Vietnam Transport Knowledge Series

Supported by AUSTRALIA–WORLD BANK GROUP STRATEGIC PARTNERSHIP IN VIETNAM and NDC PARTNERSHIP SUPPORT FACILITY

Addressing Climate Change in Transport

Volume 2: Pathway to Resilient Transport

Jung Eun Oh, Xavier Espinet Alegre, Raghav Pant, Elco E. Koks, Tom Russell, Roald Schoenmakers, and Jim W. Hall

FINAL REPORT

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1818 H Street NW, Washington DC 20433

Telephone: 202-473-1000; Internet: www.worldbank.org

Cover photo: A motorcycle crosses over a flooded road in rural Vietnam. Hanoi Photography – stock.adobe.com.

Contents

Figures and Tables

FIGURES

TABLES

Foreword

Climate change is set to have profound effects on Vietnam's development. With nearly 60 percent of its land area and 70 percent of population at risk of multiple natural hazards, Vietnam globally is among the most vulnerable countries to both chronic and extreme events. Over the past 25 years, extreme weather events have resulted in 0.4 to 1.7 percent of GDP loss, which climate change is predicted to steeply rise by 2050. At the same time, as Vietnam's economy grows, the country is becoming a significant emitter of greenhouse gases. While Vietnam's absolute volume of emissions is still small compared to that of larger and richer countries, emissions are growing rapidly and disproportionate to its economy size. Vietnam is the 13th most carbon intensive economy in the world, measured in terms of emissions per GDP, and 4th among the low- and middle-income countries in East Asia.

The transport sector plays a critical role in these recent trends. A steep rise in income and economic growth has led to rapid motorization: The country of around 96 million people is also home to nearly 40 million vehicles, including 35 million motorbikes. While car ownership is still relatively low in Vietnam, as income rises cars are quickly replacing motorbikes, especially in the largest cities. Public transport modal share remains persistently low, partly due to the low level of network development and partly to the convenience and affordability of two-wheeler-based mobility. Thanks to its economic success and rapid integration with the international trade, cargo transportation in Vietnam has seen remarkable growth in the recent years. Vietnam's long coastal lines and extensive inland waterway network have been extensively used for the movement of goods; however, their modal share vis-à-vis road transport is declining.

Vietnam's transport network, which has seen an impressive expansion over the past two decades, is increasingly vulnerable to the intensifying climate hazards. Today, Vietnam's road network extends to over 400,000 km, much of which was not built to withstand extreme hazard scenarios, which are expected to become more frequent due to climate change. Without efforts to improve the resilience of the built network, Vietnam's achievements in providing universal access to its rural communities may be undermined. Moreover, resilience of connectivity is critical to the continued success of Vietnam's economy, which heavily relies on external trade and would increasingly depend on seamless rural-urban linkages.

In this analytical work, *Addressing Climate Change in Transport* for Vietnam, carried out by the World Bank and several other partners with support from the Ministry of Transport of Vietnam, the study aims to set out a vision and strategy for climate-smart transport, in order to minimize the carbon footprint of the sector while ensuring its resilience against future risks. The analytical findings and recommendations are presented in two volumes of the report: *Volume 1—Pathway to Low Carbon Transport* and *Volume 2—Pathway to Resilient Transport*. The first volume provides how Vietnam can reduce its carbon emission by employing a mix of diverse policies and investments, under varying levels of ambition and resources. The second volume provides a methodological framework to analyze network criticality and vulnerability, and to prioritize investments to enhance resilience.

These two report volumes have been prepared at a critical time, where the Government of Vietnam is working to update its Nationally Determined Contribution and set out its next medium-term public investment plan for the period of 2021 to 2025. We hope that these findings can provide useful insights and specific recommendations towards these critical documents, contributing to Vietnam's achievement in developing a low-carbon and resilient transport sector.

Guangzhe Chen
Global Director
Transport Global Practice

Ousmane Dione
Country Director
Vietnam

Acknowledgments

This report was prepared by the Transport Global Practice and the East Asia and Pacific Region of the World Bank.

The preparation of the report was led by Dr. Jung Eun Oh (Senior Transport Economist) and Dr. Xavier Espinet Alegre (Transport Specialist) at The World Bank, along with Dr. Raghav Pant at Oxford Infrastructure Analytics (OIA). The team includes Ms. Maria Cordeiro, Dr. Jasper Cook, Mr. Duc Cong Phan, Dr. Nguyen Thanh Long, Mr. Chi Kien Nguyen at the World Bank, and Dr. Elco E. Koks, Mr. Tom Russell, Mr. Roald Schoenmakers and Prof. Jim W. Hall at OIA. All crop production outputs are gratefully acknowledged from Dr. Jawoo Koo, Dr. Zhe Guo, Dr. Ulrike Wood-Sichra, and Dr. Yating Ru at International Food Policy Research Institute.

The team extends its appreciation for the guidance of Guangzhe Chen (Global Director, Transport Practice), Franz R. Drees-Gross, (Director, Transport Practice), Ousmane Dione (Vietnam Country Director), Almud Weitz (Transport Practice Manager, Southeast Asia and the Pacific), Achim Fock (Vietnam Operations Manager), and Madhu Raghunath (Vietnam Infrastructure Program Leader).

The team conducted the study in collaboration with the Government of Vietnam, and appreciates the strong support and advice generously provided by Mr. Le Dinh Tho, Vice Minister of Transport, and Mr. Tran Anh Duong (Director General), Ms. Nguyen Thi Thu Hang (Deputy Director), Mr. Vu Hai Luu (official), Ms. Doan Thi Hong Tham (official) and Mr. Mai Van Hien (official) at the Department of Environment, Ministry of Transport (MoT). Several government entities and organizations provided vital inputs: Directorate for Roads of Vietnam (DRVN); Vietnam Inland Waterways Administration (VIWA); Vietnam Maritime Administration (VINAMARINE); Civil Aviation Authority of Vietnam (CAAV); Vietnam Railway Authority (VRA); and Vietnam Register (VR).

The work benefited from the advice provided by the following peer reviewers: Stephen Ling (Lead Environmental Specialist), Cecilia M. Briceno-Garmendia (Lead Economist), Neha Mukhi (Senior Climate Change Specialist), and Ian Halvdan Ross Hawkesworth (Senior Governance Specialist) at the World Bank, and Robin Bednall (First Secretary) and Duc-Cong Vu (Senior Infrastructure Manager) at the Government of Australia. Kara Watkins (World Bank Communications Consultant) thoroughly copyedited the report for consistency and readability, and Chi Kien Nguyen (Transport Specialist) reviewed the Vietnamese translation for accuracy, for which the team is grateful.

The team also appreciates the excellent production support provided by Nguyen Thanh Hang, Nguyen Mai Trang, Ira Chairani Triasdewi (administration), Dang Thi Quynh Nga (operations), and Nguyen Hong Ngan (communications). The team also appreciates the excellent production support provided by Nguyen Thanh Hang, Nguyen Mai Trang, Ira Chairani Triasdewi (administration), Dang Thi Quynh Nga (operations), and Nguyen Hong Ngan (communications).

The team would like to thank the Government of Australia and NDC Partnership Support Facility for their generous support and funding toward this analytical work and publication.

About the Authors

Jung Eun "Jen" Oh is a senior transport economist at the World Bank. With a background in transport engineering and economics, Jen has led a number of investment projects and technical assistance for various client countries in Southeast Asia, Central Asia, Sub-Saharan Africa, and Europe, covering a broad range of transport sector issues. Jen served as a transport cluster leader for Vietnam from 2016 to 2019, overseeing and coordinating a large portfolio of World Bank-financed projects in Vietnam's transport sector, and led several knowledge pieces on climate change in transport, transport connectivity, urban mobility, and infrastructure financing. Jen holds an MSc in economics and a PhD in transportation systems, and has authored several articles, including a chapter in the book, *The Urban Transport Crisis in Emerging Economies* (2017), published by Springer International.

Xavier Espinet Alegre, a transport specialist for the chief economist for sustainable development at the World Bank, has extended expertise in transport planning and economics, climate change adaptation, disaster risk management, and decision-making science. He has worked for more than five years developing interdisciplinary and cross-sectoral solutions, as the D*ecision-Making under Deep Uncertainties* approach, to challenges posed by climate change to transport planning in Mozambique, Sierra Leone, Albania, Vietnam, Cambodia, and Saint Lucia, among others. Prior to the World Bank, he co-founded Resilient Analytics, serving as a technical lead, and worked as a research associate at the Institute of Climate and Civil Systems. Xavier holds a PhD in civil systems from the University of Colorado at Boulder and a civil engineering degree from the Universitat Politecnica de Catalunya in Spain.

Raghav Pant serves as a senior postdoctoral researcher at the Environmental Change Institute (ECI) at the University of Oxford, and is a founder and director of Oxford Infrastructure Analytics Ltd. Raghav has more than 12 years of academic and professional experience on infrastructure and economic network risks modeling, and leads the resilience analysis research within the UK Infrastructure Transitions Research Consortium (ITRC). He has worked with the World Bank on ongoing projects on transport risk analysis in Tanzania and Argentina. His research paper on vulnerability assessment of Great Britain's railway infrastructure has been awarded the 2016 Lloyds Science of Risk Prize in Systems Modeling.

Elco E. Koks works as a postdoctoral researcher in global network analysis at ECI and assistant professor at the Institute for Environmental Studies at Vrije Universiteit Amsterdam. Elco has more than seven years of experience working on several topics related to disaster impact modeling, climate change, and water economics in the context of national (Knowledge for Climate) and EU research projects (ENHANCE and TURAS). His key research domain is the modeling of the economy-wide consequences of natural disasters on both a regional and interregional level, with a specific focus on industrial areas and critical infrastructure.

Tom Russell, a research software engineer at the Environmental Change Institute, University of Oxford, has more than seven years of experience in research software development, particularly in spatial network analysis and data-driven design and interaction. Tom is creating the infrastructure systems modeling integration framework for the Infrastructure Transitions Research Consortium (ITRC) and developing open-source tools for infrastructure risk analysis through the Oxford Infrastructure Analytics–World Bank projects on transport risk analysis in Tanzania, Vietnam and Argentina.

Roald Schoenmakers works as a research software developer, actively collaborating with domain experts to facilitate in their need of software development. He is also involved in maintaining legacy software, to ensure availability of the modeling platform to the ITRC and its industrial partners. Roald has a background in engineering, with several years of experience in professional software development for industrial control systems and embedded applications.

Jim W. Hall, the professor of climate and environmental risks at the University of Oxford, is a founder and director of Oxford Infrastructure Analytics Ltd. Jim leads the UK Infrastructure Transitions Research Consortium, which has developed the world's first national infrastructure simulation models for appraisal of national infrastructure investment and risks. His book, *The Future of National Infrastructure: A System of Systems Approach*, was published by Cambridge University Press in 2016. He sits on the Expert Advisory Group for the National Infrastructure Commission and Chairs the DAFNI Data and Analytics Facility for National Infrastructure. He is a fellow of the Royal Academy of Engineering and for the last ten years he has been a member of the UK independent Committee on Climate Change Adaptation.

Abbreviations and Acronyms

AADF	Average Annual Daily Freight
AADT	Average Annual Daily Traffic
BCR	Benefit-Cost Ratio
CAAV	Civil Aviation Administration of Vietnam
CBA	Cost-Benefit Analysis
CGE	Computational General Equilibrium
CI	Capital Investments
CMIP5	Coupled Model Intercomparison Project Phase 5
CVTS	Commercial Vehicle Tracking System
DMDU	Decision-Making Under Deep Uncertainty
DRVN	Directorate of Roads for Vietnam
EAD	Expected Annual Damages
EAEL	Expected Annual Economic Losses
GCM	Global Climate Model
GDP	Gross Domestic Product
GIS	Geospatial Information Systems
GLOFRIS	Global Flood Risk with Image Scenarios
GSO	General Statistics Office of Vietnam
GVA	Gross Value Added
IFPRI	International Food Policy Research Institute
IMF	International Monetary Fund
IMHEN	Vietnam Institute of Meteorology, Hydrology and Climate Change
IO	Input-Output
JICA	Japan International Cooperation Agency
km	Kilometers
m	Meters
MapSPAM	Spatial Production Allocation Model (MapSPAM)
MARD	Ministry of Agriculture and Rural Development in Vietnam

MoNRE	Ministry of Natural Resources and Environment in Vietnam
MoT	Ministry of Transport in Vietnam
MRIA	Multi-Regional Impact Assessment
MRIO	Multi-Regional Input-Output datasets
MT	Metric Tons
NPV	Net Present Value
OD	Origin-Destination
OIA	Oxford Infrastructure Analytics
OSM	OpenStreetMap
PDoT	Provincial Departments of Transport
RCP	Representative Concentration Pathways
TDSI	Transport and Strategy Development Institute
TEU	Twenty-Foot Equivalent Unit
UN	United Nations
UNCTAD	UN Conference on Trade and Development
UN COMTRADE	United Nations Commodity Trade statistics databases
US$	United States Dollars
VINAMARINE	Vietnam Maritime Administration
VITRANSS II	The Comprehensive Study on the Sustainable Development of Transport System In Vietnam
VIWA	Vietnam Inland Waterway Administration
VND	Vietnamese Dong
VRAMS	Vietnam Road Asset Management System
WHO	World Health Organization

CURRENCY MEASURE

Currency unit — US$

WEIGHT AND MEASURES

Metric system

BASELINE DATA YEAR

Commodity freights — 2009, 2016

Macroeconomic data — 2012

Census data — 2012

Business Survey data — 2012

EXCHANGE RATES

US$1 in 2016 = 22,500 VND

US$1 in 2012 = 22,000 VND

US$1 in 1999 = 14,000 VND

CURRENCY INFLATION

US$1 in 2016 = US$1.5 in 1999

US$1 in 2016 = US$1.05 in 2012

Executive Summary

Vietnam is one of the world's fastest growing economies—with Gross Domestic Product (GDP) growth above 7 percent in the first quarter of 2018—and strong forecasted growth for the remaining year (World Bank 2018). Vietnam is also projected to be among the fastest growing economies over the 2016 to 2050 period, capable of sustaining a potential 5 percent annual GDP growth rate (PwC 2017). However, this rapid growth is threatened by extreme weather events such as storms, floods, typhoons, and landslides. Vietnam ranks high as a natural disaster hotspot; two or more multihazard events potentially expose 60 percent of the land area and 71 percent of the population to risk (Dilley et al 2005)—which could result in annual average asset losses amounting to 1.5 percent of GDP, and consumption losses amounting to 2 percent of GDP (Hallegatte et al 2016).

Climate change will exacerbate these extreme hazards. The Ministry of Transport (MoT) in Vietnam aims to develop a national strategy for climate resilient transport and plans—as part of the transport sector's contribution to the Nationally Determined Contributions (NDCs)—to meet the Paris Climate Agreement targets. To this end, this report intends to support MoT on the development of multimodal network-level criticality and vulnerability analysis, as well as methods and tools to inform prioritization of investments in transport asset management to ensure integration of climate and natural risk considerations.

This report presents the results from the *Transport Multi-Hazard Risk Analysis for Vietnam* at two scales—national and provincial—and draws upon policy recommendation to enhance climate resilience of the transport sector. The scope of the national analysis covers key national-scale roads, railways, civil aviation, inland waterways, and maritime systems that make up Vietnam's multimodal transportation infrastructure. At the national scale, the focus is to understand the economic impacts of disruptions to multimodal freight transportation due to infrastructure failures.

The scope of the province-scale analysis covers three specific provinces—Lao Cai, Binh Dinh, and Thanh Hoa—and their road networks only, which are represented in greater granularity than the national-scale analysis. The road networks include national, provincial, district, and commune roads and other assets such as bridges and culverts, among others. At the province scale, the focus is to understand how road failures impact access to key locations within communes, thereby affecting economic output generation.

At both national and province scales, two types of natural hazard—flooding and landslides—induce transport failures. The flooding hazards considered in this study include river flooding (i.e., flooding caused by rivers overtopping their banks), surface water flooding (i.e., flooding caused by extreme rainfall—also known as "pluvial" or "flash" flooding), and tidal flooding (i.e., flooding caused by typhoon-induced storm surges). Besides looking at the present situation (the year 2016), we use climate change scenario-driven model outputs representing future flooding in the years 2025, 2030, and 2050. The landslide hazards information includes model outputs for landslide susceptibility presented for current conditions (the year 2016) and future climate change scenarios in 2025 and 2050.

The framework developed for this study outlines a system-of-systems methodology. Each transport mode (road, railways, inland waterways, maritime, and airlines) considered in this study is treated as an infrastructure system, which is the collection and interconnection of all physical facilities and human systems that operate in a coordinated way to provide infrastructure service (Hall et al 2016). The infrastructure or transport service refers to the mobility for freight and passengers between locations. The multimodal transport infrastructure is then defined as a system-of-systems, which is the collection and interconnection of individual transport systems.

The framework presents the following types of system-of-systems assessments useful for decision-making:

- Criticality assessment as the measure of a transport link's importance and disruptive impact on the rest of the transport infrastructure (Pant et al 2015).
- Vulnerability assessment as the measure of the negative consequences caused by failures of transport links from external shock events (Pant et al 2016).
- Risk assessment as the product of the probability of a hazard and the consequences of transport link failures.
- Adaptation planning as engineering measures taken to reduce risks. In the context of climate change, the planned adaptation seeks to capitalize on the opportunities associated with climate change (Füssel 2007).

Criticalities for the national-scale roads and railway networks are measured in terms of the *total economic impact metric*, measured in United States dollars (US$) per day as the sum of the macroeconomic losses and the increased freight redistribution costs incurred due to their failures.

At the province scale, the study estimates road network criticalities in terms of *economic impacts* estimated as the sum of the *economic losses* (net revenue losses) in US$ per day, due to lack of accessible routes toward the commune centers, and the increases in *rerouting costs* where it is possible to maintain access to the commune centers after the disruptions.

The study estimates the *risks* of extreme hazard failures by combining knowledge of the hazards and impacts into one metric. The network risks are estimated in terms of an Expected Annual Economic Loss (EAEL) metric. The losses signify the daily *economic impacts*, estimated in the criticality assessment, multiplied by certain duration of disruption during which the affected network link is assumed to be out of operation.

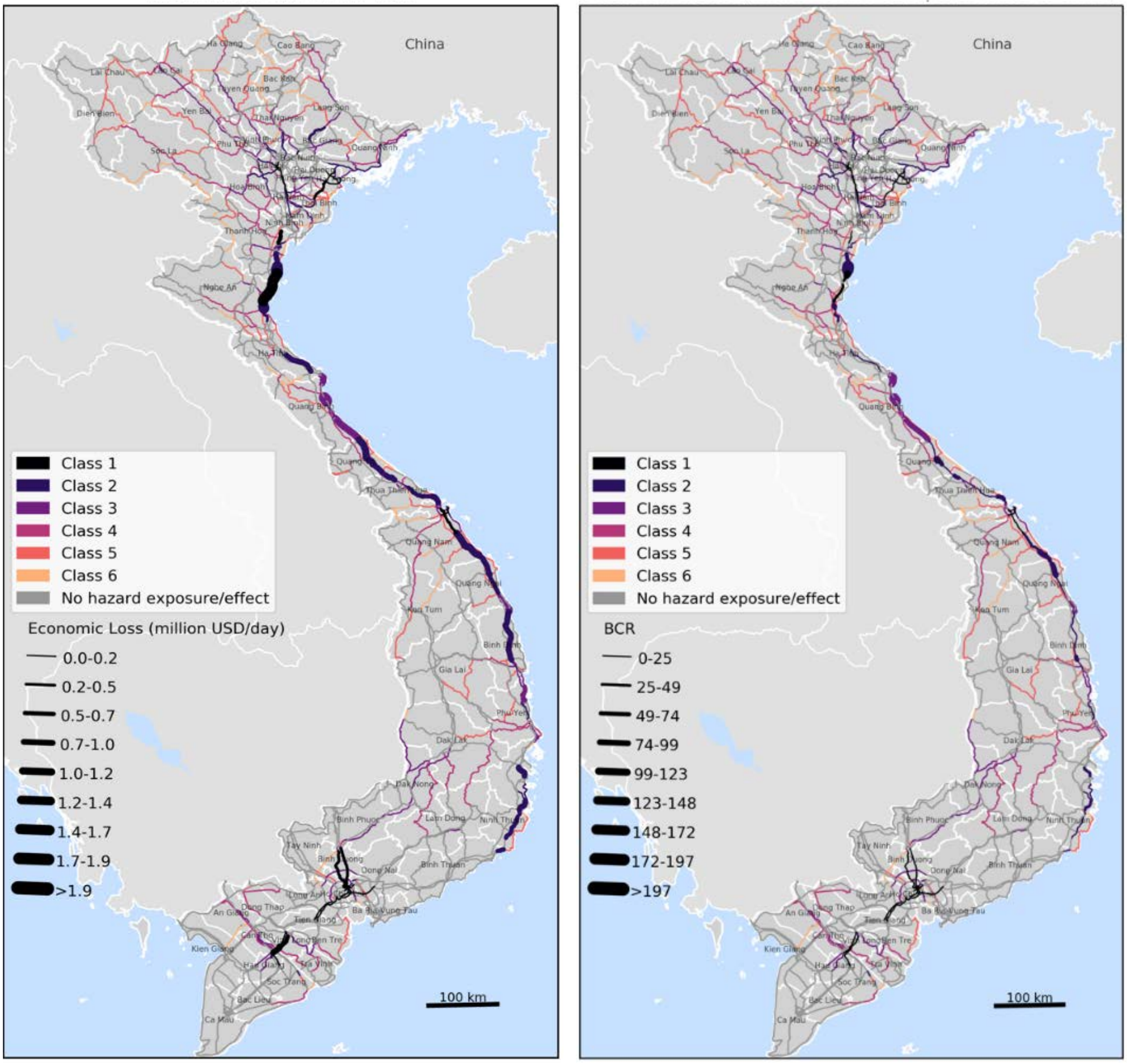
The *adaptation analysis* explores the measures intended to improve the structure reliability of road assets to make them more resistant to climate change impacts. The adaptation options for a particular road asset are quantified in terms of their costs and benefits. The costs include the initial cost of investment to implement the adaptation options, along with the routine and periodic costs of maintaining the climate resilience of the road asset. The benefits include the avoided losses, in terms of the damage (or rehabilitation) costs and the network-wide economic impacts of transport flow disruptions due to the road assets' failure, were the adaptation option not implemented. Based on the analysis, the key findings and recommendations are summarized as follows.

Vietnam's transport sector needs to prepare for extreme hazards of increasing intensities and with increasing frequency due to climate change. Our analysis shows that under climate change scenarios, exposures to extreme hazards would substantially increase for all transport sectors in Vietnam. The overall maximum kilometers (km) of national roads and railways along with province-scale road networks exposed to extreme hazard levels increases under climate change scenarios. For example, in Lao Cai, road length exposures to extreme landslides change from 142 km in the current scenarios to 210 km in the future high-emission scenario for 2050, shown in Representative Concentration Pathway (RCP) 8.5, or RCP8.5. In this scenario, extreme levels of flooding seen in 1,000-year events could start occurring in five-year events, making major inland, maritime, and airports vulnerable to river flooding with increasing frequency, translating to increased risk exposure.

Systemic understanding of locations whose failures create increasing economic risks presents a strong economic case for investing in building climate resilience of Vietnam's transport networks. The model and analysis results highlight systemic criticalities and hazard-specific, high-risk locations in the networks, which can be prioritized for further detailed investigations into climate resilience. The model results in figure E.1 show locations of road networks whose failures can result in very high daily losses of up to US$1.9 million per day, while railway failures can result in losses as high as US$2.6 million per day. When factoring such losses, the wider implications of macroeconomic losses due to transport disruptions become quite crucial. Generally, such effects are often ignored in transport analysis, which results in underestimating the impacts of transport disruptions.

Comparisons of current and future hazard risks prominently highlight the strong case for Vietnam to invest in building climate-resilient national-scale roads and railways. Comparisons also strongly indicate that access to economic opportunities in several provincial areas will be severely affected without investment in building climate-resilient roads. The expected annual economic losses by 2030—a measure of risks—due to transport failures from future climate change-driven river flooding significantly increase by more than 100 percent at several locations across national roads, railways, and province road networks. Such increases are recorded at all network links with high impacts. The analysis also shows the three Vietnamese provinces will experience a dramatic increase in risk due to climate change scenarios, up to 400 percent (Lao Cai), 900 percent (Binh Dinh), and 4,000 percent (Thanh Hoa) on road links with the highest losses. Additionally, several new instances of significant losses also emerge in future flooding scenarios for the three provinces.

Figure E.1. Maximum Economic Losses and Benefit-Cost Ratios of National Road Networks Due to Transport Disruptions



A. Maximum total economic loss **B. Maximum BCR of adaptation over time**

Vietnam's road networks require investments to overhaul existing road assets to higher climate-resilient design standards. Though such investments could be costly, their benefits outweigh the costs for priority network assets, making adaptation investments viable options for roads. The analysis has demonstrated that the national-scale and province-scale road networks all need adaptation planning to protect against future climate-related hazards. The analysis shows the Benefit-Cost Ratios (BCR) of adaptation investments into national-scale roads are mostly greater than one. The analysis suggests that, for some national-scale roads, upgrading to climate-resilient designs could cost up to US$3.4 million per kilometer—very high and comparable to costs of constructing high-standard new highways. But the high economic benefits of such investments justify such high costs. When the top 20 road links with highest maximum BCRs are selected, the analysis shows that cumulative climate adaptation investments amount to approximately US$95 million initially, and over

35 years total approximately US$153 million. The cumulative benefits over 35 years of such investments—estimated by adding the benefits from individual links—are substantial, ranging between US$651 million and US$3.66 billion. When looking at adaptation to flooding, the number of links with BCR > 1 doubles when considering climate change projections.

