*, October 31, 2017, https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/10/31/five-feet-of-ice-falls-in-15-minutes-unbelievable-hail-storms-pummel-argentina/.

[63] Jake P. Mulholland, Stephen W. Nesbitt, Robert J. Trapp, Kristen L. Rasmussen, and Paola V. Salio, "Convective Storm Life Cycle and Environments near the Sierras de Córdoba, Argentina," *Monthly Weather Review* 146, no. 8 (August 2018): 2541–2557, doi:10.1175/MWR-D-18-0081.1.

[64] World Bank, Argentina – *Análisis Ambiental de País*.

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Table A-1: Examples of Major Natural Hazards Recorded in Argentina, 2015–2018

Timeline	Hazard type	Regions affected	Transport failure incidents	Other impacts
29 April, 2018	Storm	Buenos Aires	Air transport disrupted in Ezeiza Airport due to flooding in the airport facilities	Electricity and telecommunications services disrupted; urban floods
January – February, 2018	Fluvial flooding	Salta Province and La Pampa	Roads damaged and access to settlements cut off	3 dead, 17,000 people affected, 2,500 evacuated; 800,000 hectares affected
February 2017	Fluvial flooding and flash flooding	Buenos Aires	Roads damaged and closed	3 dead, hundreds displaced; schools closed; crops of cocoa, palm oil, and rice in Mbeya adversely affected
January 5 – 20, 2017	Flash flooding	Corrientes, Córdoba, Santiago del Estero, Entre Ríos	Roads cut off and road network deteriorated	4 million soy hectares flooded (1.5 critically); 1.8 million liters of milk lost per day
18 February, 2017	Fluvial flooding	Santa Fe Province	Pavement damaged and main roads closed	
4 April, 2017	Torrential rain and fluvial flooding	Chubut, Buenos Aires, La Rioja, Entre Ríos, La Pampa, Chaco, and Tucumán Provinces	Roads flooded and closed; many remained closed until November	8,000 people displaced; 2,000 people lost their homes
29 April, 2017	Torrential rain	La Plata Province	Roads affected and bridge collapsed	
11 September, 2017	Torrential rain and fluvial flooding	Buenos Aires and La Pampa Province	Roads closed and cut off	Up to 10 million hectares affected – agricultural emergency declared
November, 2017	Torrential rain, hailstorms, high winds	Buenos Aires	Roads damaged	Agricultural production lost, as crops could not be transported
10-15 January, 2016	Torrential rain and Fluvial flooding	Corrientes, Chaco, Formosa, Santa Fe, Misiones, and Entre Ríos Provinces	Roads damaged and cut off	Thousands of people displaced; agricultural sector impacted, with about US$1 billion
9 February, 2016	Flash flooding and storm surge	Salta and Santa Fe Province	Roads closed	3 people died as the river levels increased, 1,700 displaced; crops destroyed
15-28 April, 2016	Storms and fluvial flooding	Entre Ríos, Chaco, Santa Fe, Corrientes and Córdoba	Roads damaged and closed; several landslides	250 families affected
25 October, 2016	Flash flooding	Neuquen Province	Roads damaged and closed	1 dead, hundreds displaced
25-26 December, 2016	Torrential rain and fluvial flooding	Entre Ríos, Corrientes, Formosa, Chaco, and Santa Fe	Roads destroyed and closed	3 dead, 75,000 displaced; crops destroyed

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