Similarly, for province-scale road networks a relatively small, but significant, number of assets have BCRs > 1. Many of these are bridges and local roads, which are crucial for accessing locations of economic activities. For all road networks, the increasing BCRs under future climate-hazards scenarios strengthen the case for investing in climate resilience to protect again future climate risks. Table E.1 summarizes the results of the adaptation analysis at the provincial level.

Table E.1. Climate Adaptation Analysis for Province-Scale Road Networks

Road network assets	Lao Cai	Binh Dinh	Thanh Hoa
Percent of assets with BCR > 1	15	2–3	2–3
Number of assets with BCR > 1	190	220–330	530–800
Adaptation Investment over 35 years (US$ millions)	12.9	1.6	2.3
Adaptation Benefits over 35 years (US$ millions)	16.4–22.5	14.2–31.4	7.8–22.3

Vietnam's transport networks can become more resilient if they function as integrated multimodal systems, achieved by improving existing and creating new multimodal linkages. This study has shown economic impacts of disruptions can be reduced by building additional transport multimodal connectivity. Often known as increasing a network's "redundancy," this phrase might be interpreted as being wasteful and inefficient. However, providing extra connectivity and capacity will assist the everyday flow of goods and people, as well as providing new opportunities for rerouting when major disruptions occur.

This study shows a very clear benefit of redistributing flows from the road network to the railways and inland and maritime networks. Even a 10 percent shift of road freights, especially to railways, can lead to a 20 to 25 percent reduction of economic impacts. In addition, enhancing railway and waterway efficiency can reduce risks for already congested roads. Moreover, existing unused capacity in the railways accommodates the additional modal shift from roads. The potential railway losses are also significantly reduced through the availability of multimodal options, which should be considered in the future.

It would be important to invest in improving data gaps in future studies in order to make more robust economic case for investment in the transport network. Vietnam's transport resilience planning can benefit from a system-of-systems transport risk analysis. Importantly, creating cross-sector and cross-organization collaborations helps increase capacity to undertake further studies and pursue continued efforts to improve the underlying datasets. The study has dealt with severely limited data, highlighted throughout the report. Some of these limitations exist in assembling and standardizing:

- Topological representations of infrastructure networks with proper attributes
- Transport flows that represent latest conditions and trends
- Transportation cost assignments reflective of existing conditions
- Economic flows data showing current structure of the country and regional economies
- Probabilistic hazards at similar spatial resolutions and with Vietnam-specific climate scenarios
- Seasonality information of extreme levels of hazards and transport network flows
- Information on disruption durations and response behaviors
- Costs of various adaptation options most relevant to Vietnam.

Next steps: Creating a cross-sector and cross-organization collaboration involving various government agencies is extremely important for increasing capacity to standardize and share data. While the model developed in this study can be readily adapted to accommodate further improvements, this study addresses only some of the economic and social functions of transport infrastructure. Notably, it has not explored the role of transport infrastructure in enabling passenger travel for work or other purposes, or for labor market participation. That should be included in future studies, alongside other wider economic and social benefits of transport infrastructure. In these recommendations we have already identified that prioritizing investments to improve transport network resilience would require consideration of the costs and effectiveness of alternative interventions. Building on this study of transport network vulnerability and risks, we recommend studying the costs and effectiveness of alternative interventions as the next step.

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Chapter 1: Introduction

Background and Objectives

The Socialist Republic of Vietnam (henceforth referred to as Vietnam) is one of the world's fastest growing economies with Gross Domestic Product (GDP) growth above 7 percent in the first quarter of 2018, with strong forecasted growth for the remaining year (World Bank 2018). This follows from a consistent average GDP growth of 6.4 percent since the 2000s.[1] Vietnam is also projected to be among the fastest growing economies over the 2016 to 2050 period, capable of sustaining a potential 5 percent annual GDP growth rate (PwC 2017).

However, such rapid growth is threatened by extreme weather hazards (storms, floods, typhoons, landslides). Previous reports suggest Vietnam already ranks high as a natural disaster hotspot of two or more multi-hazard events, potentially exposing 60 percent land area and 71 percent population to risk (Dilley et al 2005)—which could result in annual average asset losses amounting to 1.5 percent of GDP and consumption losses amounting to 2 percent of GDP (Hallegatte et al 2016). It is possible that climate change will exacerbate these extreme hazards, even after factoring uncertainties in downscaled global climate model predictions (MoNRE 2009; World Bank 2011; Irish Aid 2017). Recognizing that the country's vulnerability to impacts of climate change can impede its growth, and as part of its Nationally Determined Contributions (NDCs) to meet the Paris Climate Agreement targets, the Ministry of Transport (MoT) in Vietnam aims to establish national transport strategies and plans as part of the transport sector's contribution to deliver on NDC implementation. To this end, this report supports MoT in the development of multimodal network level criticality and vulnerability analysis, as well as methods and tools to inform prioritization of investments in transport asset management to ensure integration of climate and natural risk considerations.

In delivering the multimodal transport network criticality and vulnerability analysis to prioritize maintenance, rehabilitation, and infrastructure upgrading, this study answers some key questions relevant to transport planners, investors, and relevant stakeholders, namely:

1. Where and what are the key transport network locations exposed to different types of extreme natural hazards?
2. In which areas in the country are transport assets particularly exposed to hazards, as predicted by model outputs of current and future climate change-driven natural hazard scenarios?
3. What are the wider macroeconomic losses at the national scale when freight transport is disrupted due to transport failures?
4. What are the impacts on the local commune-scale economies due to lack of access to key locations of economic activity, because of local road failures?
5. What are the impacts of transport disruptions in terms of increased transportation costs of rerouting traffic for maintaining service continuity?

6. How resilient are the multimodal transport networks in providing continuous service when individual transport modes are damaged or disrupted due to external natural hazard shocks?
7. When considering the key climate resilience investments and strategies evaluated for current and future climate scenarios, what are the net benefits of adaptation?
8. Where and what are the key transport network locations prioritized according to highest net benefits of climate adaptation measures?
9. What are the most robust climate resilience interventions or policies to reduce the vulnerability of critical segments to future climate change impacts, taking account of the uncertainties and sensitivities?

In answering the above questions, some specific objectives satisfied in this report include the following:

1. Creating multi-scale geospatial network flow models to represent the multimodal transport infrastructures in Vietnam, both in the present and future
2. Modeling traffic flow disruptions and flow reallocations when network assets fail due to natural disasters
3. Evaluating the potential economic and social impacts when the multimodal transport networks are disrupted by natural disasters
4. Creating network criticality metrics to systemically measure and identify critical segments of the multimodal transport networks that lack or have built-in resilience and/or redundancy
5. Performing exhaustive scenario-based simulations to incorporate multiple uncertainties in underlying model assumptions. This aligns with the decision making under deep uncertainty (DMDU) approaches (Espinet et al 2015)
6. Incorporating various climate-resilient transport investments and policies to evaluate the adaptation options and identify robust interventions or policies to reduce the vulnerability of critical segments to future climate change impacts, taking account of the uncertainties and sensitivities.

Scope of the Study

This report focuses its recommendations at two scales: national and provincial. The focus area of this study is the mainland of Vietnam,[2] which on the west and north shares land borders with neighboring countries (Lao PDR, Cambodia, and China) accessible by road, and is surrounded by coastal lines on the east and south. For the national-scale analysis, input data is derived from provincial, district, or commune-level statistics where appropriate. The province-scale analysis focuses on three specific provinces—Lao Cai, Binh Dinh, and Thanh Hoa—where information is derived from commune-level statistics.

Figure 1.1 provides a representation of the regional and international boundaries of Vietnam relevant to this study. The three provinces of Lao Cai, Binh Dinh, and Thanh Hoa, for which the detailed road network analysis is conducted, are highlighted in dark gray.

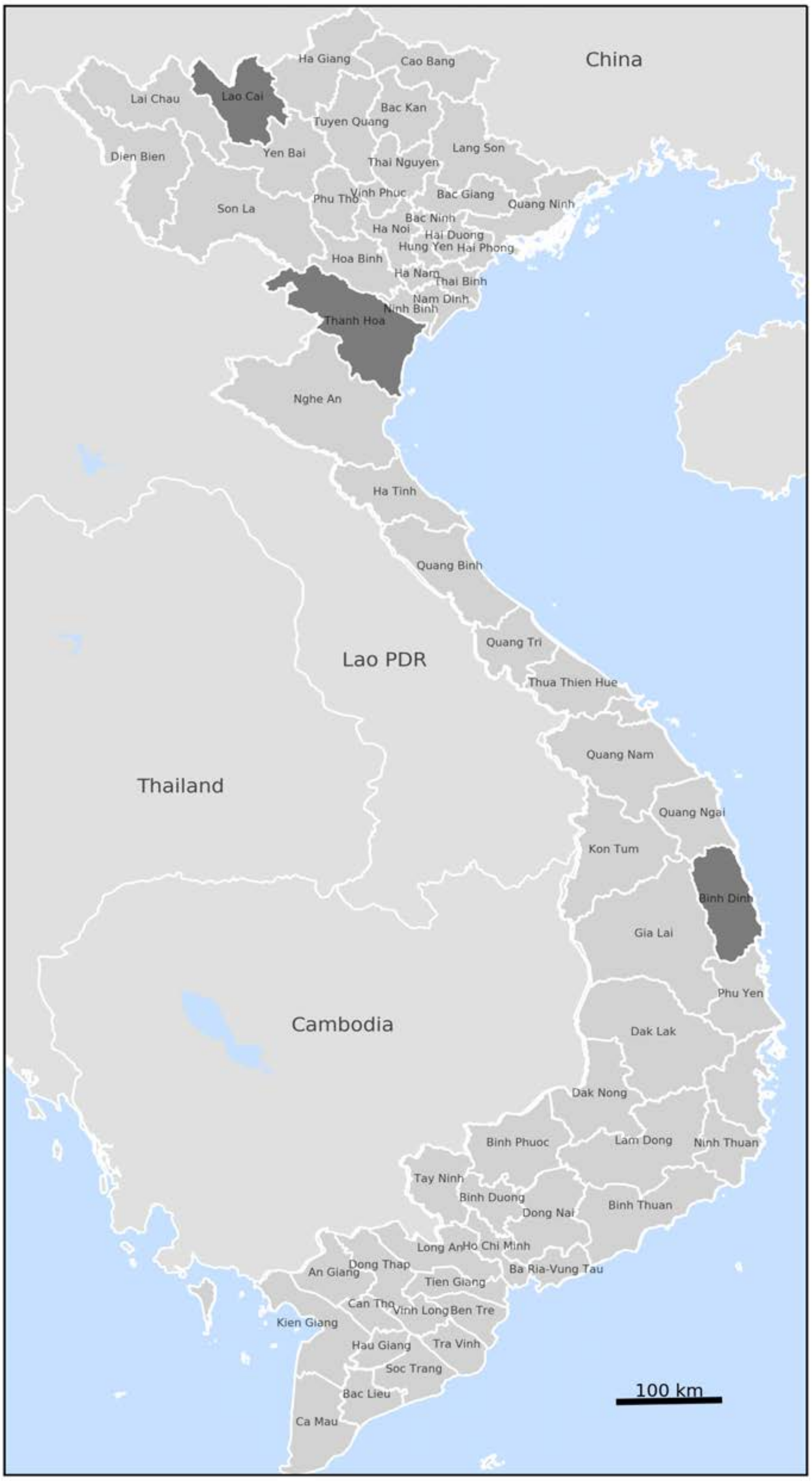
The scope of the *national analysis* covers the key national-scale roads, railways, airline, inland waterways, and maritime systems that make up Vietnam's multimodal transportation infrastructure. *At this scale the study focuses on understanding the economic impacts of disruptions to freight transportation due to transport failures*.

The scope of the *provincial analysis* is confined to road networks only, which are represented in greater granularity than the national-scale roads and include national, provincial, district, and commune roads and other assets such as bridges and culverts, among others. *At this scale, the study focuses on understanding how road failures impact access to key locations within communes, thereby affecting economic output generation*.

Specifically, for all *road networks* considered in this study, a *detailed adaptation analysis model* is created to quantify the benefits and costs of adaptation, identify the road network assets where climate-resilient investments should be prioritized, and provide estimates of the scales of investments required. An overview of all infrastructure related datasets used in this study is given in appendix B of this report.

At both national and provincial scales, transport failures are induced by two types of natural hazards: *flooding and landslides*. The flood hazards considered in this study are *river flooding* (i.e., flooding caused by rivers overtopping their banks), *surface water flooding* (i.e., flooding caused by extreme rainfall—also known as "pluvial" or "flash" flooding) and *tidal flooding* (i.e., flooding caused by typhoon-induced storm surges). Besides looking at the present situation (the year 2016), we use climate change scenario-driven model outputs representing future flooding in the years 2025, 2030, and 2050. The landslide hazards information includes model outputs for subsets of landslides quantified in terms of *landslide susceptibility* presented for current conditions (the year 2016) and future climate change scenarios in 2025 and 2050. Chapter 2, section "Natural Hazard Exposure of Transport Networks" and appendix B provide further details for flood hazard data.[3]

Figure 1.1. Vietnamese Provinces and Neighboring Countries Considered in the Study



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Study Contributions and Limitations

The main contribution of this study is to provide detailed spatial evidence of systemic vulnerabilities and risks on the multimodal transport systems of Vietnam. Several study contributions would be valuable to stakeholders in Vietnam such as Ministry of Transport (MoT), Directorate of Roads for Vietnam (DRVN), Provincial Departments of Transport (PDoT), Civil Aviation Administration of Vietnam (CAAV), Vietnam Maritime Administration (VINAMARINE), Vietnam Inland Waterway Administration (VIWA), Transport Development and Strategy Institute (TDSI), Ministry of Agriculture and Rural Development (MARD), and Ministry of Natural Resources and Environment (MoNRE).

This study includes the following specific useful contributions:

1) Creating unique datasets and modeling resources
    a. First-of-a-kind representations of topologically connected geospatial national-scale roads, railways, inland waterways, and maritime multimodal transport networks with flow assignments for Vietnam
    b. Detailed agriculture crops and commodity or industry level network flows mapped onto the multimodal transport networks increase understanding of the domestic freight flow patterns in the country
    c. Detailed transport cost estimates increase understanding of realistic criteria for transport freight flow assignments
    d. Long-term growth forecasts incorporated onto the geospatial networks
    e. The study's codebase, developed in Python programming language as an open-source resource, is available to the public at https://github.com/oi-analytics/vietnam-transport. The methodology behind the code has been documented in detail through this report, and a separate user document on the compilation and creation of underlying data and code is also available publicly at: https://vietnam-transport-risk-analysis.readthedocs.io/en/latest/.
    f. Testing of the underlying codes to perform billions of computations of network flow assignments and failure scenarios with optimal performance, a fundamental requirement for a study of this scale.
2) Prioritizing criticality-based networks
    a. The key metrics created and analyzed in this study answer the previously highlighted questions relevant to transport stakeholders, who want to know the effects of transport disruptions on continued provision of service and transport costs.
    b. The detailed network assessment conducted in this study helps identify locations most important for the continuity of the transport service in the country, and whose failures can potentially lead to large-scale socio-economic consequences.
    c. The study's ranking of critical assets, based on their disruptive potential, provides a means to prioritize and sequence risk reduction activities.
    d. Ranking of critical assets further supports the rationale for prioritizing investments to reduce vulnerability and build systemic resilience, forming the basis for long-term adaptation planning (Thacker et al 2018).

3) Increasing the understanding of hazard vulnerability
    a. The study spatially depicts the exposure of transport networks to various natural hazards at detailed spatial scales, enabling understanding of the potential severity of different threats to infrastructure networks.
    b. Study results presented at national and provincial scales highlight areas where several transport assets are more prone to be exposed to hazards in the current scenarios and how this might change in the future due to climate change driven scenarios.
    c. The study's spatial information on extreme hazard exposures of transport networks can inform national and provincial transport planning decisions to allocate adequate budget for short-term and long-term transport risk reductions.
4) Developing a roadmap for adaptation planning
    a. A key contribution of this study is to provide the tools to undertake adaptation analysis whereby the benefits and costs of different strategies designed to build transport structural resilience can be assessed under various hazard scenarios.
    b. The study presents various adaptation options at the scale of individual road assets, as well as the cost-benefit analyses metrics to deliver a detailed understanding of investment options for each asset under different hazard scenarios.
    c. The study performs key analysis to understand whether asset level adaptation planning should be done proactively to protect against future climate hazards.
    d. The study catalogues and presents locations of all road assets with high benefits of adaptation to provide decision-makers with information that will help prioritize resources toward the most critically important assets in the networks.
5) Assessing multimodality
    a. The study's presentation of key methods and analyses quantifies the effects of transport failures, if multimodal options were available.
    b. As one of its key aims, the study's multimodality assessment provides evidence supporting the need for enhanced multimodal connectivity as an adaptation strategy.
    c. Understanding the benefits of multimodality at detailed geospatial network scales provides a means to target network locations where multimodal options could be strengthened through more investments.
6) Assessing uncertainty
    a. The models and analyses presented in this report have many sources of uncertainties coming from lack of proper data on physical transport network structures and their usage statistics, among others. These uncertainties have been accounted for throughout the analysis.
    b. The study follows a robust decision-making approach (Lempert et al 2013) whereby the analysis quantifies the extreme ranges (minimum and maximum) of potential flows, criticalities and adaptation. This approach provides a decision-making tool that accounts for robust performance of different adaptation options under different scenarios.

The analysis presented in this report offers a high-level indicative assessment of transport systems and their natural hazard risks, providing a first-order screening whereby locations and assets with high risks can be narrowed down for further investigation. Hence, certain considerations should be made in interpreting this work. Nevertheless, most of these limitations exist due to lack of proper data; with improvement in input data the underlying model is fully capable of correcting several limitations underlined below:

1) Physical infrastructure network data and representations
    a. The transport data created in the model serves as a network presentation of functional connectivity of the transport system, rather than a detailed master plan representation of each location's detailed spatial layout and attributes. For example, in this analysis, Ho Chi Minh port is represented as a point in space, while in reality it exists over a large area.
    b. Similarly, the represented road, railways, airports, ports, and multimodal links show general travel routes. Any details provided for the physical width, number of lanes or lines, or navigational channels of these systems have been estimated.
    c. The representation of the networks' built-in functional and physical connectivity is also heavily contingent of the availability or lack of data. For example, if the available data does not show a road or rail connection that exists, the model will not be able to represent that connection.
    d. The multimodal links in this analysis represent derived connectivity, with as many links as possible verified through satellite imagery.
2) Network flow assignments
    a. As explained later in the report, the model estimates network flow assignments from several sources and datasets. Several assumptions have been taken in interpreting the flows.
    b. Representation of future flows and losses are estimated based on high-level forecasts of growth for the whole country.
    c. Hence, the flow and failure values in the analysis show the high-level trends, rather than the exact estimates of actual flows.
3) Failure and hazard vulnerability analysis
    a. Gridded datasets show hazards at different spatial resolutions, which are sometimes very coarse. Thus, the hazard information should not be used for detailed site-specific analysis.
    b. Derived from the analysis of transport network exposures to hazards, the main insights provide useful overviews of the likely hazards around specific locations.
4) Adaptation analysis
    a. The adaptation analysis presented in this report reflects the underlying data of cost estimates for different options under consideration. Therefore, the cost estimates derived from datasets represent best estimates.
    b. The main insights from the adaptation analyses provide a means to understand how different options can be evaluated and which scenarios should be considered.

Report Structure

Following this introductory chapter, the remainder of the report is structured as follows:

Chapter 2 — Vietnam Profile: Transport Network and Exposure to Natural Hazard: Chapter 2 describes the underlying transport network information assembled and created in this study, the types of hazards considered—with their source—climate change scenarios (if considered), spatial resolutions, and spatial coverage. The chapter infers some information regarding the state of the infrastructure from the underlying network data, which is compared with relevant literature wherever possible.

Chapter 3 — Vulnerability, Criticality and Risk Assessment: Chapter 3 presents the results for the transport criticality assessment of freight flow disruptions on the assembled transport networks in Vietnam. The criticality assessment considers an exhaustive set of individual network link scenarios exposed to hazards for failure. In addition, the assessment considers impacts in terms of metrics that give a sense of the network locations with the most socio-economic impacts. A risk assessment to infer the hazards that cause the impacts follows. The ranges of disruptive impacts across each hazard are quantified for each network to better understand whether hazard impacts will increase due to future climate scenarios.

Chapter 4 — Adaptation Strategy and Analysis: Chapter 4 presents the adaptation options considered for national-scale and province-scale road network assets, with a detailed benefit-cost analysis performed for each asset under different hazard scenarios. In addition, the chapter evaluates the ranges of adaptation options and their benefits, exploring the advantages of adapting to future climate scenarios.

Chapter 5 — Exploring Multimodal Options for National-Scale Transport: This chapter explains the development of the study's multimodal transport system. Following this, the chapter evaluates the effect of multimodality on failures by exploring modal shifts from road and rail networks.

Chapter 6 — Conclusions and Policy Recommendations: Chapter 6 presents recommendations for building and enhancing transport resilience to climate change impacts.

Notes

1. See the World Bank's online country page for Vietnam: http://www.worldbank.org/en/country/vietnam/overview.

2. For the purposes of this study, the analysis was confined within the mainland of Vietnam, considering the data availability and significance of traffic flows.

3. The natural hazard datasets used in this study have been obtained from third party sources—either from the Government of Vietnam or through the World Bank partners—and have not been altered in any way by the authors.

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Chapter 2: Vietnam Profile: Transport Network and Exposure to Natural Hazard

Transport Networks

This section describes the current networks with freight flow volumes and costs across national-scale roads, railways, inland waterways, maritime ports, and airline networks. Similarly, flows are also identified on province roads networks in terms of the access to important commune centers within provinces, uncertainties of flows due to rice-crop seasonality, and network cost assignments are considered.

National-scale road infrastructure networks

The national-scale network model created for the study extends to about 30,900 km and consists of 2,130 nodes and 2,512 links. Of the 30,900 km of the network analyzed, 30,032 km or 97.2 percent, is paved; a mere 868 km remains unpaved. Roads have been classified in scale of 1 to 6, with a greater traffic volume associated with higher road class (table 2.1). Table 2.2 presents the estimated classification.

Table 2.1. Road Categories by Average Daily Vehicle Traffic Counts

Road traffic count	Road category
> 6000	1
3000 – 6000	2
1,000 – 3000	3
300 – 1,000	4
50 – 300	5
<= 50	6

Source: MoT Vietnam 2000.

Table 2.2. Estimated Total Lengths by Road Category in the National-Scale Road Network Model for Vietnam

Road class	Length (km)	Length (%)
1	1,656	5.35%
2	2,331	7.54%
3	4,951	16.02%
4	6,449	20.87%
5	8,561	27.70%
6	6,952	22.70%

Source: Authors' estimation using CVTS GPS data mapping

Province-scale roads networks

Given the underlying geospatial datasets had the same attributes, the province-scale network models used similar types of assumptions across all provinces. Table 2.3 shows the estimated lengths of paved and unpaved roads of different levels in each of the province road network models. The estimates indicate these provinces contain mostly unpaved roads.

Table 2.3. Estimated Lengths by Road Category in the Province-Scale Road Network Model for Vietnam

Province	Nodes	Links	Road level	Paved (km)	Unpaved (km)	Paved (%)	Unpaved (%)
Lao Cai	3,744	4,697	National	579	0	14.71%	0.00%
			Provincial	435	0	11.06%	0.00%
			Local (district/ commune)	65	1,342	1.65%	34.11%
			Other	0	1,514	0.00%	38.48%
			Total	**1,079**	**2,857**	**27.42%**	**72.58%**
Binh Dinh	21,686	26,213	National	341	0	6.31%	0.00%
			Provincial	321	0	5.93%	0.00%
			Local (district/ commune)	226	446	4.17%	8.25%
			Other	0	4,075	0.00%	75.34%
			Total	**887**	**4,522**	**16.41%**	**83.59%**
Thanh Hoa	66,863	91,304	National	921	0	4.58%	0.00%
			Provincial	457	0	2.27%	0.00%
			Local (district/ commune)	394	2,312	1.96%	11.49%
			Other	5	16,025	0.03%	79.67%
			Total	**1,777**	**18,337**	**8.83%**	**91.17%**

Railway infrastructure network

The rail infrastructure network model was derived from data on station point locations and rail line geometries provided from the Ministry of Transport (MoT) dataset, including the VITRANSS II datasets from 2009 (JICA and MoT 2010). The resulting network contains 313 nodes, of which 234 are stations and 324 are links. The modeled length of the rail network is approximately 2,662 kilometers. Table 2.4 reports the lengths of some main routes. The main hub of the rail network lies around Hanoi, with the Hanoi to Ho Chi Minh route as the longest line of the network by far.

Due to an aging railway infrastructure largely comprised of a single-track system, railway usage is very limited in Vietnam, which limits train lengths in the difficult and narrow terrains along routes (Systra 2018).

Table 2.4. Estimated Total Link Lengths and Percentages of Rail Routes Identified in the National-Scale Rail Network Model for Vietnam

Rail route code	Route description	Length (km)	Length (%)
DSTN	Hanoi – Ho Chi Minh	1,719	64.56%
YV-LC	Hanoi – Lao Cai	297	11.16%
HN-DD	Hanoi – Lang Son	171	6.42%
GL-HP	Hanoi – Hai Phong	106	3.98%
K-HL	Bac Giang – Quang Ninh	104	3.90%
DA-QT	Hanoi – Thai Nguyen	58	2.16%
K-LX	Bac Giang – Thai Nguyen	55	2.07%
BH-VD	Hanoi	39	1.47%
MP-LD	Lang Son	31	1.17%
CG-ND	Nghe An	30	1.12%
CL-PL	Hai Duong	17	0.65%
MM-PT	Binh Thuan	12	0.45%
PL-KK	Ha Nam	9	0.34%
DT-QN	Binh Dinh	9	0.34%
L-TM	Unknown	6	0.22%

Inland waterway infrastructure network

The study identified inland waterway network model nodes from data obtained from the Vietnam Inland Waterway Administration (VIWA)[1] and the VITRANSS II study. The resulting network contains 131 inland waterway port nodes and 502 links. The modeled length of the inland waterway network is approximately 5,407 kilometers, concentrated along the Mekong Delta in the south, or the Red River Delta in the north, with a very small section in Quang Binh.

Maritime infrastructure network

The study identified maritime network model nodes from geospatial port location data obtained from the MoT, and maritime routes published by the Ministry of Natural Resources and Environment (MoNRE). The resulting network contained 45 maritime ports and 206 links. The modeled length of the maritime network is approximately 5,254 kilometers, for domestic transportation uses only. The Vietnam Maritime Administration (VINAMARINE) classifies international hubs classified as Class 1A ports, and domestic hubs as Class 1 ports (MoT 2015).

Air transport infrastructure network

The study identified air transport infrastructure network model nodes from geospatial airport location data obtained from the MoT. Based on a previous MoT study of the VITRANSS II model (JICA and MoT 2010), the study identified main airports with any freight flows between them and created straight-line link geometries to join the paired airports. The resulting network contains 23 airport nodes, of which 8 are connected via 10 links. While the share of air transport of total cargo movement in Vietnam is increasing rapidly, detailed data for air freight volumes were not available at the time of this study. Given this limitation, the study analyzed the air transport sector as a standalone sector, rather than as a multimodal transport option in Vietnam.

Modeling Freight Flow on Transport Networks

This study modeled and estimated the following transport flow metrics:

- *Average annual daily freight volumes (AADF)*: The estimated volume of freight in tons per day on an average day between different network locations; and
- *Net revenue measures*: The estimated daily net revenue of goods and services with access to an important location via a transport network. These measures are estimated to understand local road access to important locations at province scale.

Traffic flows were constructed based on available existing data, including information received from relevant ministries and departments in Vietnam, data compiled in previous studies and reports on transport planning and development in Vietnam, and open-source data and online information of transport estimates. The study relied on previous origin-destination (OD) matrix provided by MoT, CVTS data from 2017, input-output (IO) matrix, traffic count data from DRVN, crop production data from IFPRI (Koo et al 2018), and other socio-economic statistics, among others. The process of assigning freight transport flows is described in detail in appendix A.

Results of freight flow mapping at national scale

The results of the flow assignments provide insights into the following important questions:

- Where are the locations on the network links with the most flow concentrations?
- Which links and routes have the largest concentrations of economic values?

First the results of the national-scale OD matrix are mapped in figure 2.1 and shown in table 2.5, which presents the different daily tonnages for each commodity considered in the study and split of these daily tonnages by each transport mode (road, railway, air, inland waterways, and maritime). For each commodity, the mode with the highest percentage share is highlighted (in gray) in table 2.5. The result shows the following:

- The fluctuations in the rice volumes show a significant change in the daily tonnage volumes on the transport systems, which can have huge implications on the values of failure estimates.
- Inland waterways and roads are the two most dominant transport modes for these commodities. Depending upon the fluctuations in the rice transport tonnages, the mode shares between these two transport modes varies between 44 and 48 percent.
- Maritime transport is the next significant mode, with around 4 to 5 percent modal shares, followed by railways, with a 1.9 to 2.1 percent modal share. Airline transport is almost insignificant.
- For commodities such as cement, coal, construction materials, fertilizer, fishery, and sugar, inland waterways represent the most dominant mode. Roads rank as the dominant mode for manufacturing, steel, meat, petroleum, and all crop commodities used in this study.

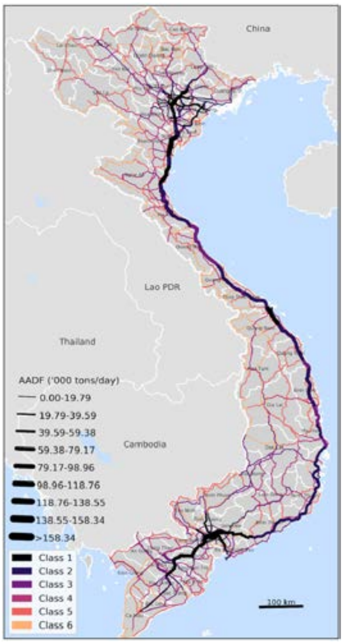
The tonnage volumes and modal shares presented are a subset of the estimated annual tonnages that focus on major national inter-provincial commodity flows and are based on the best available origin-destination data of some commodities. This results in modal share figures that are somewhat different from those from the statistics of the General Statistics Office (GSO) of Vietnam.[2] According to the GSO figures for 2015, roughly 76.5 percent of trade flows occurred on road, 17.5 percent on inland waterways, 5.3 percent on maritime, 0.6 percent on railways, and 0.02 percent on airline networks. *Hence, the estimated mode shares in this study under-represent the dominance of roads, while over-representing the contributions of inland waterways and railways*.

The maps in figure 2.1 show the how daily transport flows in Vietnam happen at long distances, connecting the region of economic activities in the south (Mekong Delta) to those in the north (Red River Delta). For the national-scale road network, the high-volume freight routes run through the national highways and expressways on the eastern coast. The railway flows are more concentrated toward the northern sections. The inland waterways have key high-volume routes in the north and south, while the cross-country domestic maritime are the busiest routes. Based on the available data for airlines, the connectivity between the Hanoi and Ho Chi Minh airports is most important for freight transport.

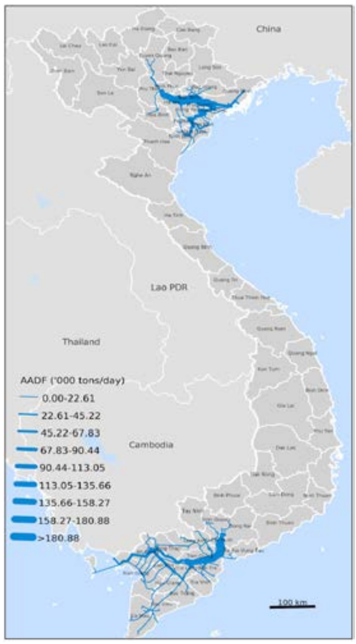
Table 2.5. Daily Traffic Volumes by Commodity and Transport Mode

Commodity	Road		Railway		Air		Inland waterways		Maritime		Total
	Tons/day	Percent share	Tons/day	Percent share	Tons/day	Percent share	Tons/day	Percent share	Tons/day	Percent share	
Cement	34,534	30.93%	3,581	3.21%	1	0.00%	60,626	54.31%	12,898	11.55%	**111,640**
Coal	14,963	13.49%	2,022	1.82%	0	0.00%	83,917	75.68%	9,977	9.00%	**110,879**
Construction materials	108,721	23.37%	8,423	1.81%	5	0.00%	346,189	74.41%	1,904	0.41%	**465,241**
Fertilizer	10,940	26.58%	1,973	4.79%	3	0.01%	27,058	65.74%	1,185	2.88%	**41,158**
Fishery	7,138	36.96%	30	0.16%	1	0.00%	11,912	61.67%	234	1.21%	**19,315**
Manufacturing	153,121	82.40%	4,702	2.53%	152	0.08%	13,933	7.50%	13,921	7.49%	**185,828**
Coffee Arabica	57	99.61%	0	0.37%	0	0.00%	0	0.00%	0	0.03%	**57**
Cashew	2,996	99.61%	1	0.03%	0	0.00%	2	0.07%	9	0.29%	**3,008**
Cassava	19,416	92.85%	436	2.09%	1	0.00%	146	0.70%	912	4.36%	**20,911**
Maize	5,354	83.90%	199	3.11%	12	0.18%	299	4.68%	518	8.12%	**6,382**
Pepper	404	97.94%	3	0.71%	0	0.00%	4	1.07%	1	0.29%	**413**
Coffee robusta	2,033	99.64%	7	0.33%	0	0.00%	0	0.00%	1	0.03%	**2,040**
Rubber	2,570	98.57%	20	0.76%	0	0.00%	2	0.07%	16	0.60%	**2,608**
Sweet potatoes	1,034	59.22%	87	4.98%	6	0.35%	387	22.15%	232	13.31%	**1,746**
Teas	162	77.75%	13	6.20%	0	0.03%	0	0.01%	33	16.02%	**208**
Meat	50,940	72.79%	555	0.79%	48	0.07%	14,019	20.03%	4,425	6.32%	**69,987**
Petroleum	32,532	71.49%	384	0.84%	8	0.02%	5,301	11.65%	7,284	16.01%	**45,509**
Steel	33,446	77.08%	2,350	5.42%	2	0.01%	6,840	15.76%	751	1.73%	**43,389**
Sugar	3,064	37.98%	13	0.16%	0	0.00%	4,844	60.06%	145	1.80%	**8,066**
Wood	10,748	46.51%	325	1.40%	7	0.03%	11,211	48.51%	820	3.55%	**23,110**
Rice (min)	73,557	70.96%	1,210	1.17%	9	0.01%	25,762	24.85%	3,114	3.00%	**103,653**
Rice (max)	361,478	59.64%	8,043	1.33%	43	0.01%	204,781	33.78%	31,799	5.25%	**606,144**
Total tons (min)	**567,729**	**44.87%**	**26,332**	**2.08%**	**254**	**0.02%**	**612,452**	**48.41%**	**58,380**	**4.61%**	**1,265,147**
Total tons (max)	**855,650**	**48.41%**	**33,165**	**1.88%**	**287**	**0.02%**	**791,471**	**44.78%**	**87,065**	**4.93%**	**1,767,638**

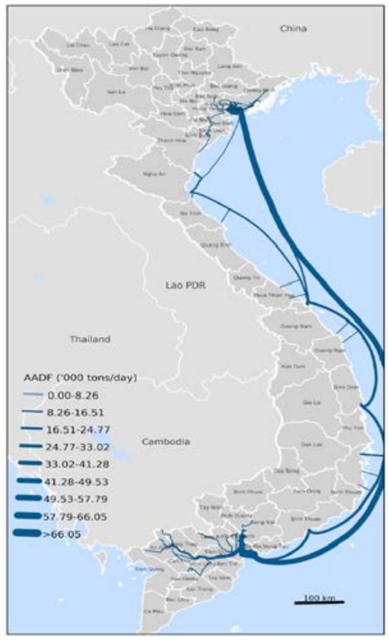
Figure 2.1. Maximum AADF for the National-Scale Transport Network



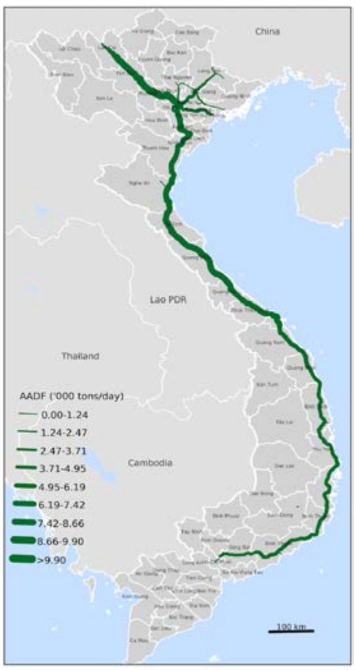
A. Total tonnage (Road)



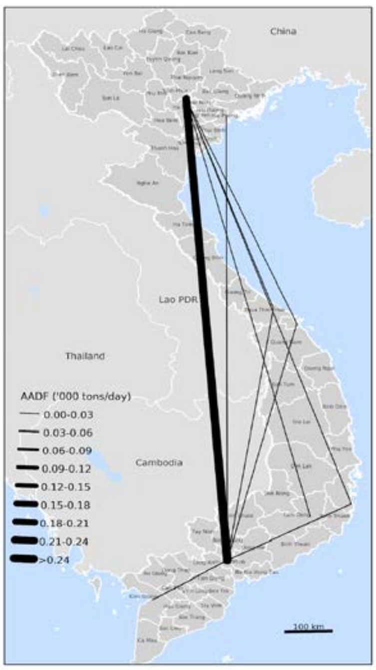
B. Total tonnage (Inland waterway)



C. Total tonnage (Maritime)



D. Total tonnage (Railway)



E. Total tonnage (Air)

Results of province-scale flow mapping

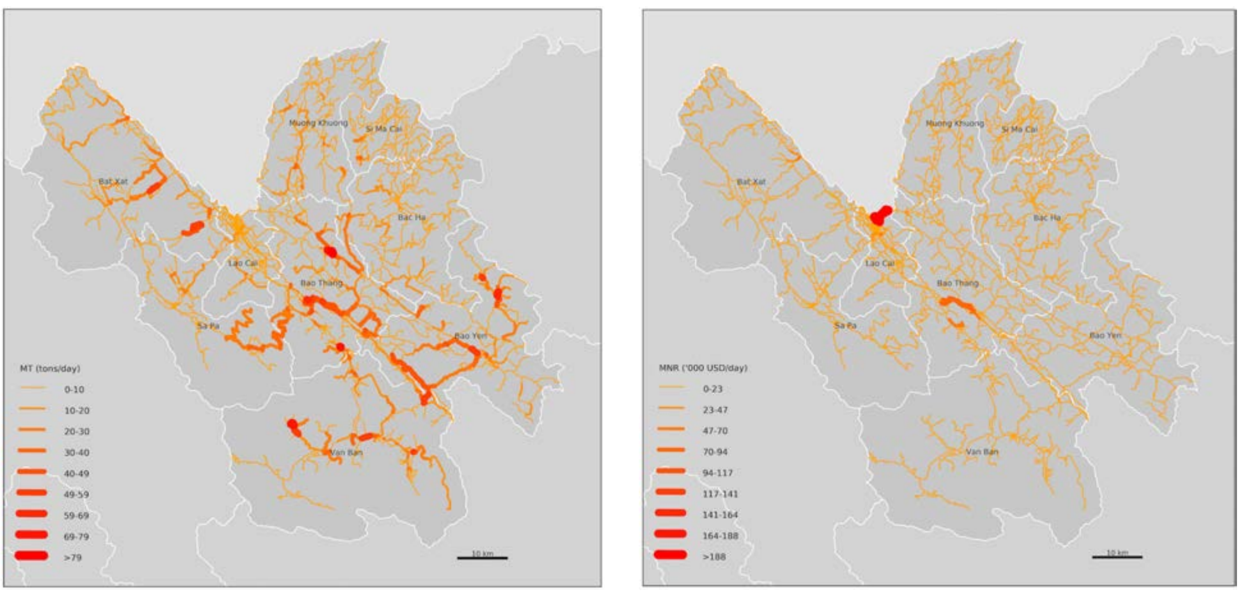
Traffic flows and revenues on province-scale road networks have been calculated based on the IFPRI crops data (Koo et al 2018), and commune-level revenue statistics from GSO.[3] Figure 2.2 (Lao Cai), figure 2.3 (Binh Dinh), and figure 2.4 (Thanh Hoa) show heat maps of flow concentrations due to maximum daily crop tonnages (panel A) and maximum daily net revenues (panel B), in US$ thousands per day) being directed toward commune centers of the respective provinces.

The results predominantly highlight the effect of road density in the provinces. For Lao Cai, where the road network is not very dense, some road clusters (e.g., in the Bao Yen district) have more significant usage than others. On the other hand, for Thanh Hoa the road network is very dense, with many route options, making the flows patterns more distributive with few clusters of very significant roads. The road network is sparse in parts of Binh Dinh, which creates more significant clusters in locations such as Lao Cai, while fewer clusters exist in areas where the network is dense, as in Thanh Hoa.

The analysis by commodity highlights the net revenue's dependence on agriculture productivity:

- For Lao Cai, the non-agriculture firm revenues dominate the minimum and maximum net revenue distributions on the network, which result in little variations in flow patterns.
- In Binh Dinh, the dependence on agriculture production results in some differences between the minimum and maximum net revenue allocations.
- In Thanh Hoa, again, the amount of agriculture production affects the net revenue.

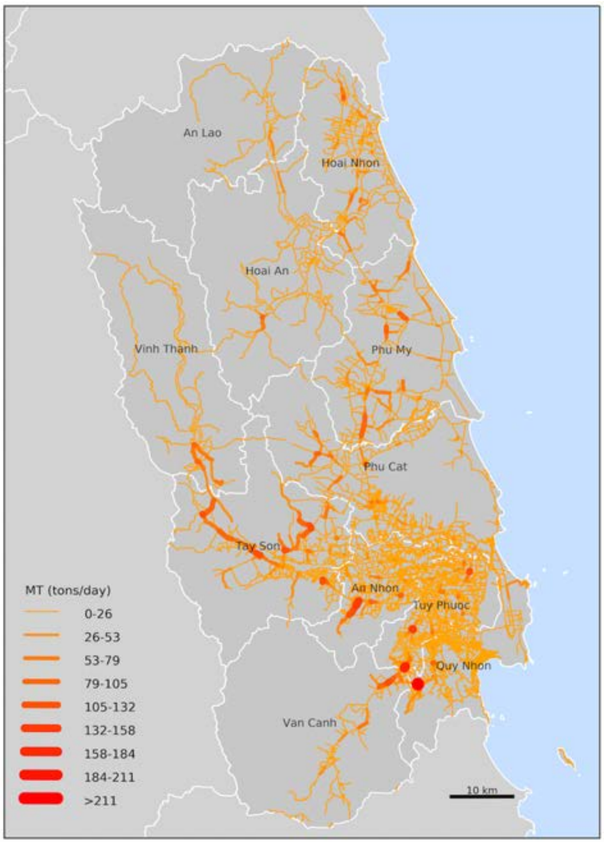
Figure 2.2. Maximum Crop Flows toward Nearest Commune Centers and Maximum Net Revenues on Lao Cai Provincial Roads



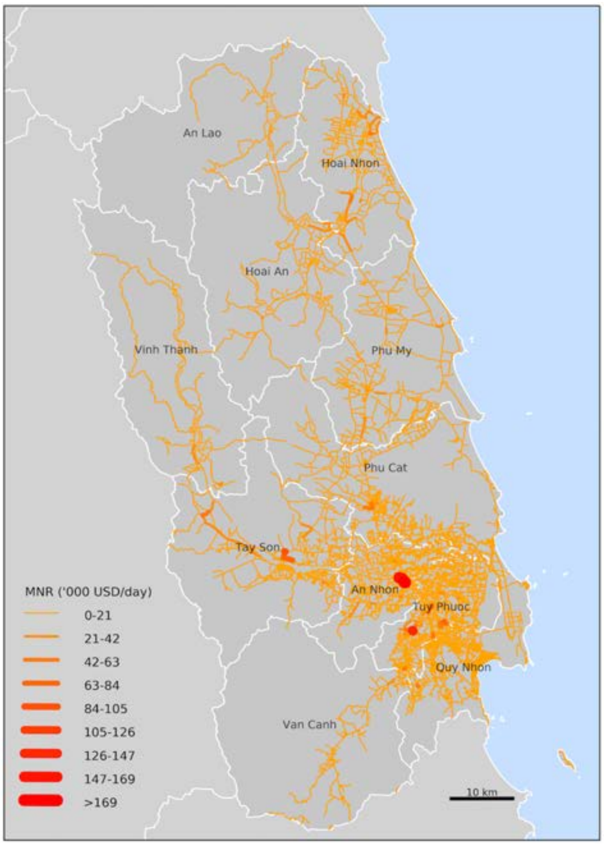
A. Maximum tons of crop flows in Lao Cai

B. Maximum net revenue of crop flows in Lao Cai

Figure 2.3. Maximum Crop Flows toward Nearest Commune Centers and Maximum Net Revenues on Binh Dinh Provincial Roads

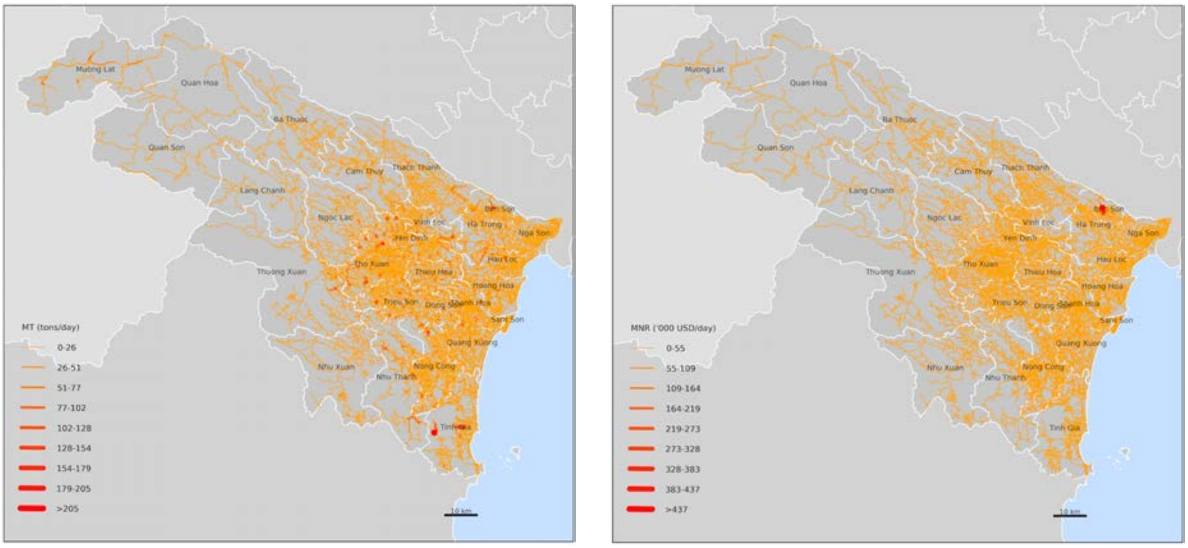


A. Maximum tons of crop flows in Binh Dinh



B. Maximum net revenue of crop flows in Binh Dinh

Figure 2.4. Maximum Crop Flows toward Nearest Commune Centers and Maximum Net Revenues on Thanh Hoa Provincial Roads



A. Maximum tons of crop flows in Thanh Hoa

B. Maximum net revenue of crop flows in Thanh Hoa

Uncertainties in freight flow mapping

The national-scale results show the maximum estimates of flow under the following assumptions:

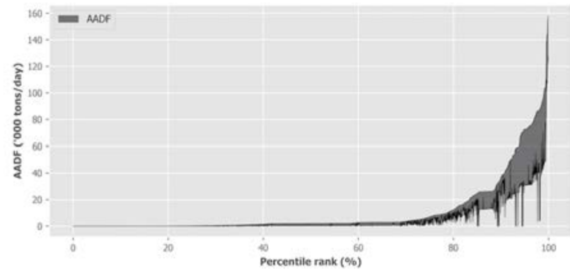
- Estimated from the high-level OD matrices, daily OD tonnages represent the highest daily tonnages allocated on the transport links.
- Based on the highest generalized costs of the flows, flow assignments depend on travel speeds and transport tariffs.

Considering the range of OD tonnage, this report captures and presents the uncertainties in estimated flows. Figures 2.5A through 2.5D show the ranges of daily freight flow estimates along network links for the national road, railway, inland waterway, and maritime sectors. The results illustrate the flows, ranked from lowest to highest, based on the maximum estimated flows along links. Accordingly, the x-axis is labeled as "percentile rank," where the percentile rank of 80 implies that 80 percent of links have flows lower than that link.

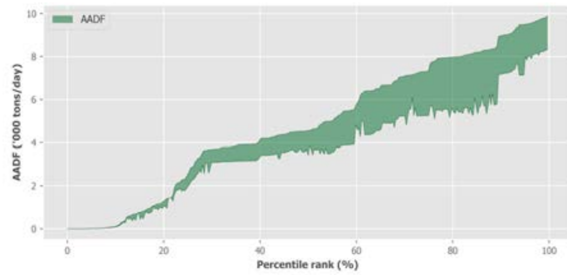
Each of these figures gives a sense of the uncertainties of flow estimates along links. These uncertainties are driven mainly by two factors: a) fluctuations in OD estimates, which depend upon the seasonality of production and transport; and b) changes in route choice due to fluctuating generalized transport costs, which depend upon speeds and transport tariffs. The relative contributions of these factors toward flow uncertainties can be measured by comparing the minimum and maximum flow assignment routes for the same OD pairs. If the minimum and maximum flow assignment routes are the same, then flow assignments are only sensitive to the volumes of OD tonnages. If the minimum and maximum flow assignment routes differ, then the flow assignments are sensitive to the generalized costs of transports.

The analysis for the national-scale road network shows a 28 percent difference between the minimum and maximum flows for the same OD pairs, suggesting 28 percent of the flow is sensitive to the transport costs. In figure 2.5A, some links show significant variability between minimum and maximum average annual daily freight (AADF) flows, resulting in some noticeable spikes in the plot. Analysis shows small differences in the railway, inland waterway, and maritime network flows, signifying that the flow uncertainties in figures 2.5B through 2.5D are driven by changing OD tonnages rather than changes in the transport costs assigned to these networks. This is explained by the greater variability in attributes of the road network, such as roads types, terrains, speeds, and tariffs, which leads to greater sensitive of traffic flows.

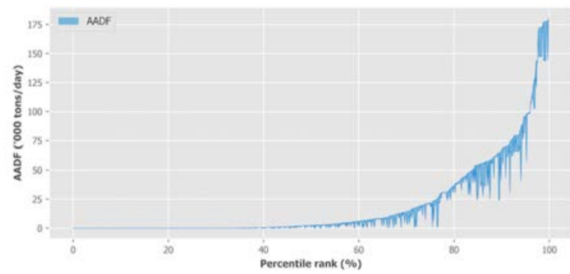
Figure 2.5. Ranges of AADF Flows by Mode



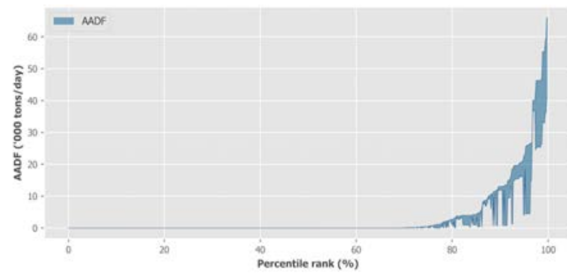
A. Range of AADF flows on road links



B. Range of AADF flows on railway links



C. Range of AADF flows on inland waterway links

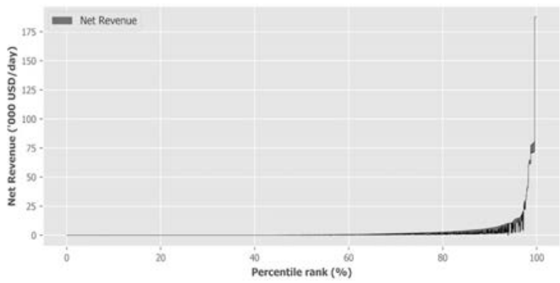


D. Range of AADF flows on maritime links

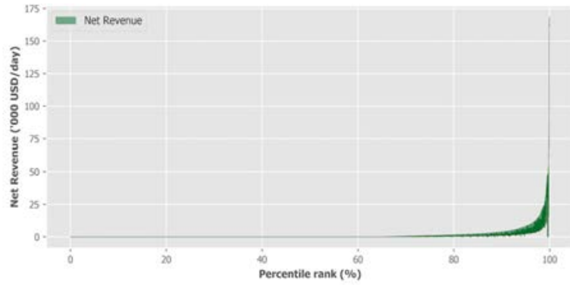
Similar to the national-scale network, flow assignments on the province-scale networks are also uncertain due to changing values of net revenues generated within communes, and the changing transport costs on roads used to gain access to the nearest commune centers. Figures 2.6A through 2.6C show the ranges of ranked net revenue flow estimated along network links for the province-scale road networks of Lao Cai, Binh Dinh, and Thanh Hoa. When compared to other network links, most road links in each province produce lower values of assigned net revenue flows, due to the concentration of economic activities near a handful of communes with limited access to road routes.

The analysis shows small differences between the chosen routes in the minimum and maximum net revenue flow assignments between villages, crop production sites, and the commune centers. For Lao Cai, only 1.6 percent of the minimum and maximum flow assignment routes differ, with a 2.6 percent difference for Binh Dinh, and a difference of 3.3 percent for Thanh Hoa. Thus, the changing transport costs have very little influence on the transport patterns and the resulting uncertainties in the values of net revenue flows along links, due mainly to most commutes between origins (villages and crop production sites) and destinations (communes) covering small distances along local networks with few alternative routes.

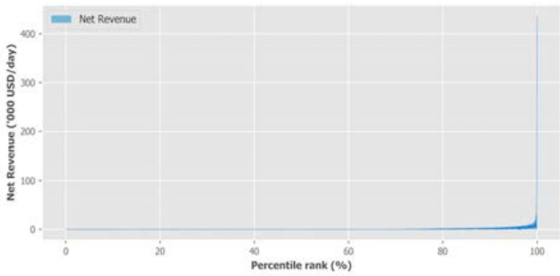
Figure 2.6. Ranges of Net Revenue Flows Assigned to Road Networks in Lao Cai, Binh Dinh, and Thanh Hoa



A. Net revenue flows on links in Lao Cai



B. Net revenue flows on links in Binh Dinh



C. Net revenue flows on links in Thanh Hoa

Natural Hazard Exposure of Transport Networks

The study assembled four main types of natural hazard datasets:

- *Landslide susceptibility zonation maps* include classification of the types, areas, and spatial distribution of existing and future landslides. These maps show the relative spatial likelihood for the occurrence of landslides by type and volume—or area (Fell et al 2008).
- *Flashflood susceptibility zonation maps* similarly show the relative spatial likelihood that a heavy rain event will become stationary and protracted over an area (Hapuarachchi et al 2011).
- *Typhoon induced flood maps* estimate the increases in storm surge heights induced by pressure gradients created by typhoons along coastal areas, which translate to over-land inundations (Lapidez et al 2015).
- *Fluvial flood maps* show inundation caused by rivers overtopping their banks.

Of the above hazards, only the fluvial flood map data offered a country wide spatial coverage, whereas all other types of hazard map data covered only certain parts of the country. The study assumed all hazard maps without any future climate change scenarios represent hazard events for the present risks in the year 2016. From the underlying datasets, the study selected spatial extents and areas where hazard levels exceeded the threshold needed to be considered *catastrophic enough to cause transport failures.*

The study accessed some of the natural hazards maps with future climate change model outputs developed by MoNRE, based on the internationally recognized Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios (Meinshausen et al 2011). RCP4.5 scenarios assume that global emissions peak around the year 2040 and then decline, while RCP8.5 scenarios assume no decline in global emissions through the 21st century.

In addition, the study looked at flashflood and landslide susceptibility maps for fifteen northern provinces generated for RCP4.5 and RCP8.5 scenarios in 2025 and 2050. The study also accessed fluvial flood maps for the whole country showing current flooding and future flooding under RCP4.5 and RCP8.5 scenarios in 2030, from the GLOFRIS (Winsemius et al 2013) model. See appendix B, including table B.2, for a detailed description of the hazard datasets.

Per the IPCC definition (IPCC 2014), the study conducted a hazard exposure analysis as the first component of a vulnerability assessment. Only areas of high and very high landslide and flashflood susceptibility as well as areas of flood depths greater than or equal to 1 meter were considered in the study's extreme hazard scenarios. The analysis aimed to identify the types of hazards to which transport assets are most exposed to and the changes in the hazard exposures due to various climate change scenarios.

National-scale road and railways hazard exposures

Table 2.6 shows the overall minimum and maximum total kilometers of the national-scale road and railway networks in Vietnam that are exposed to different extreme hazard levels. For every hazard where future climate change scenarios are considered, the lengths of road and railway networks exposed to extreme hazards would increase due to climate change. For instance, while approximately 720 km to 1,163 km of the national road network is exposed to extreme river flooding in the current flooding scenarios, the network lengths would increase to between 786 km and 1,180 km under a future RCP4.5 scenario. In the case of river flooding, the minimum exposure values correspond to the lowest return periods (two or five years), while the maximum exposure values correspond to the 1,000-year return period flood maps.[4] While the road networks are most exposed to river flooding, railways are most exposed to landslides, primarily in the coastal provinces.

Table 2.6. Lengths of National Roads and Railway Networks Exposed to Different Types of Hazards

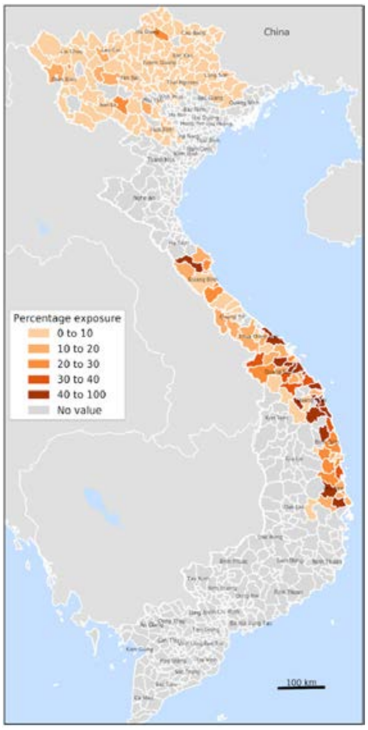
Hazard type	Climate scenario	Year	National roads exposures (kilometers)		National rail exposures (kilometers)	
			Min.	Max.	Min.	Max.
Flashflood susceptibility[a]	—	2016	188	188	3	3
	RCP 4.5	2025	197	197	3	3
		2050	222	222	3	3
	RCP 8.5	2025	211	211	3	3
		2050	235	235	3	3
River flooding	—	2016	720	1,163	88	117
	RCP 4.5	2030	786	1,180	97	121
	RCP 8.5	2030	785	1,174	97	119
Landslide susceptibility[b]	—	2016	896	896	189	189
	RCP 4.5	2025	276	276	7	7
		2050	320	320	9	9
	RCP 8.5	2025	289	289	7	7
		2050	334	334	10	10
Typhoon flooding[c]	—	2016	783	783	123	123

Note:
a. The flashflood susceptibility data cover only 15 northern provinces.
b. The landslide susceptibility data for current scenarios cover 8 central and 15 northern provinces. The future climate scenarios cover only 15 northern provinces.
c. The typhoon flooding data cover only 28 coastal provinces.

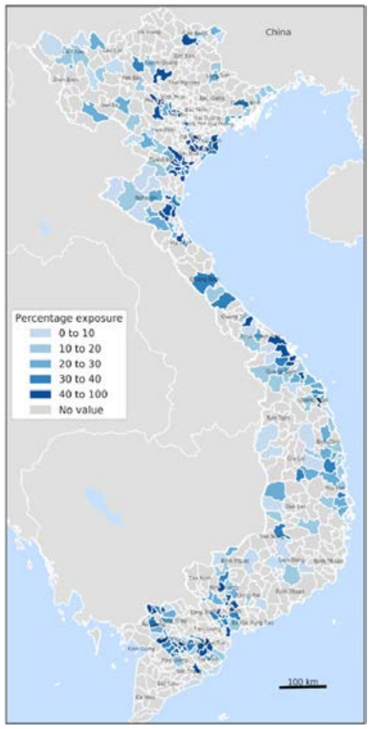
By examining the spatial patterns of the hazard exposures presented in figure 2.7 and figure 2.8, additional insights can be derived by examining the spatial patterns of the hazard exposures for the national-scale road and railway networks respectively.[5] Each of the figures shows (at the district-level) the percentage network kilometers exposed to the worst-cases of current (2016) levels. The spatial patterns of extreme hazard exposures reveal the districts with very high percentages (greater than 40 percent) of networks exposed to extreme hazards, especially for landslides, river flooding, and typhoon flooding. Based on the above findings, the study analysis indicates districts with elevated percentages of exposure face high potential for transport failures.

The study next considered the effects shown in climate change scenarios, examining the spatial changes to national-scale road and railway networks caused by exposures to extreme river flooding. Figure 2.9 shows the change in percentage kilometers with road links exposures to the 1,000-year return period river flooding. Panel A shows the effects in 2030 under the RCP 4.5 emission scenario and panel B illustrates the RCP 8.5 emission scenario. These changes compare to the figure 2.7b result. Though the worst-case scenarios of river flooding in general show a very slight decrease in risk, the results shared in figure 2.9 and 2.10 provide an important takeaway: climate change could cause some regions to face a substantial increase in network flooding. In consideration of advanced planning for climate change, such locations should be examined further for potential failure impacts.

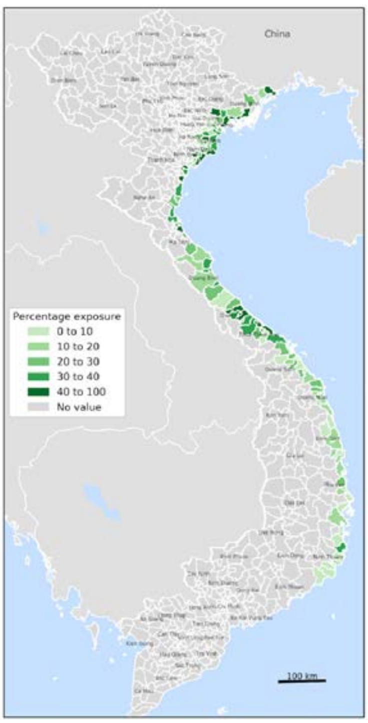
Figure 2.7. Hazard Exposure of National-Scale Roads Network in Vietnam



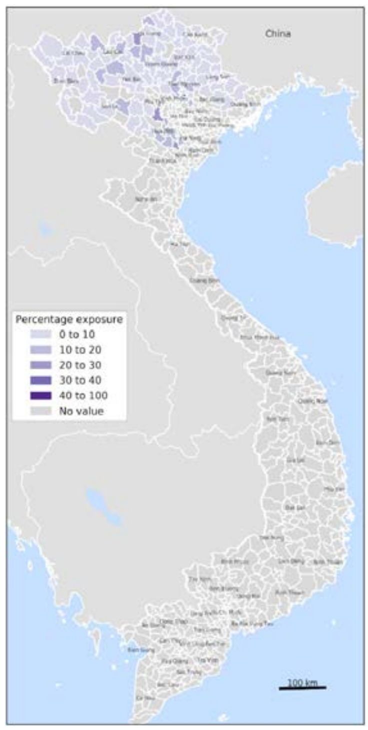
A. Extreme landslide susceptibility exposures



B. Extreme 1,000-year river flooding exposures



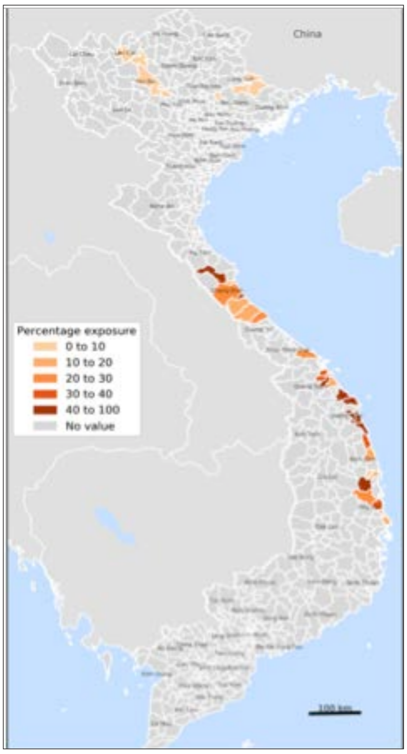
C. Extreme typhoon flooding exposure



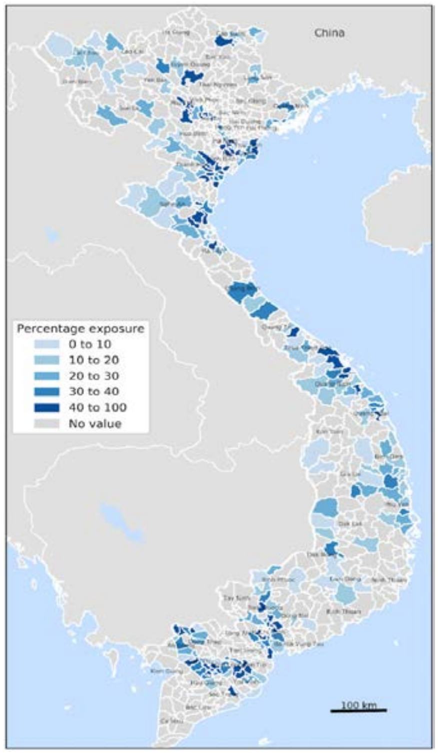
D. Extreme flashflood susceptibility exposure

Note: Panel A= landslides, where landslide susceptibility is high and very high; panel B = river flooding, where flooding depth exceeds 1 meter for a 1,000-year event; panel C = typhoon flooding, where flooding depth exceeds 1 meter; and panel D = flashfloods, where flashflood susceptibility is high and very high.

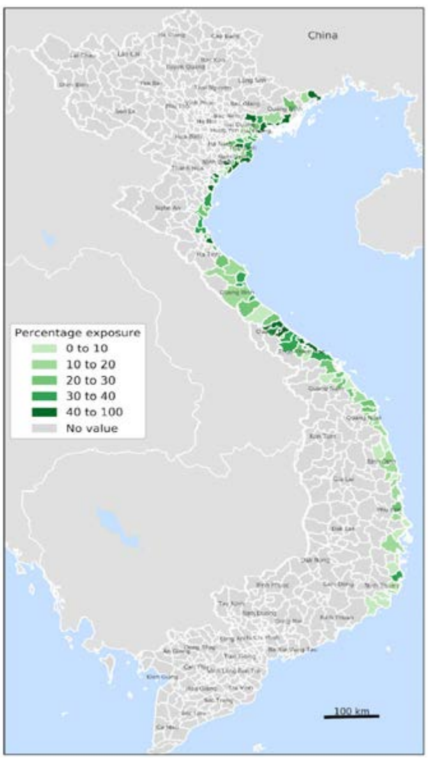
Figure 2.8. Hazard Exposure of National-Scale Railway Network in Vietnam



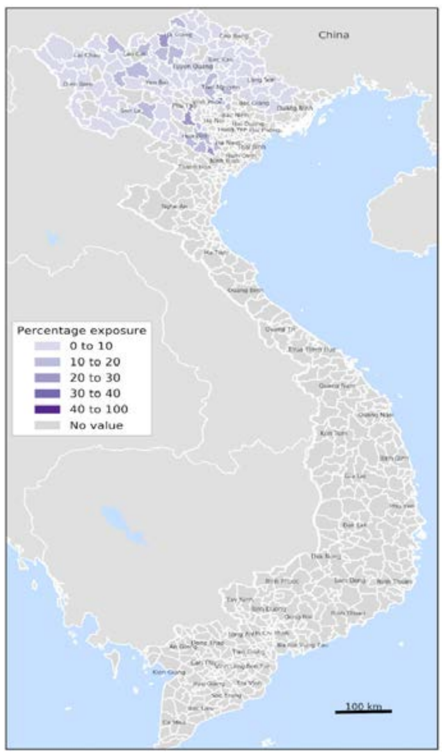
A. Extreme landslide susceptibility exposure



B. Extreme 1,00-year river flooding exposure

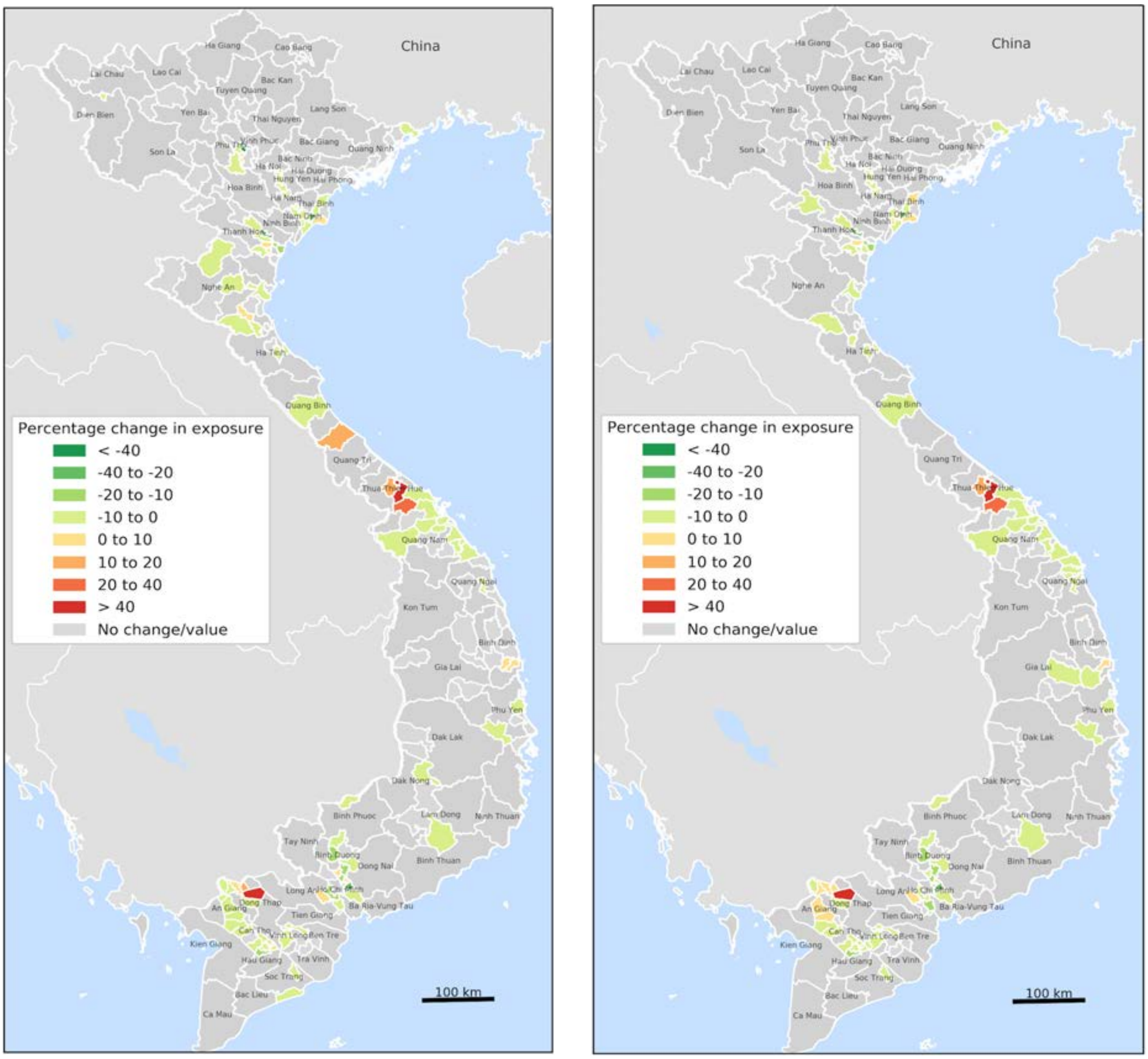


C. Extreme typhoon flooding exposure



D. Extreme flashflood susceptibility exposure

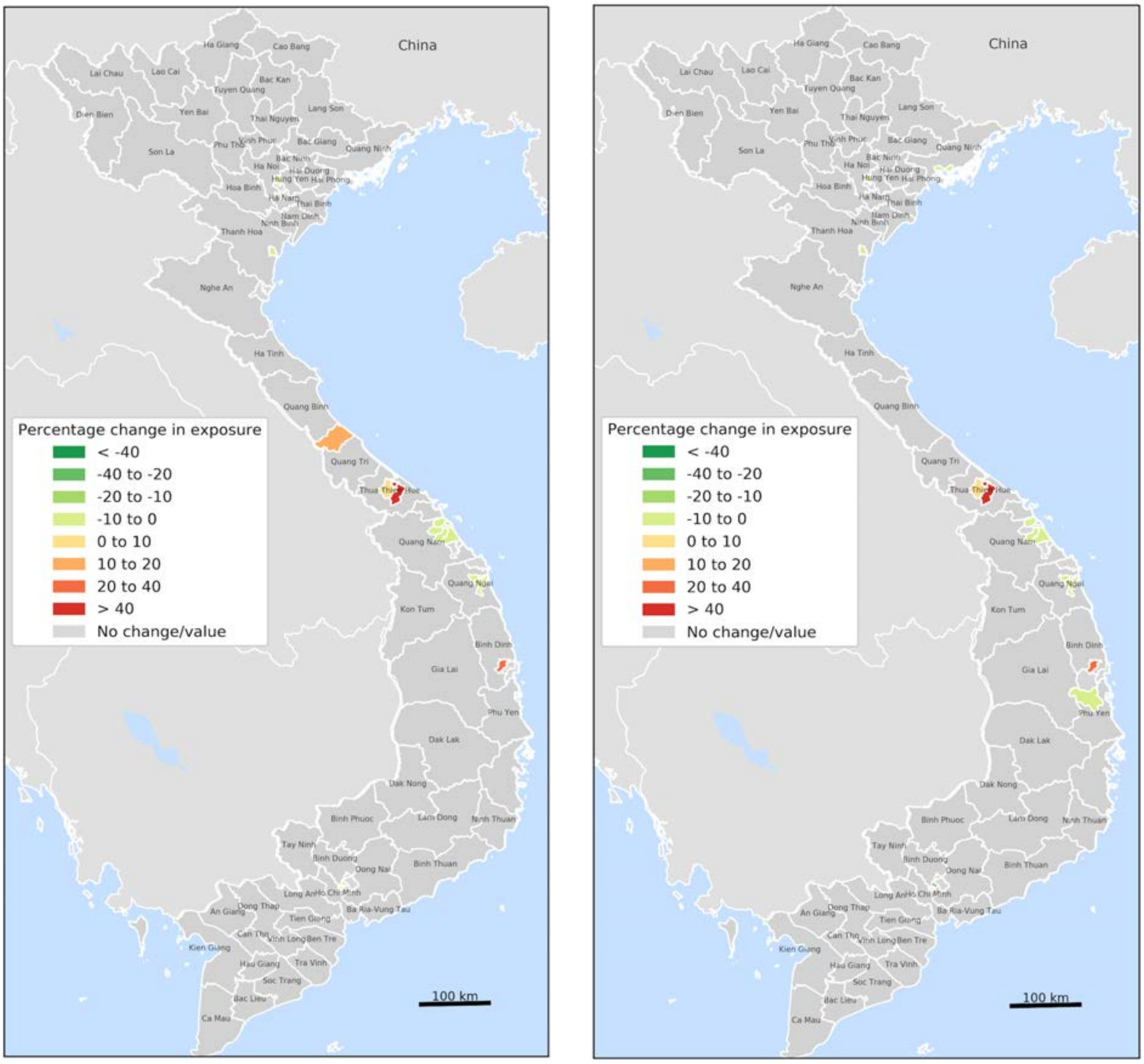
Figure 2.9. Percentage Change in Exposure of National-Scale Road Network to 1,000-Year River Flooding by 2030



A. Percentage change for fluvial flooding (RCP 4.5 2030)

B. Percentage change for fluvial flooding (RCP 8.5 2030)

Figure 2.10. Percentage Change in Exposure of National-Scale Rail Network to 1,000-Year River Flooding by 2030



A. Percentage change for fluvial flooding (RCP 4.5 2030)

B. Percentage change for fluvial flooding (RCP 8.5 2030)

Province-scale hazard exposure of roads

The study conducted similar analysis for the province-scale roads. Table 2.7 shows the minimum and maximum kilometers of the province-scale road networks exposed to various extreme hazard levels, as specified by the underlying hazard data. The results show that Lao Cai and Binh Dinh experience the highest exposures to extreme landslides, while in Thanh Hoa, river flooding causes the highest exposures. Generally, the current and future climate change scenarios indicate minor differences between the worst-case hazard exposures.

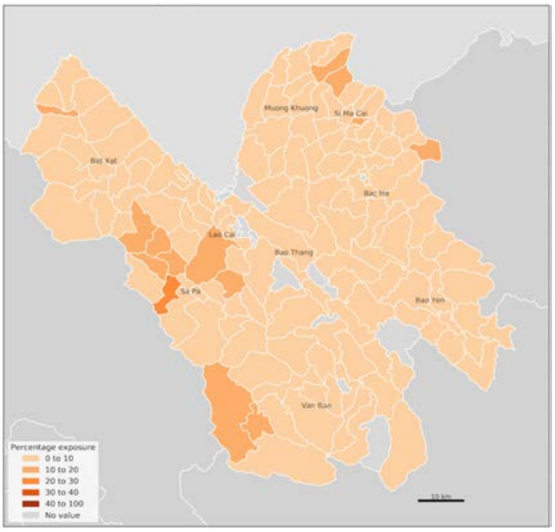
Table 2.7. Exposure of Province Roads Networks to Hazards

Hazard type	Climate scenario	Year	Road hazard exposures (km.)					
			Lao Cai		Binh Dinh		Thanh Hoa	
			Min.	Max.	Min.	Max.	Min.	Max.
Flashflood susceptibility	—	2016	88	88				
	RCP 4.5	2025	88	88				
		2050	93	93				
	RCP 8.5	2025	90	90				
		2050	132	132				
River flooding	—	2016	57	57	534	539	1,803	1,841
	RCP 4.5	2030	57	57	535	543	1,875	1,910
	RCP 8.5	2030	55	57	534	539	1,864	1,889
Landslide susceptibility	—	2016	142	142	801	801	921	921
	RCP 4.5	2025	145	145				
		2050	180	180				
	RCP 8.5	2025	163	163				
		2050	210	210				
Typhoon flooding	—	2016			315	315	592	592

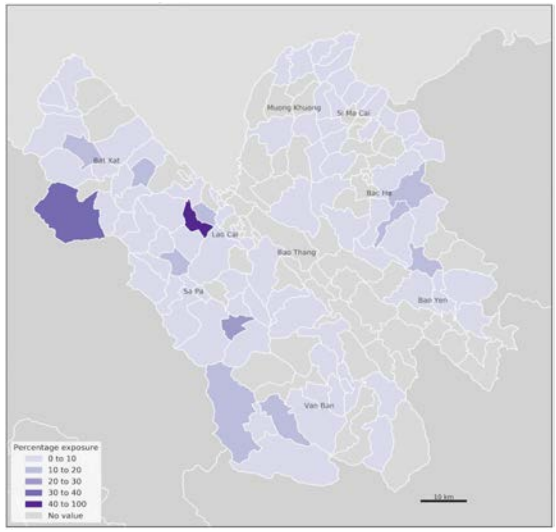
Geospatial analyses highlight the locations where much higher percentages of road network kilometers are exposed to extreme hazards. Figure 2.11 shows the commune-level percentages of roads exposed to hazards in Lao Cai, where the spatial landslides are more prevalent more communes are prone to flashfloods and river flooding. As shown in figure 2.13, exposures of roads to landslides are far more pronounced throughout Binh Dinh and similarly in Thanh Hoa, as shown in figure 2.15. From these maps, the study identified the *communes facing increased multiple hazard threats due to the high percentages of roads exposed one or more hazards* (see appendix D).

The study also looked at climate change-induced exposure scenarios for hazards affecting provincial road networks. In Lao Cai, figure 2.12 shows changes in exposures to extreme landslides in 2050 under RCP 4.5 and RCP 8.5 scenarios, which results in a greater number of communes experiencing increased percentages of roads exposed to extreme landslides, with a more pronounced increase under the RCP 8.5 climate scenario. In figure 2.14, similar comparisons are seen in Binh Dinh for extreme 1,000-year river flooding under climate scenarios, with an increased exposure of roads to extreme river flooding. The results for Thanh Hoa, shown in figure 2.16, highlight substantial clusters of communes where climate change causes a potentially significant (greater than 40 percent) increase of roads exposed to extreme 1,000-year river flooding (see appendix D).

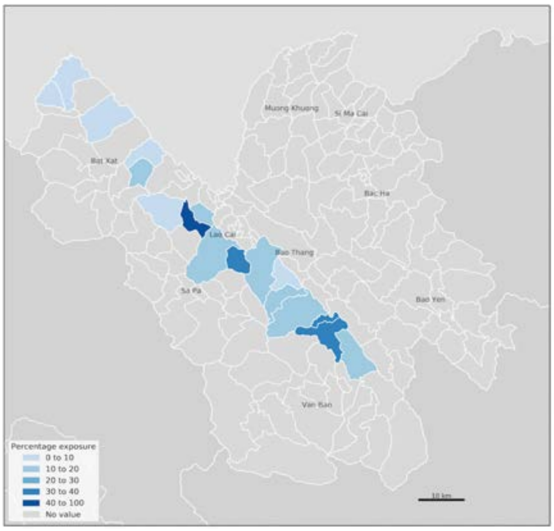
Figure 2.11. Hazard Exposure of Province Roads Network in Lao Cai



A. Extreme landslide susceptibility exposures

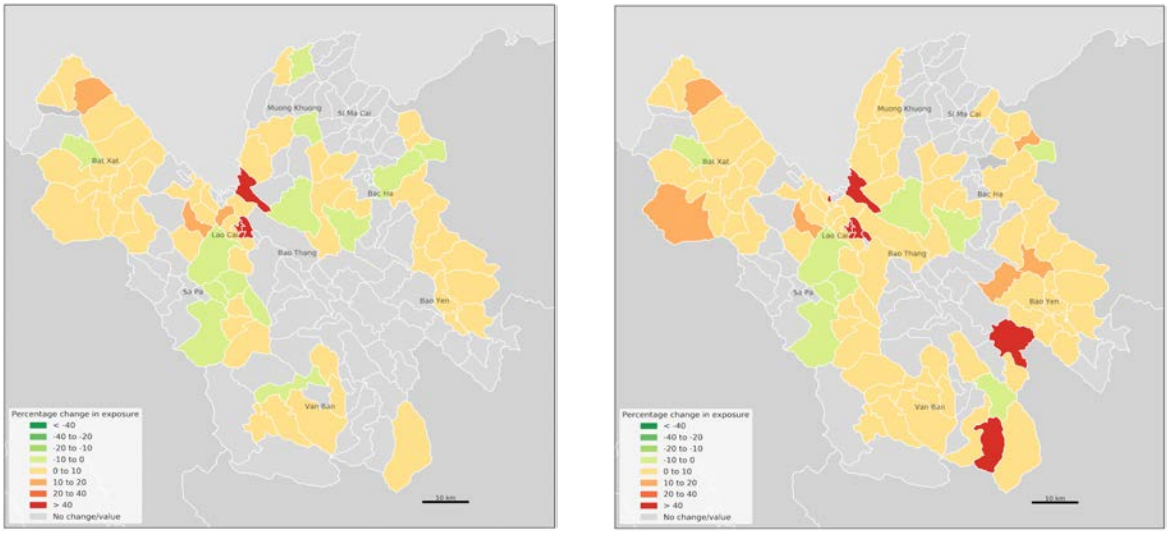


B. Extreme flashflood susceptibility exposures



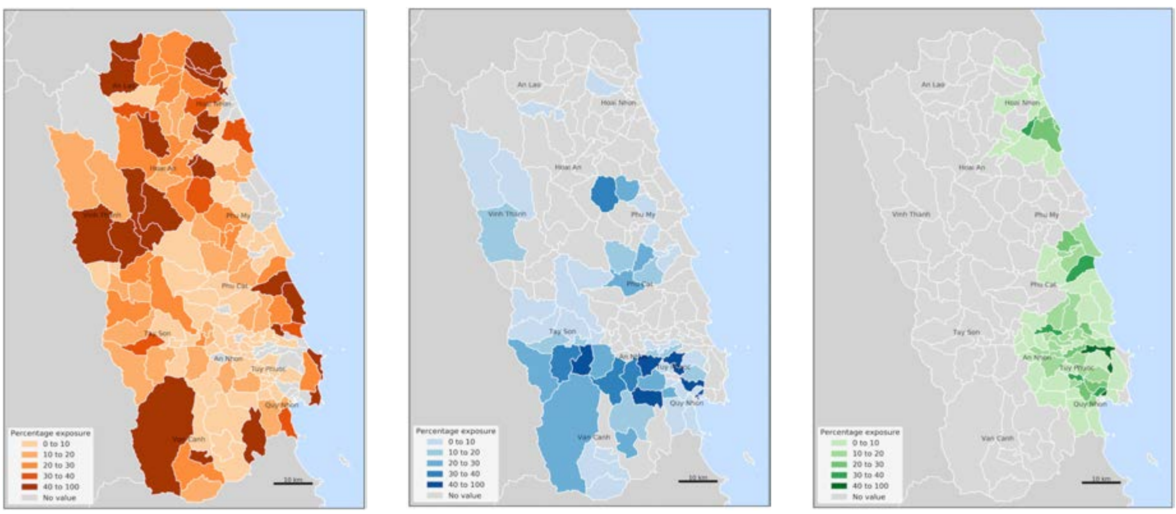
C. Extreme river flooding

Figure 2.12. Percentage Change in Exposure of Lao Cai Road Network Links to Landslides by 2050



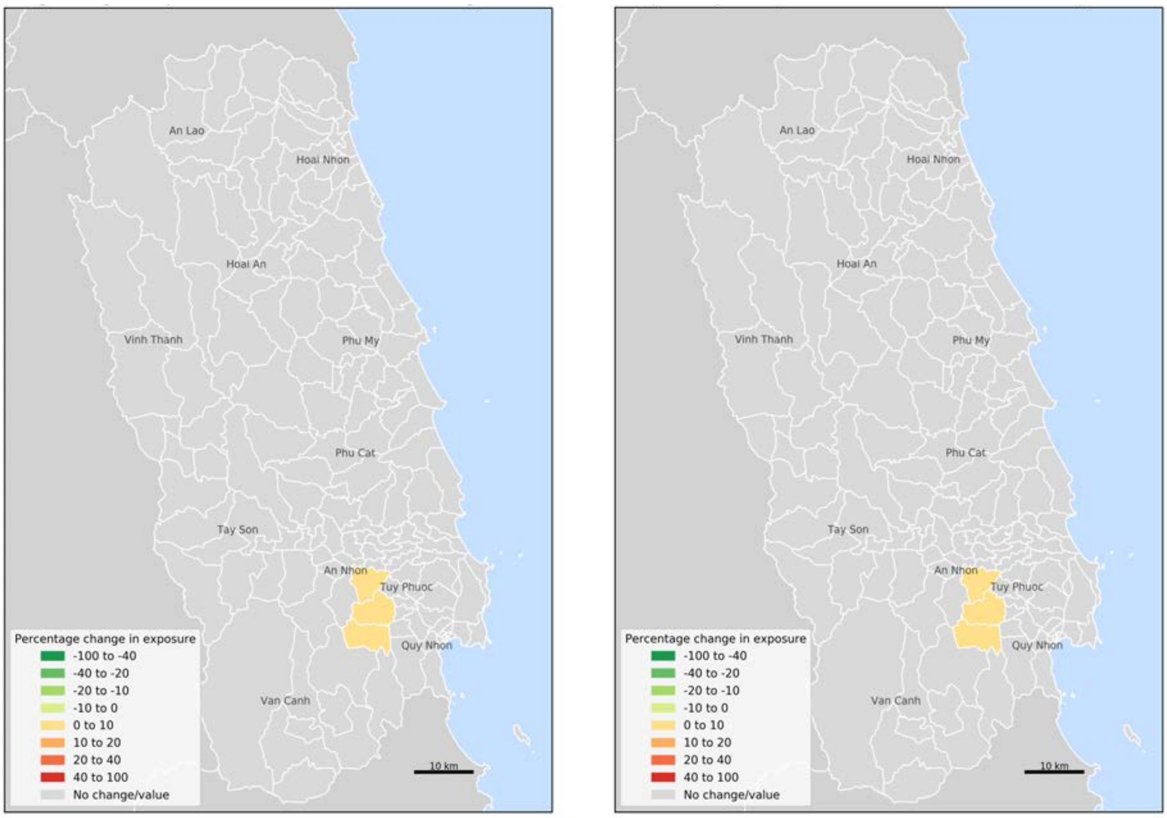
A. RCP 4.5 2050 **B. RCP 8.5 2050**

Figure 2.13. Hazard Exposure of Province Roads Network in Binh Dinh



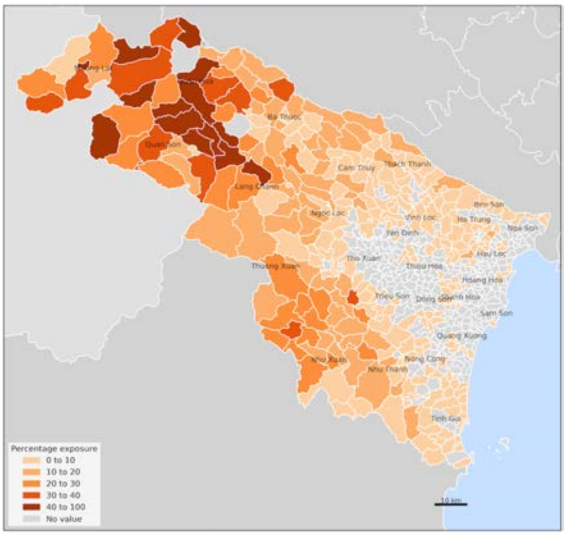
A. Extreme landslide susceptibility exposures **B. Extreme river flooding exposures** **C. Extreme typhoon flooding exposures**

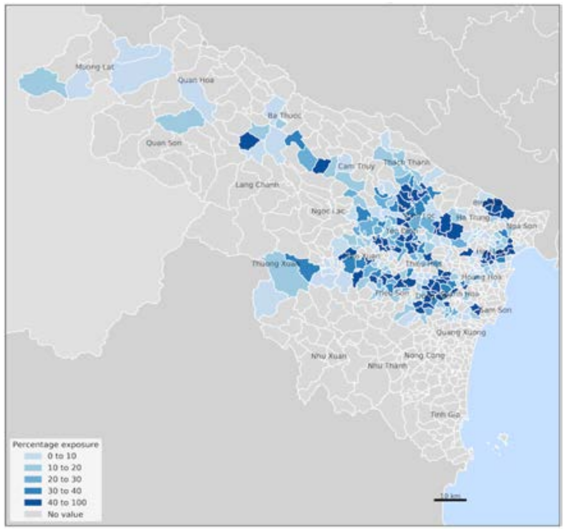
Figure 2.14. Percentage Change in Exposure of Binh Dinh Road Network Links to 1,000-year River Flooding by 2030



A. RCP 4.5 2030 **B. RCP 8.5 2030**

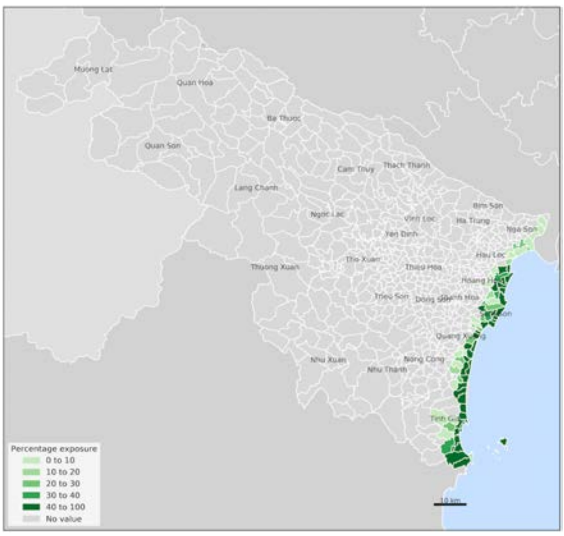
Figure 2.15. Hazard Exposure of Province Roads Network in Thanh Hoa





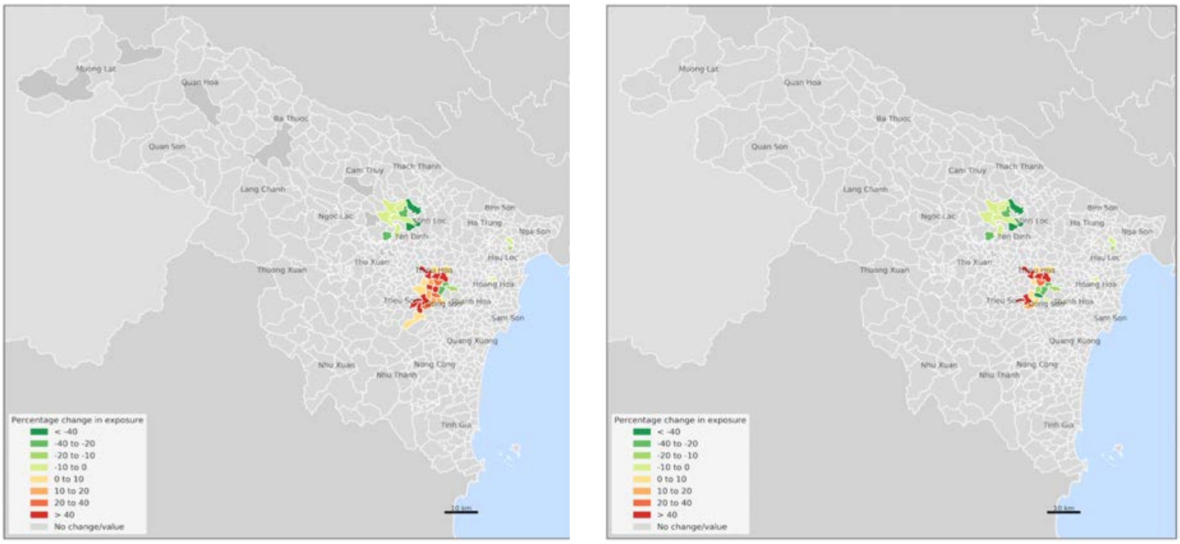
A. Extreme landslide susceptibility exposures

B. Extreme flashflood susceptibility exposures



C. Extreme typhoon flooding exposures

Figure 2.16. Percentage Change in Exposure of Thanh Hoa Road Network Links to 1,000-Year River Flooding by 2030



A. RCP 4.5 2030 **B. RCP 8.5 2030**

Notes

1. Data accessed at: http://cangben.viwa.gov.vn.

2. GSO transport statistics, available at: https://www.gso.gov.vn/default_en.aspx?tabid=781.

3. GSO transport statistics, available at: https://www.gso.gov.vn/default_en.aspx?tabid=778.

4. No variation between the minimum and maximum values results from the underlying hazard data having one realization.

5. The maps in figure 3.9 and figure 3.10 provide a sense of the spatial extents and disaggregation of the underlying hazard data, where flashflood exposures are clearly confined to northern areas because the underlying hazard data only existed for those regions. Similarly, landslides exposures are limited by the spatial coverages of the underlying data. As stated previously, only river flooding datasets offered whole-nation coverage.

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Chapter 3: Vulnerability, Criticality, and Risk Assessment

This chapter brings the results of the analyses presented in Chapter 2, to analyze vulnerability, criticality and risk assessment of flow disruptions on the assembled transport networks for Vietnam. Here, the analysis considers an exhaustive set of exposure scenarios for failure, assessing the socio-economic impacts through a variety of metrics to identify the network locations with the greatest impacts. For each network, the analysis quantifies the ranges of disruptive impacts across each hazard to understand whether hazard impacts will increase in future climate scenarios.

Vulnerability and Criticality Assessment

After identifying the network links exposed to different extreme levels of hazards, a vulnerability assessment can be conducted. Vulnerability assessments, completed within the context of the hazards, result in understanding the relative impacts of hazards on the continued transport availability. Once the vulnerability assessment is done, a criticality assessment can provide results in ranking network elements, based on their relative impacts on the serviceability of the transport networks (Arga Jafino 2017).

The criticality analysis performs an exhaustive analysis of the individual network links' "what if failure" scenarios. Having been exposed to the extreme levels of hazards, these links exist in potential failure locations. The criticality analysis serves as useful as a first step in exploring and evaluating the systemic performance in a generalized context, impartial to the nature of the external shock event. The assessment can identify the most critical links in the networks, which can then be used to help select a smaller set of links for further hazard risk analysis. Such exploratory analysis can be used to examine whether the most critical links identified have also been exposed to hazards, thus providing a strong case for detailed site-specific analysis.

The criticality assessment aims to answer the following questions:

- Which links and routes along the networks are most important to the continued service of network flows?
- Which individual links failures result in macroeconomic disruptive impacts, and what are the magnitudes of those disruptive impacts?
- Which individual links failures have most impacts on the costs of rerouting flows?

In response, the study created and estimated the following criticality metrics:

- *Average annual daily freight (AADF) disruptions*: The potential daily tonnage of freight flow disrupted by the failure of individual network links exposed to any hazard considered in the study.
- *Total macroeconomic loss*: The sum of the direct and indirect macroeconomic losses in US$ per day, due to the losses of commodity flows that create economic supply and demand imbalances in the economy. Such losses arise from individual links whose failure causes trip isolations, where the only available route option along the origin-destination (OD) route becomes physically inaccessible through the failed edge.

- *Freight redistribution cost metric*: The total difference between the post-disruption and pre-disruption generalized cost estimates of all OD flows rerouted due to edge failure. The freight redistribution costs are assigned to the edge whose failure causes those redistributions. These values show the most cost-effective links in the network.
- *Total economic impact metric*: The overall economic criticality of network links is measured as the sum of their macroeconomic losses and the freight redistribution costs incurred due to failures.

For the vulnerability and criticality assessments, the analysis selected individual network links based on the spatial intersection of networks and the hazards listed in table 3.1. The selection was limited to *the landslide and flashflood susceptibility areas with high and very high likelihood values as well as river and typhoon flooding areas with flood depths ≥1 meter*. Each selected transport network's links was intersected with all selected hazards to identify the exhaustive set of all unique nodes and links subjected to a hazard. The subsequent sections present and discuss only the following network results:

Table 3.1. Selected Numbers of Single Link Failure Scenarios for Different Transport Networks

Transport network selected	Unique single link failure scenarios
National-scale roads	968
National-scale railways	164
Lao Cai province roads	1,299
Binh Dinh province roads	11,042
Thanh Hoa province roads	26,852

National-Scale Road Network Criticality

Figure 3.1 shows the national-scale road network criticality results, including the maximum *AADF disruption* values in figure 3.1A. *The result highlights the network locations with very high flows, where there are threats of systemic disruptions due to exposures to extreme hazards*. The results show a cluster of roads around Ho Chi Minh and large sections of the QL1A trans-Vietnam highway with high AADF flows that could be disrupted by hazards. The highest ranges of potential AADF disruptions substantial, between 124,000 to 156,000 tons per day.

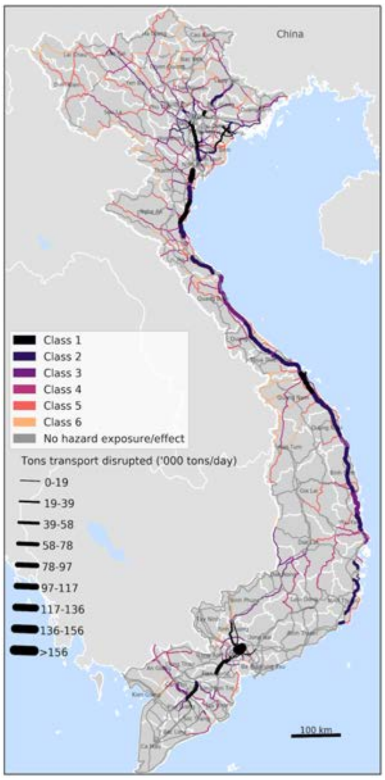
Figure 3.1B shows the maximum *total macroeconomic losses* in US$ million per day, based on the identified cases, where some of the AADF disruptions reported in figure 3.1A result in immediate macroeconomic losses. These trip isolations, where the commodities comprising the AADF mix cannot be transported, create supply and demand imbalances in the macroeconomic system. The process of estimating these macroeconomic losses is explained in appendix A. *This process can be treated as a worst-case assumption; realistically a disruption lasting a day will probably not produce macroeconomic losses. Therefore, the results can be interpreted to highlight the macroeconomic importance of network links*. Quite significantly, the results show that disruption of the major link toward Ho Chi Minh (DT743) could potentially create an estimated US$0.074 to US$0.44 million per day in macroeconomic losses. If this link is disrupted for a significant time, such losses could realistically materialize. The macroeconomic loss results also, importantly, highlight that large disruptions in tonnage might not necessarily result in significant economic losses in every case. In some cases, economic gains have resulted from regions substituting for production capacity losses in other regions, leading to reduced macroeconomic impacts and even net macroeconomic gains post-disruption.

Where the disrupted AADF flows can be rerouted along alternative routes, freight redistribution cost increases along disrupted links create significant failure impacts on the national road network. However, this comes at the price of increased transportation costs (figure 3.1c), where the values show the systemic freight redistribution costs on the whole network reported at the individual failed links. The highest rerouting costs can range between US$0.67 million per day (minimum flow disruption scenario) to US$1.90 million per day (maximum flow disruption scenario). Most of these are throughout sections of the QL1A trans-Vietnam highway, a very significant route in the country. In particular, the sections of this highway through Nghe Ah to Thanh Hoa show highest impacts on rerouting costs.

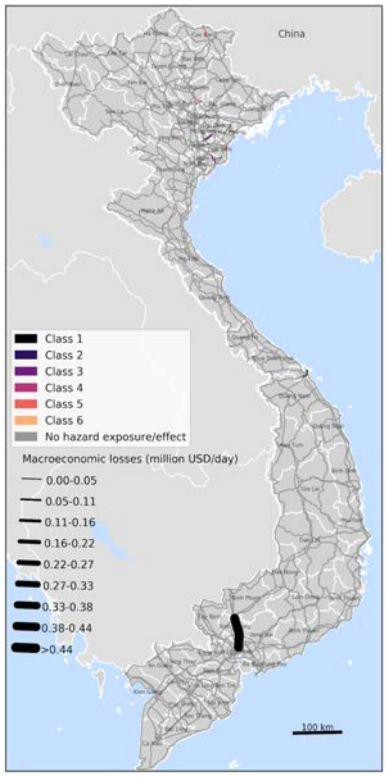
The *economic impacts* of road disruptions are shown in figure 3.1D, which combines the results from figures 3.1B and 3.1C. As discussed, the significant economic impacts are created by redistribution cost increases, rather than macroeconomic losses from trip isolations—with a few exceptions, such as the DT743 link.

Based on the model results, it could be worth considering whether the high costs of rerouting will result in companies' non-use of the roads while waiting for disrupted roads to be fixed, or partial use of the rerouting options during route reconstruction. This behavior has not been explored here, but this analysis provides a means to consider such possibilities.

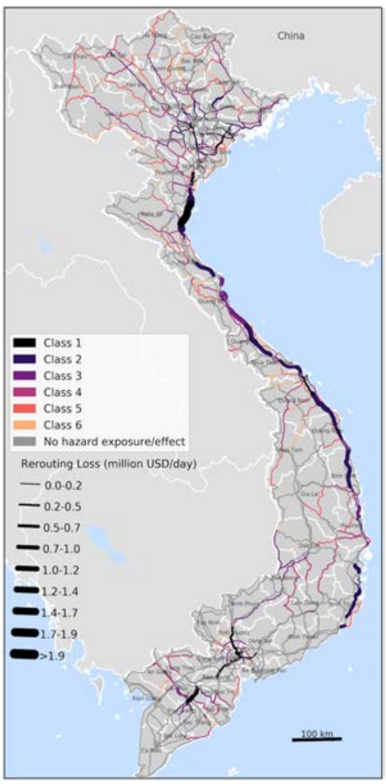
Figure 3.1. National-Scale Roads Criticality Results



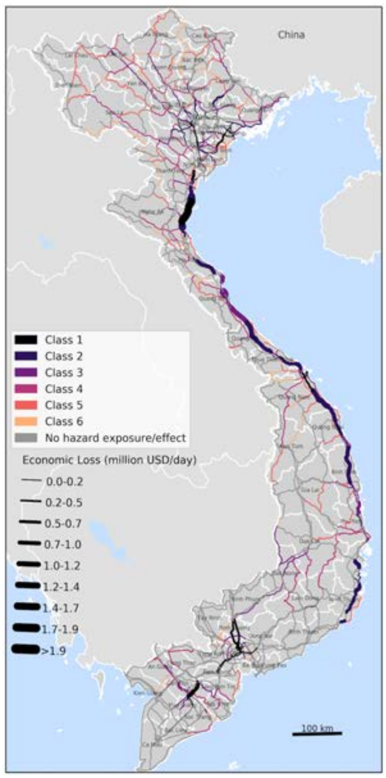
A. Maximum daily tons disrupted



B. Maximum macroeconomic losses



C. Maximum rerouting loss



D. Maximum total economic loss

National-Scale Railway Criticality

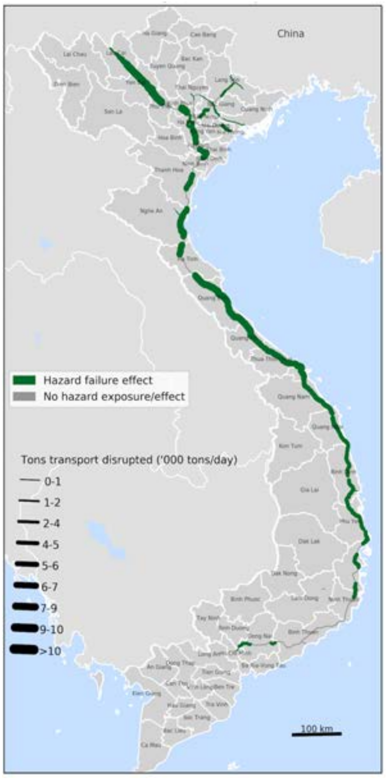
Figure 3.2 shows the results for the railway network. Given the single route structure along most of the railway network, link failures impact significant routes with very high flows, resulting in worst-case AADF disruptions between 8,000 to 10,000 tons per day (figure 3.2A).

Following the cases of AADF disruptions, figure 3.2B shows maximum *total macroeconomic losses* in US$ million per day, based on the assumption that the AADF losses reported result in immediate economic impacts. Quite significantly, the results show that railway disruptions can potentially result in very high economic losses, with economic losses on the busiest routes ranging from US$2.3 to 2.6 million per day. These results show that though the overall railway network usage is much less compared to roads, use is significant in the regions vulnerable to disruptions. The high impacts caused by railway distributions could be responsible for declining railway usage in Vietnam

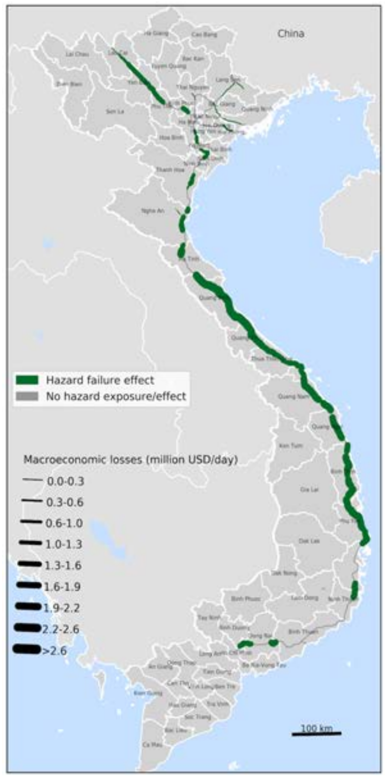
Figure 3.2C highlights the *freight redistribution cost*s, with a few links causing only minor impacts on redistribution cost increases along the railway network; the highest rerouting costs, at most US$9,000 per day, occur around the Hanoi hub.

The *economic impacts* of railway disruption (figure 3.2D) are created by the macroeconomic losses resulting from trip isolation redistribution cost increases, rather than redistribution cost increases alone. Based on the model results, the railway network shows very little redundancy in coping with disruptions.

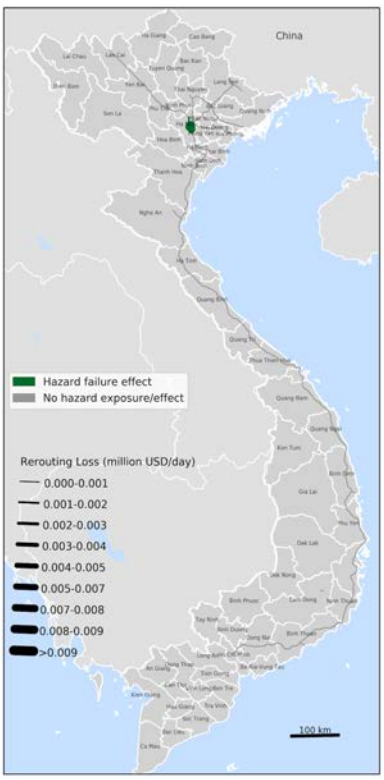
Figure 3.2. National-Scale Railway Criticality Results



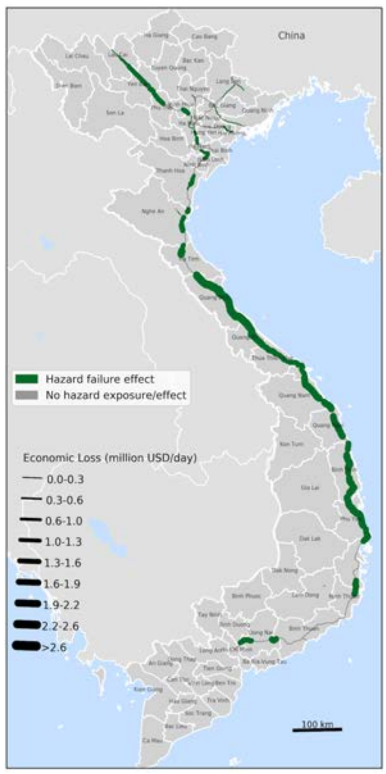
A. Maximum daily tons disrupted



B. Maximum macroeconomic losses



C. Maximum rerouting loss



D. Maximum total economic loss

Province-Scale Road Criticality

At the province scale, the study estimates road network criticalities in terms of:

- *Net revenue* flow disruptions, which potentially arise from hazard induced disruptions along accessible routes toward the commune centers.
- *Economic impacts* estimates, which represent the sum of the economic losses (the net revenue disrupted) due to the lack of accessible routes toward the commune centers, and the increases in *rerouting costs,* where post-disruption access to commune centers is maintained.

The results that follow highlight, through the net revenue flow disruption maps, potential disruptions to the network links most important in providing access to commune centers. Also, the maps highlight any rerouting options around each disrupted network link. Taking such rerouting into account, the results underline the economic impacts of disruptions. Crucially, the results show that the existence of rerouting options decreases the impacts of flow disruptions. The economic loss results prominently reveal the network links used most heavily for net revenue generation, whose failures would result in complete lack of access.

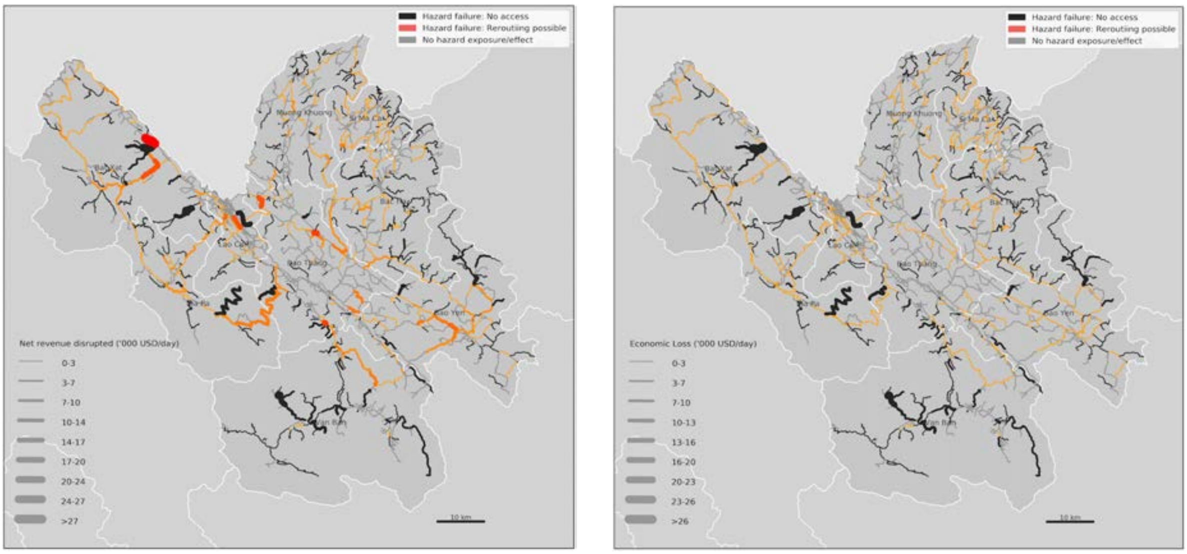
To give a sense of the worst-case scenarios of failures, the sub-sections that follow show only the maximum net revenue flow disruptions and maximum economic impacts.

Lao Cai province roads disruptions

The heat-map for Lao Cai province in figure 3.3A shows the maximum *net revenue flow disruptions* due to hazard-driven road failures. The spare concentration of roads in Lao—especially in the Bao Yen, Bat Xat, and Van Ban districts—focuses flow disruptions along fewer routes. Potentially, these net revenue flow disruptions can cause up to US$27,000 per day in economic losses.

The *economic impacts* shown in figure 3.3B reflect how the existence of rerouting options absorbs most of the potential disruptions in net revenue flows. However, some link failures cause complete loss of access to commune centers, resulting in worst-case economic losses of up to US$26,000 per day.

Figure 3.3. Maximum Estimated Disruption in Net Revenue and Maximum Economic Loss for Lao Cai Province Road Network



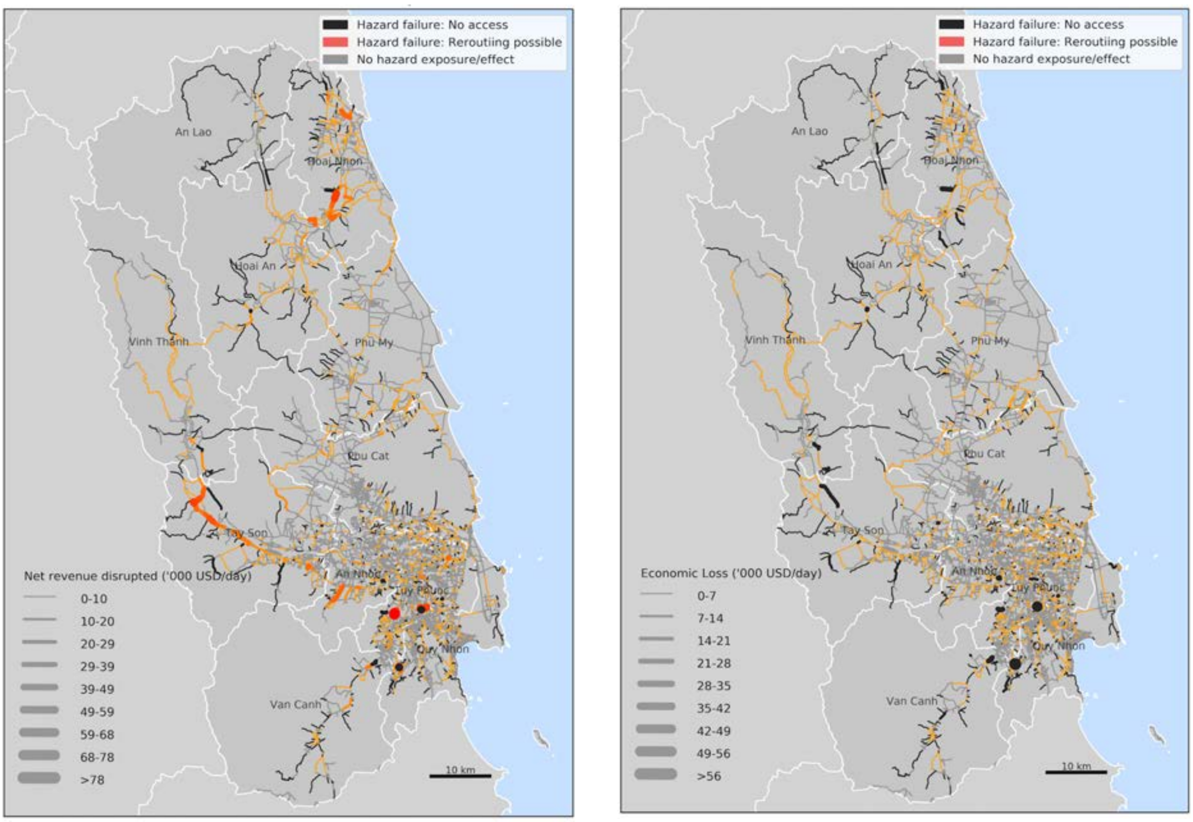
A. Maximum net revenue disruption in Lao Cai province

B. Maximum economic loss in Lao Cai province

Binh Dinh province roads disruptions

In figure 3.4, heat-maps for Binh Dinh province show the maximum *net revenue flow disruptions* (panel A) and maximum *economic impacts* (panel B) caused by hazard-driven road failures. Most of the network is very redundant, leading to insignificant impacts due to disruptions. However, a significant cluster in the Quy Nhon district, which has very high disruptive impacts, could see potential economic impacts of US$56,000 per day.

Figure 3.4. Maximum Estimated Disruption in Net Revenue and Maximum Economic Loss for the Binh Dinh Province Road Network



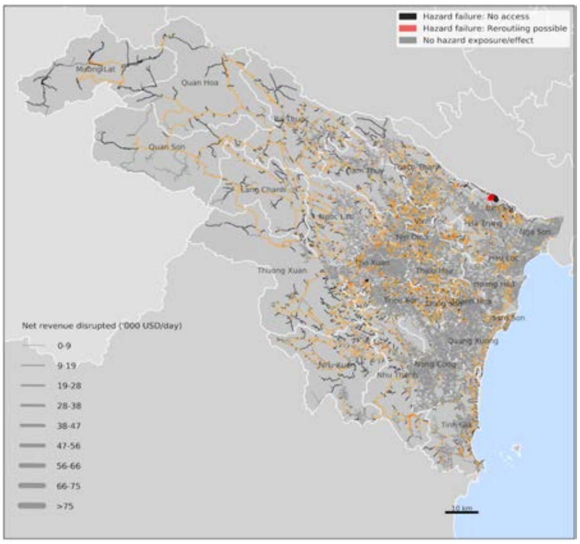
A. Maximum net revenue disruption in Binh Dinh province

B. Maximum economic loss in Binh Dinh province

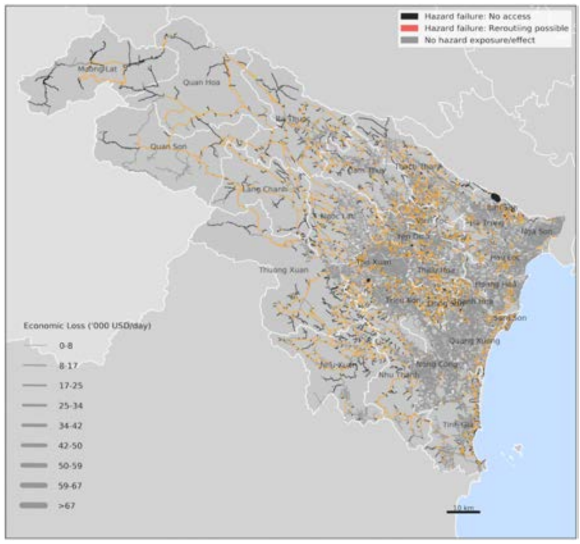
Thanh Hoa province roads disruptions

In figure 3.5, heat-maps for Thanh Hoa province show the maximum *net revenue flow disruptions* (panel A) and maximum *economic impacts* (panel B) resulting from hazard-driven road failures. Here again, most of the network is very redundant, leading to insignificant disruption-induced impacts. However, significant clusters in the Bim Son district with the highest disruptive impacts could see potential economic impacts of US$67,000 per day.

Figure 3.5. Maximum Estimated Disruption in Net Revenue and Maximum Economic Loss for the Thanh Hoa Province Road Network



A. Maximum net revenue disruption in Thanh Hoa province



B. Maximum economic loss in Thanh Hoa Province

Risk Assessment

Following the assessment of network link criticalities, the risk of extreme hazard failures can be estimated by combining the knowledge of the hazards and impacts into one metric. The main aim of the risk estimation is to identify:

- Which types of hazards have the most impacts on transport links?
- What are the changes in the hazard impacts due to different climate change scenarios?

The losses here signify the daily *economic impacts*, estimated in the criticality assessment, and multiplied by certain duration of disruption—during which the affected network link is assumed to be out of operation. To differentiate between the severities of events with different probabilities, the analysis assumed that the duration of disruption will depend upon what percentage of the network link's length is exposed to the extreme hazard for that event.

Limitation: The risk calculation results presented in the subsequent sections show very high values for the landslide and typhoon flooding events—and to some extent the flashflood events—based on the assumption that these hazards have a probability equal to one. The analysis made the assumption in the absence of any probabilistic information for these hazards. Because only the underlying river flooding hazards information is probabilistic, only the results for the river flooding risks capture the true nature of risk estimation.

National-scale networks

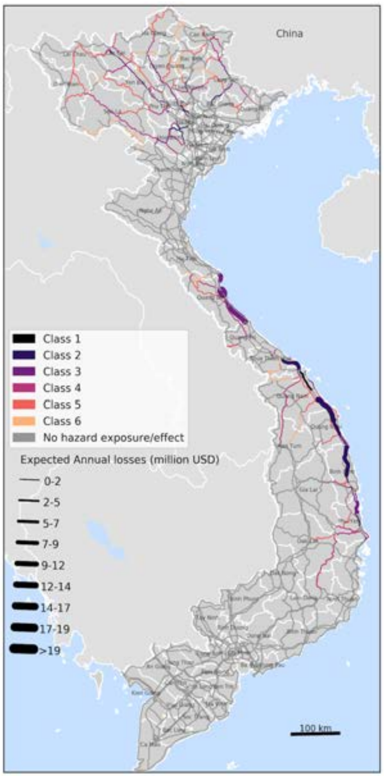
The results that follow for the national-scale road and railway network assume a maximum duration of disruption of 10 days, with a 500 m threshold length of exposure of a network link. Hence, if a network link length greater than 500 m was exposed to the chosen extreme hazard scenario, the results assumed a 10-day disruption. Below that length, the disruption duration depended upon the fraction of network length exposed to the hazard.

National-scale road network risks

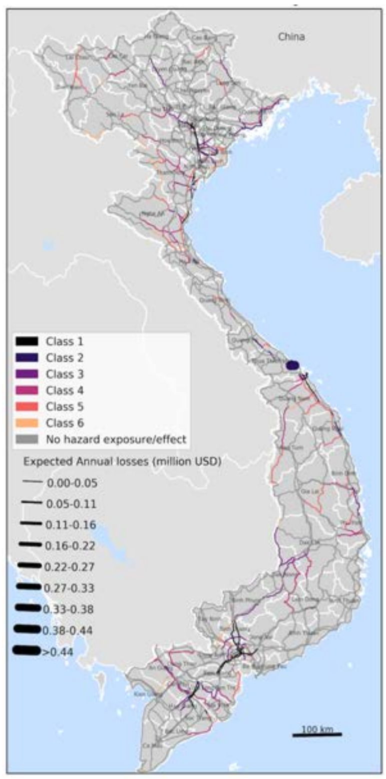
Figure 3.6 shows the maximum value of economic risks on the national-scale road network due to current 2016 hazards of, respectively, (A) landslide susceptibility, (B) river flooding, (C) typhoon flooding, and (D) flashflood susceptibility. *The results aim to highlight the hazard-specific high-risk locations on the network, which can be prioritized for further detailed investigations into climate resilience*. The analysis shows that risks along key sections of the QL1A trans-Vietnam highway are mainly driven by landslides and typhoon flooding, while river flooding affects links around Ho Chi Minh and Thua Then Hue, and flashfloods affect some mountain provinces due to the underlying hazards concentrated only in those regions.

To understand the changes in the hazard impacts due to climate change scenarios, the analysis compares road network risks due to future climate hazards with those due to the current day hazards. Such a comparison is possible only for river flooding because it is the only hazard that gives full national coverage of different probabilistic hazards under climate change scenarios. Both climate change scenarios for river flooding see a substantial increase in the value of systemic risks of future failure of national-scale road network links (figure 3.7). On almost all affected network links, the potential risks of failure due to river flooding increase by at least 40 percent in the future 2030 hazard scenarios, a substantial increase in risks that highlight a strong case to invest in building networks resilient to future climate hazards.

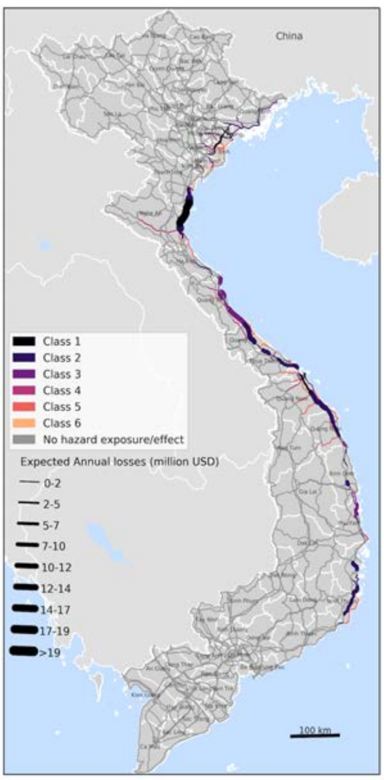
Figure 3.6. Maximum Estimated Risks for National-Scale Road Network Links



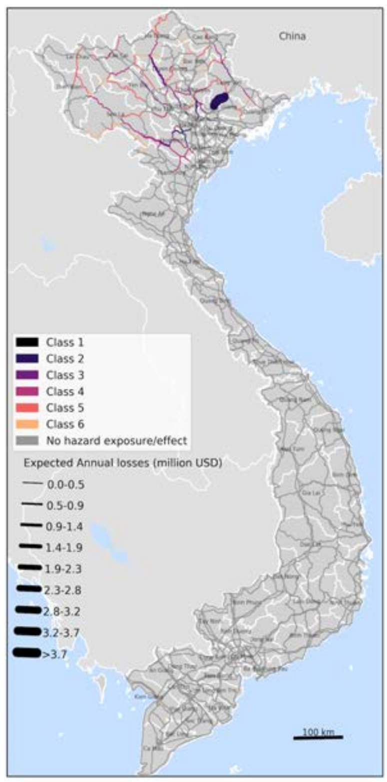
A. Landslide susceptibility maximum risks



B. River flooding maximum risks

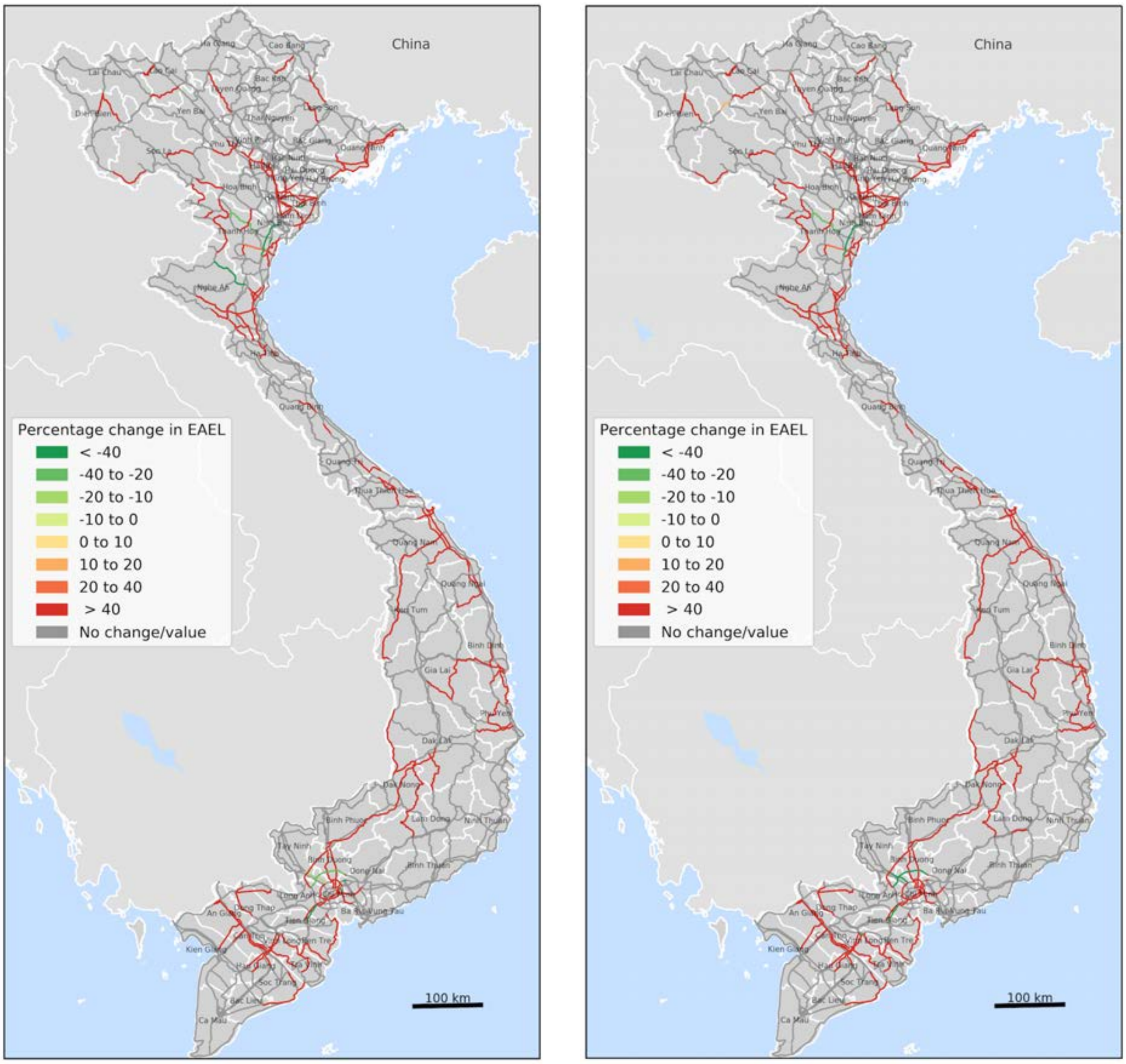


C. Typhoon flooding maximum risks



D. Flashflood susceptibility maximum risks

Figure 3.7. Percentage Change in Maximum Failure Risks of National-Scale Road Network Links for Future 2030 River Flooding under Climate Scenarios



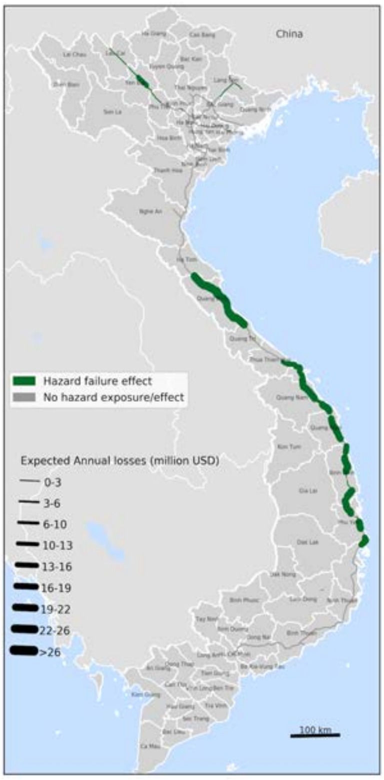
A. RCP 4.5 2030 **B. RCP 8.5 2030**

National-scale railway network risks

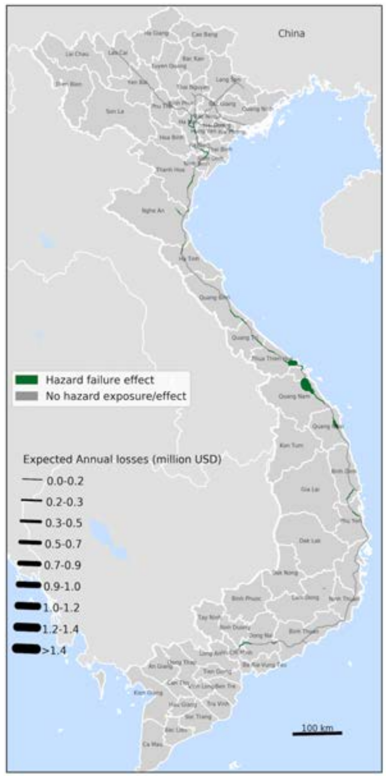
Similar to the results of the previous section, figure 3.8 shows the maximum value of economic risks on the national-scale rail network links due to current 2016 hazards of, respectively: (A) landslide susceptibility, (B) river flooding, (C) typhoon flooding, and (D) flashflood susceptibility. The analysis shows that large sections of the railways are at risk mainly due to landslides and typhoon flooding, while river flooding affects a small section of links around Quang Nam and Thua Then Hue, and flashfloods affect some mountain provinces due to the underlying hazards concentrated only in those regions.

For the railway network as well, the risks due to future climate change scenario-driven river flooding hazards in 2030 compare with those due to the current day river flooding hazards in 2016 (figure 3.9). Under both climate change scenarios of river flooding, systemic risks of national-scale rail network failure increases substantially in the future. Similar to the national-scale road network links, at almost all affected network links the potential risks of failure due to river flooding face a substantial increase of at least 40 percent in the future 2030 hazard scenarios, highlighting a strong case in Vietnam to invest in building national railways resilient to future climate hazards.

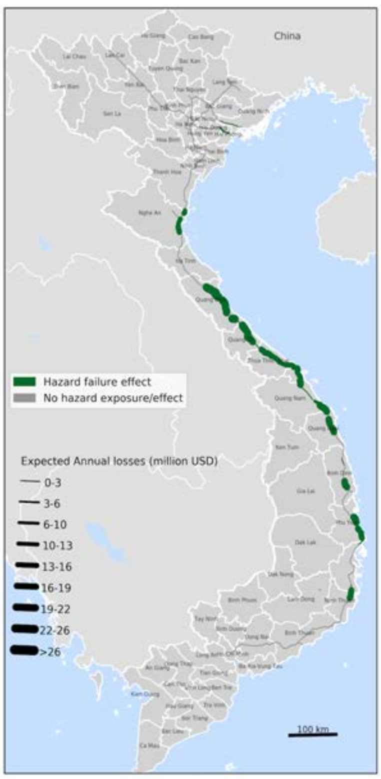
Figure 3.8. Maximum Estimated Risks for National-Scale Railway Network



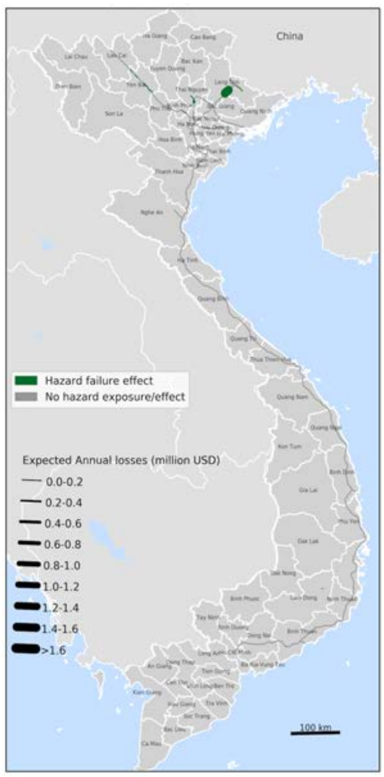
A. Landslide susceptibility maximum risks



B. River flooding maximum risks

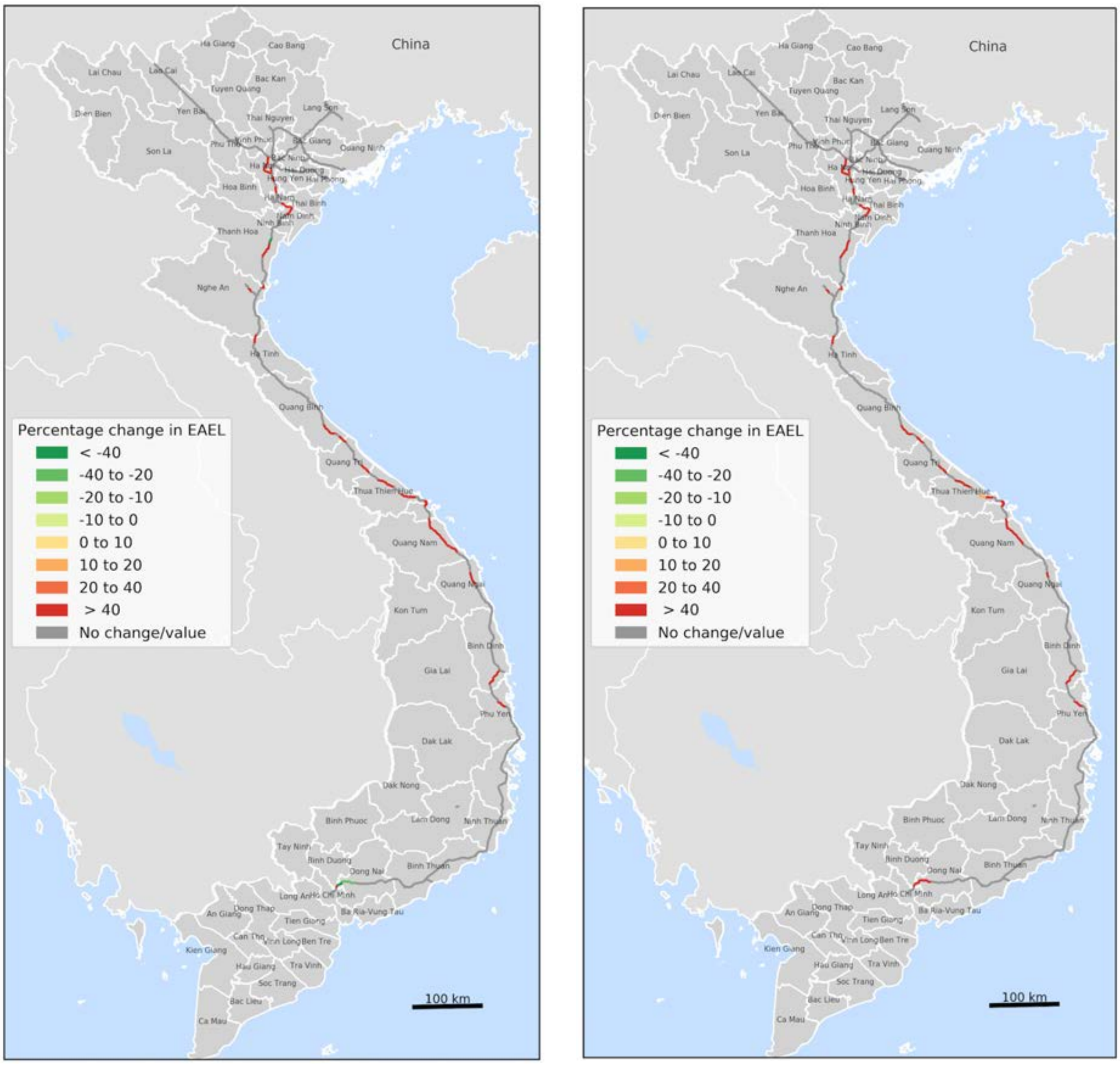


C. Typhoon flooding maximum risks



D. Flashfloods susceptibility maximum risks

Figure 3.9. Percentage Change in Maximum Failure Risks of National-Scale Rail Network for Future 2030 River Flooding under Climate Scenarios



A. RCP 4.5 2030 **B. RCP 8.5 2030**

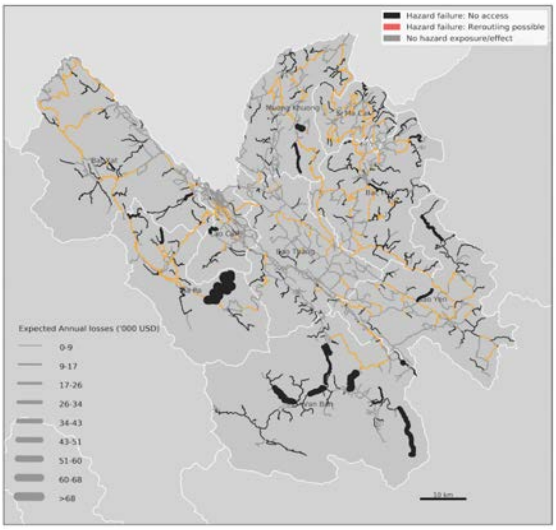
Province-scale analysis

The results for the province-scale road networks assume a maximum disruption duration of 10 days, with a 100 m exposure threshold length of a network link. Hence, if a network link greater than 100 m was exposed to the chosen extreme hazard scenario, the results assumed a 10-day disruption. Below that length, the duration of disruption depended upon the fraction of the length exposed to the hazard.

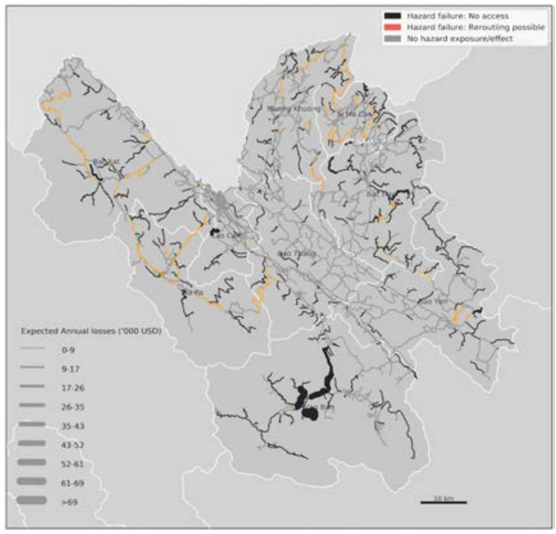
Lao Cai province-scale roads risks

The analysis highlights key sections of the network links in the Van Ban and Sa Pa districts affected by landslides, flashfloods, and river flooding (figure 3.10), whose failures results in high risks due to lack of access to their nearest commune centers.

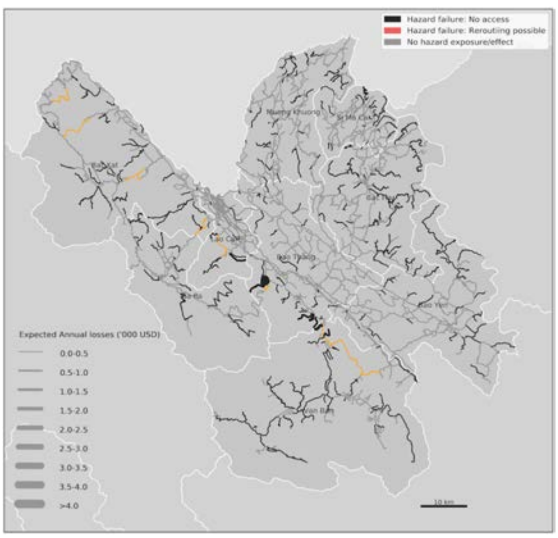
Figure 3.10. Maximum Risks of Lao Cai Province-Scale Road Network



A. Landslide susceptibility maximum risks



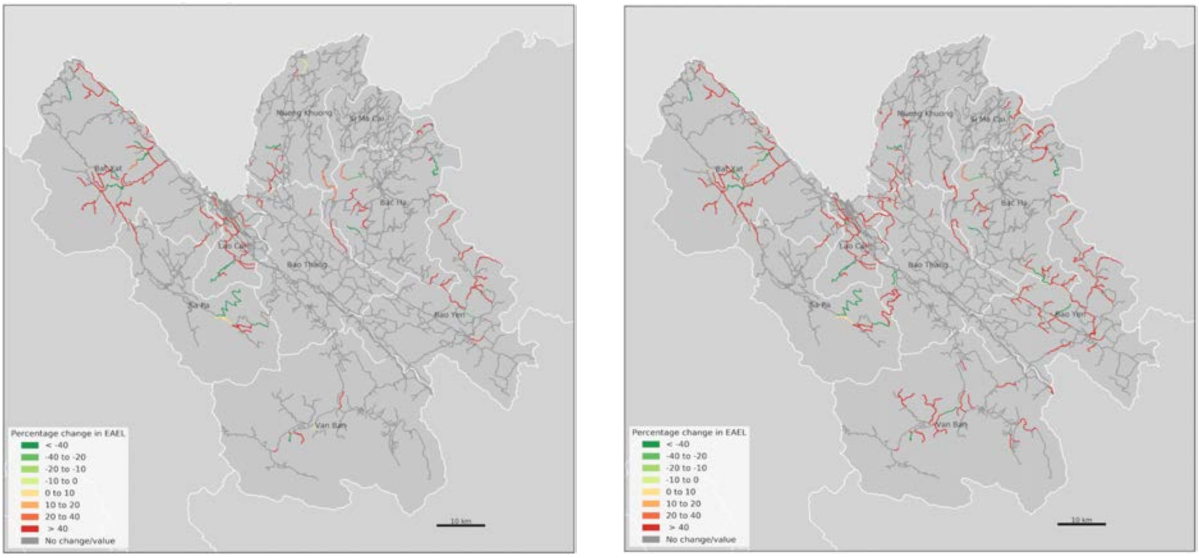
B. Flashflood susceptibility maximum risks



C. River flooding maximum risks

The analysis shows that along several roads in the Bat Xat, Lao Cai, Van Ban, and Bao Yen districts the future landslide-driven failure risks of large continuous sections of the road network increase substantially by at least 40 percent, with more severe changes under RCP 8.5 scenarios (figure 3.11). Hence, strongly indicating that future access to economic opportunities in this part of the province will be severely affected without investment in building climate-resilient roads.

Figure 3.11. Percentage Change in Maximum Failure Risks of Lao Cai Province-Scale Road Network Links for Future 2050 Landslide Susceptibility under Climate Scenarios



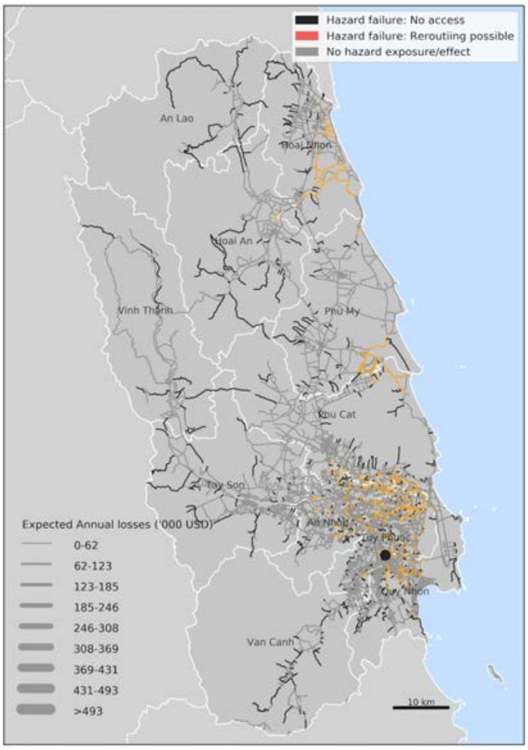
A. RCP 4.5 2050 **B. RCP 8.5 2050**

Binh Dinh province-scale roads risks

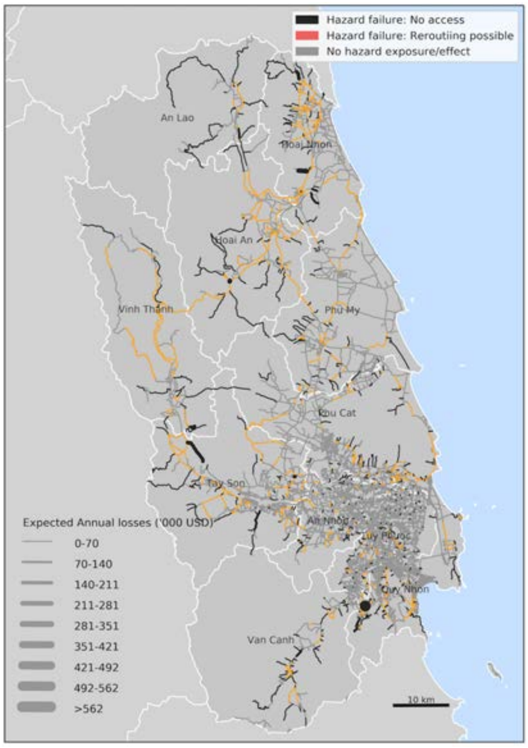
The analysis highlights key sections of the road network links in the Tuy Phuoc and Quy Nhon districts affected by landslides, typhoon flooding, and river flooding (figure 3.12), whose failures result in high risks due to large areas of economic activity experiencing a lack of access to their nearest commune centers.

The changing percentages of maximum risks due to climate change in the Binh Dinh province clearly indicate increasing risks due to road link failures from future climate change driven hazard scenarios, with expected annual losses in almost every case substantially increased by at least 40 percent (figure 3.13). Again, there is a strong indication that in the future, access to economic opportunities will be severely affected without investment in building climate-resilient roads.

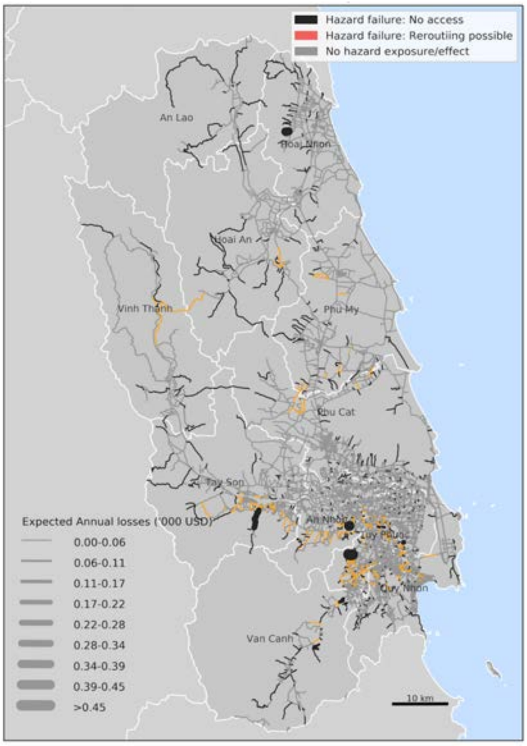
Figure 3.12. Maximum Risks of Binh Dinh Province-Scale Road Network



A. Typhoon flooding maximum risks

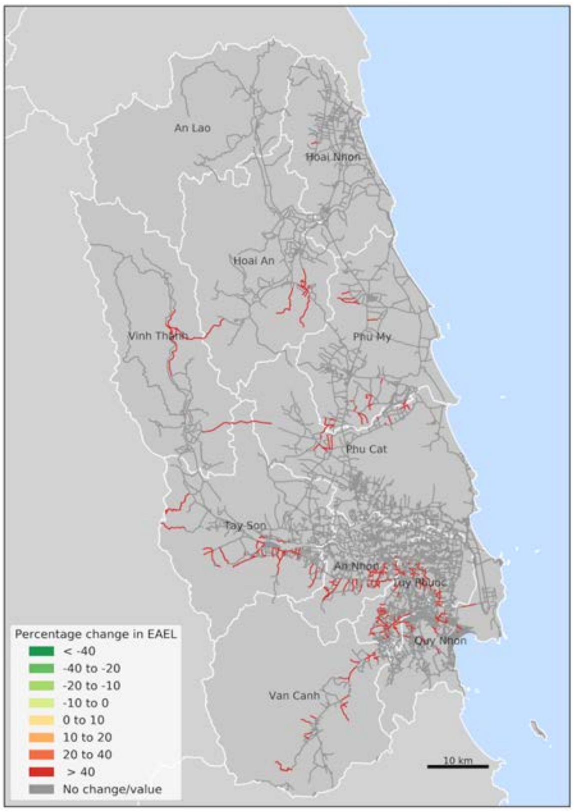


B. Landslide susceptibility maximum risks

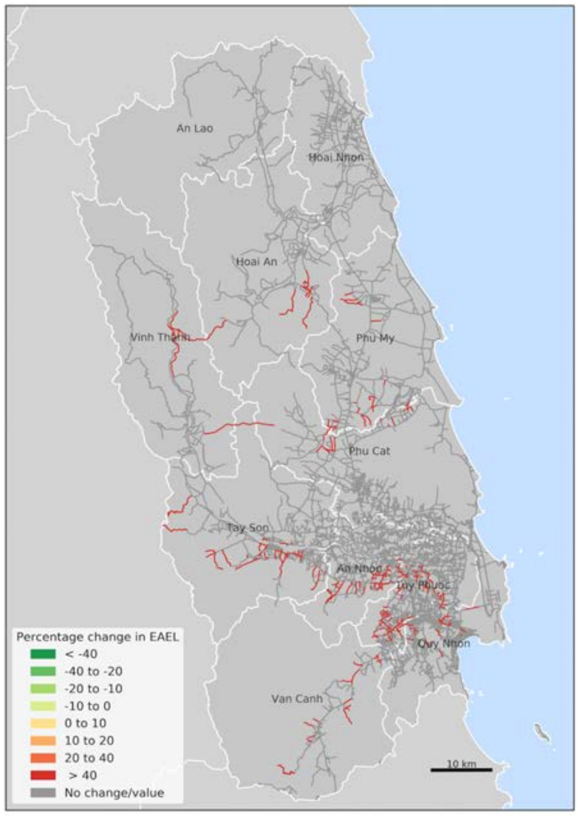


C. River flooding maximum risks

Figure 3.13. Percentage Change in Failure Risks of Binh Dinh Province-Scale Road Network for Future 2030 River Flooding under Climate Scenarios



A. RCP 4.5 2030



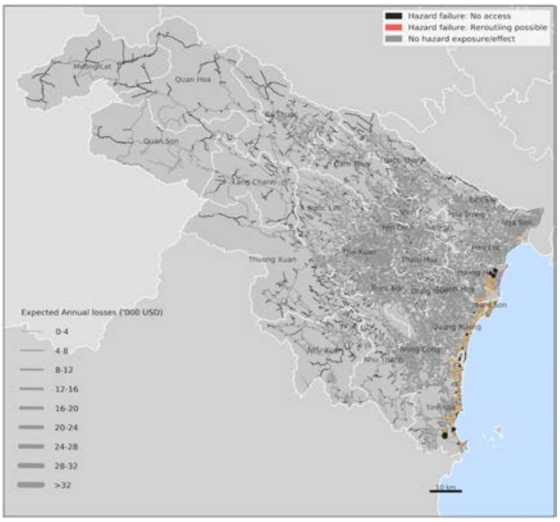
B. RCP 8.5 2030

Thanh Hoa province-scale roads risks

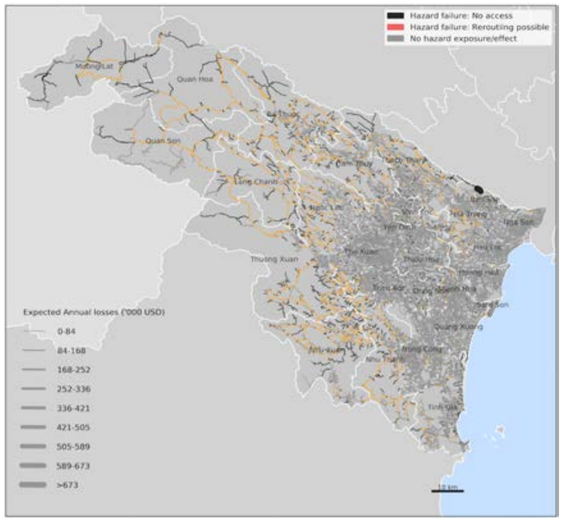
The analysis highlights key sections of network links in Bim Son district affected by landslides, whose failures results in high risks due to large areas of economic activity experiencing a lack of access to their nearest commune centers (figure 3.14).

As shown in figure 3.15, the changing maximum risks due to climate change in the Thanh Hoa is a clear indication of increasing risks due to road link failures from future climate change-driven hazard scenarios, with *expected annual losses in almost every case substantially increased by at least 40 percent. Again, there is a strong indication that access to economic opportunities may be severely affected without investment in climate resilience.*

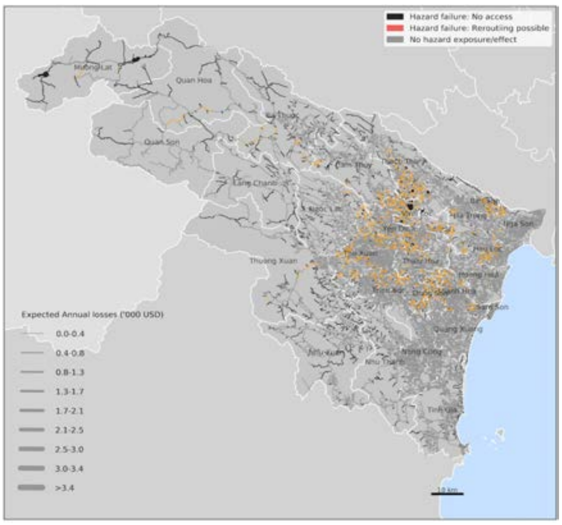
Figure 3.14. Maximum Estimated Risks for Thanh Hoa Province-Scale Road Network



A. Typhoon flooding maximum risks

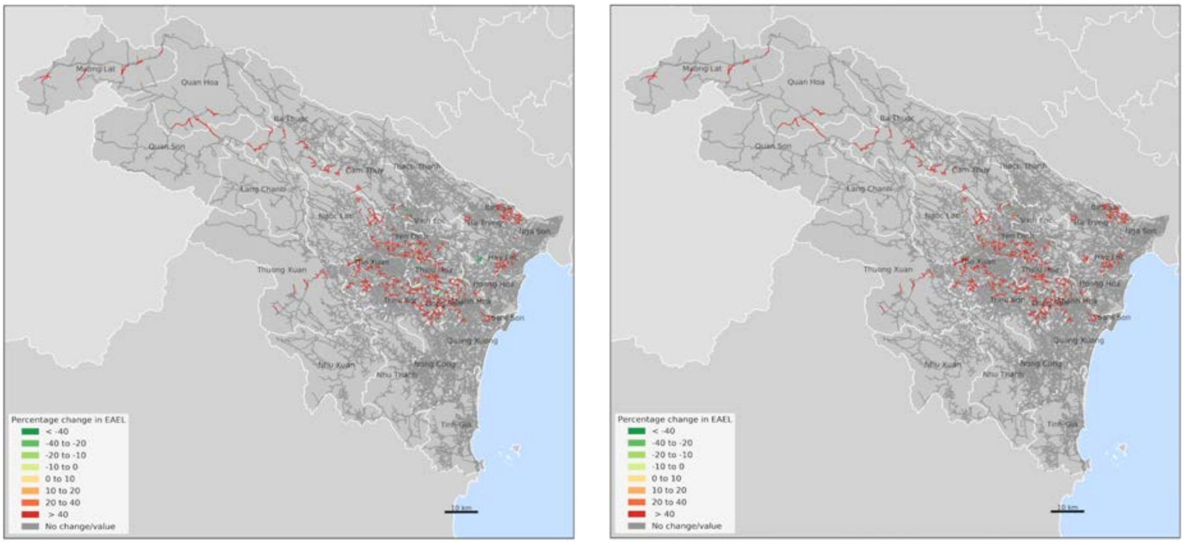


B. Landslide susceptibility maximum risks



C. River flooding maximum risks

Figure 3.15. Percentage Change in Failure Risks of Thanh Hoa Province-Scale Road Network for Future 2030 River Flooding under Climate Scenarios



A. RCP 4.5 2030 **B. RCP 8.5 2030**

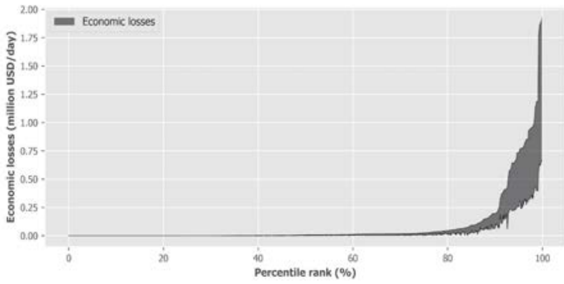
Uncertainties in Criticalities and Risks

Uncertainties are a natural part of estimating the criticalities and risks of failures of transport links. The estimated network link criticality uncertainties are sensitive to the modeled ranges of flow assignments and rerouting on the networks as well as to the parameters in the macroeconomic loss model.

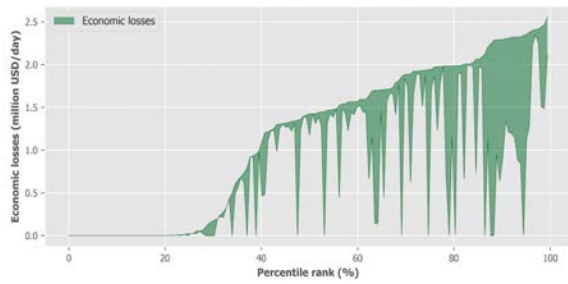
The result shown in figure 3.16A highlights the high variability in the estimated road losses, where the largest losses vary between US$0.67 and US$1.9 million per day. These losses, mainly driven by the increases in transport costs from rerouting of network flows, follow individual link failures. The resulting increased transport costs are primarily influenced by the volumes of rerouted freight. Hence, the uncertainties in estimated losses are mainly sensitive to the volumes of disrupted flows.

As discussed in the section "Rail Failure Analysis Results" in Chapter 5, the economic losses for railways are mainly driven by macroeconomic losses. The macroeconomic loss estimates take into account the ability of the multiregional economy to substitute for lost freight in a region, which in turn depends on the percentage of regional economic production dependent upon the lost freight. Substitutions for a high failure percentage will not be sufficient to offset macroeconomic losses due to freight disruptions; however, a low failure percentage allows a multiregional economy to substitute and offset macroeconomic losses. The large fluctuations in economic losses shown in figure 3.16B are mainly sensitive to these substitution effects in the macroeconomic model. Hence, losses for several links range between very small values (~0)—when the volumes of disrupted tonnages do not affect the regional economies—and very high values (in excess of US$2 million per day), because the volumes of disrupted tonnages substantially disrupt the regional economies' ability to substitute.

Figure 3.16. Estimated Ranges of Daily Economic Losses for Individual Network Link Failures in Vietnam's National-Scale Road and Rail Networks



A. Roads:
Range of economic losses due to link failures



B. Railways:
Range of economic losses due to link failures

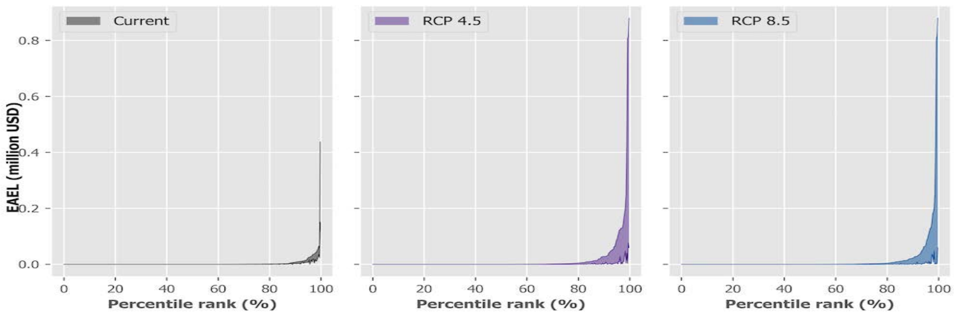
The estimated risks are sensitive to the type of hazards, in addition to factors influencing the criticalities. Thus, comparing ranges of hazard-specific risks across different scenarios of the same hazard type shows how the hazard uncertainties influence network risks. Such a comparison is made for the case of national-scale road and railway network risks due to river flooding in current and future conditions under the RCP4.5 and RCP8.5 scenarios.

Figures 3.17A and 3.17B show the ranges of current (2016) and future (2030) climate change-driven river flooding risks, calculated as the Expected Annual Economic Losses (EAEL) in US$ millions for 10-day maximum disruption of individual network links, in the national-scale road and railway network respectively. The results show the uncertainties of failure risks due to climate change significantly increase under the RCP4.5 and RCP8.5 scenarios. Also, both climate scenarios show significant increases in the maximum estimates of risks, due to increasing severity and frequency of future extreme river flooding. Analysis for the road network shows the highest EAEL increases from US$0.44 to US$0.88 million, an increase of 100 percent. For the railway network, the highest EAEL increases from US$1.4 to US$2.8 million, a significant increase of 100 percent in highest losses.

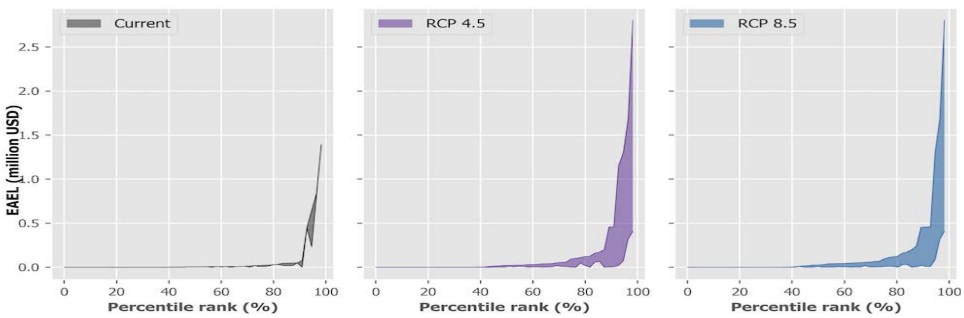
Figures 3.18 to 3.20 present the uncertainties in estimating criticalities and risks for the three province-scale networks (Lao Cai, Binh Dinh, and Thanh Hoa). The plot on the left panel (panel A) of each figure shows the range of daily economic impacts for all impacted links, ranked by maximum daily impacts. The plot on the right panel (panel B) shows the EAEL for all links affected by current and future extreme river flooding.

Each criticality result indicates the dominance of a relatively small percentile of links in each province. High losses in Lao Cai are concentrated in approximately the top 20 percent of links, in Binh Dinh they are concentrated in approximately the top 10 percent of links, and in Thanh Hoa in approximately the top 5 percent of links. The high ranges of losses occur mainly for those links whose failures result in complete lack of access to commune centers. The magnitudes of such losses are mainly sensitive to the changing net revenues assigned to these links, which in turn are sensitive to the changing tonnages of crop (rice) productions assumed in the flow estimation model. The analysis in figure 3.18 shows that for Lao Cai, the highest daily economic impacts range from US$23,000 to US$26,000 per day, for Binh Dinh (figure 3.19) the highest daily losses range from US$47,000 to US$56,000 per day, and for Thanh Hoa (figure 3.20), the highest daily losses range from US$64,000 to US$67,000 per day.

Figure 3.17. Estimated Ranges of Minimum and Maximum Risks for Individual Link Failures Due to Current and Future River Flooding on National-Scale Networks



A. Roads: River flooding risks

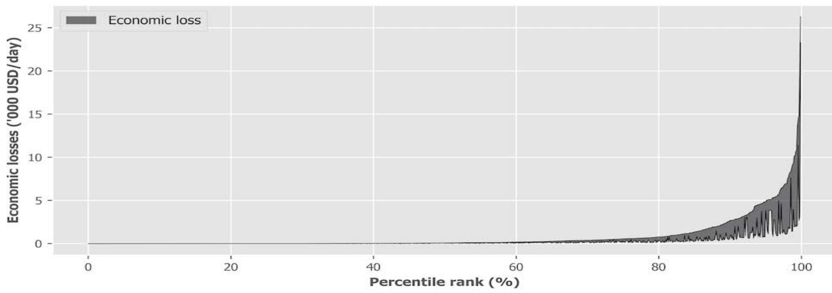


B. Railways: River flooding risks

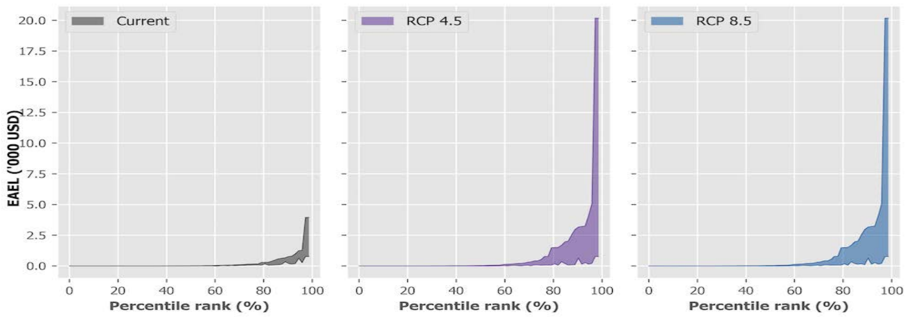
However, these ranges of highest losses might not necessarily be recorded for the same links, as the underlying distributions of net revenue allocated to links vary widely.

The risk results, in the context of river flooding, show significantly increased uncertainties of failure risks due to climate change, under both RCP4.5 and RCP8.5 scenarios. Similar to the national-scale analysis, both climate scenarios show significant increases in the maximum risk estimates, due to increasing severity and frequency of extreme river flooding in the future. In both future climate scenarios for Lao Cai road network (figure 3.18), the link with the highest maximum EAEL (around US$20,000) showed a maximum EAEL of around US$4,000 in the current scenario—reflecting an increase of more than 400 percent. Analysis for the Binh Dinh road network (figure 3.19) shows the link with the highest maximum EAEL of around US$4,500 in the future RCP4.5 climate scenario had a maximum EAEL in the current scenario, approximately US$450, indicating an increase of more than 900 percent. In the Thanh Hoa road network, analysis shows the link with highest maximum EAEL (approximately US$11,900) in the future RCP 8.5 climate scenario had a maximum EAEL of about US$300 in the current scenario, an increase of more than 3,800 percent. All three provinces show substantial increases in risks due to climate change-driven flooding for individual links.

Figure 3.18. Estimated Ranges of Daily Economic Losses and Risks Due to Current and Future River Flooding of Individual Link Failures on the Lao Cai Road Network

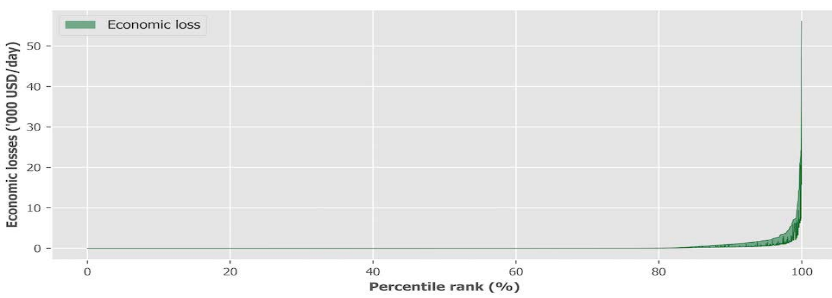


A. Daily economic losses in Lao Cai

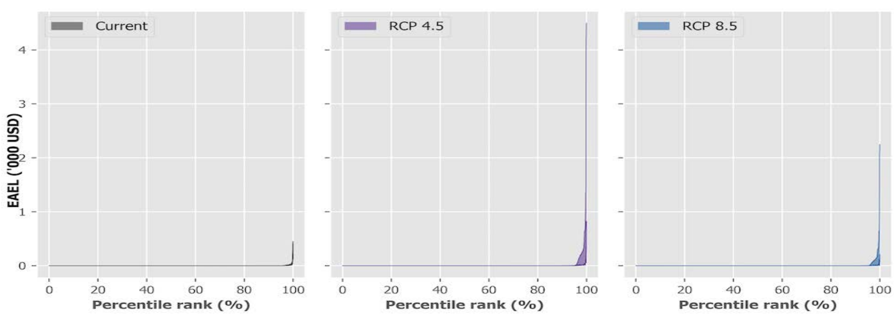


B. River flooding risks in Lao Cai

Figure 3.19. Estimated Ranges of Daily Economic Losses and Risks Due to Current and Future River Flooding of Individual Link Failures on the Binh Dinh Road Network

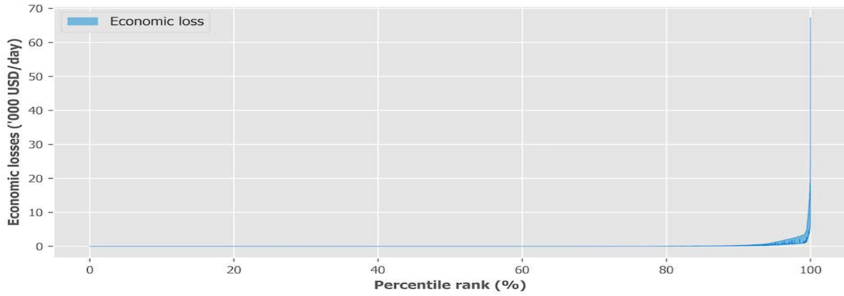


A. Daily economic losses in Binh Dinh

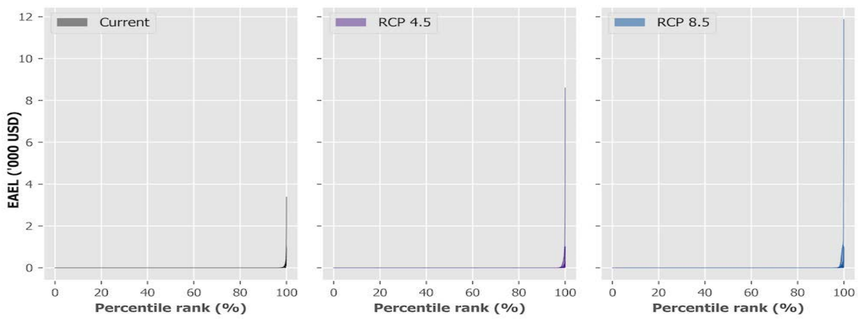


B. River flooding risks in Binh Dinh

Figure 3.20. Estimated Ranges of Daily Economic Losses and Risks Due to Current and Future River Flooding of Individual Link Failures on the Thanh Hoa Road Network



A. Daily economic losses in Thanh Hoa



B. River flooding risks in Thanh Hoa

Criticalities and Vulnerabilities of Ports

The following section presents criticality and vulnerability assessment results for the air transport, inland waterways, and maritime sectors at the major ports scales, as these are the most important assets on these networks.

The results aim to provide evidence on:

- The main ports in three sectors identified with known exposures to extreme hazards.
- The effect of climate change on the changing risks of exposure.

The results demonstrate that, for each sector, the risks of climate change-driven hazard exposures will increase.[1] For example, the maximum hazard probability of flooding of the Ho Chi Minh port increases to 0.2 (1 in 5-year flooding) under the RCP4.5 and RCP8.5 scenarios, in comparison to the 0.04 (1 in 25-year flooding) probability. From this, the analysis concludes the Ho Chi Minh port will be about 5 times more prone to frequent flooding in the future, and observed similar trends for all major ports in every sector.

Based on risk estimates for airports produced with older statistics, the analysis reveals that only Da Nang airport shows significant AADF flows exposed to extreme hazard. Since 2006 development around Da Nang has increased, and at present Da Nang serves as a major passenger hub in central Vietnam.[2] Because of this, impacts on the airline sector should be interpreted in terms of passenger usage, a much more substantial metric than cargo transport.

Results show exposure to extreme hazards in the major maritime ports of Ho Chi Minh, Hai Phong, and Can Tho, with analysis for the Ho Chi Minh and Can Tho ports clearly indicating that climate change will increase the frequency of extreme hazards. The significance of these ports to the economy of Vietnam is immense, with the analysis showing that under worst-case scenarios approximately 68,000 to 106,000 tons of cargo flows per day could be affected. Even though this study included domestic flows, these ports have far greater significance as major import and export hubs for Vietnam.

In terms of the country's inland waterway ports (a total of around 41), results suggest that major inland hubs in An Giang, Hai Phong, Thai Binh, Quang Ninh, and Ho Chi Minh are identified as exposed to extreme hazards, with the frequency of hazard exposures for An Giang increasing in the future due to climate change. The implications of disruptions to these ports could be immense, with analysis indicating that under worst-case scenarios approximately 25,000 to 55,000 tons of cargo flows per day could be affected.

Notes

1. Appendix C shows detailed results of vulnerability assessment of the airports, major identified maritime ports, and major identified inland waterway ports. The analysis showed the 44 inland waterway ports and 10 maritime ports with significant commodity flows were exposed to extreme hazards, mostly typhoon flooding and river flooding.

2. Source (in Vietnamese): https://web.archive.org/web/20130729200548/http://www.mt.gov.vn/PrintView.aspx?ArticleID=10663.

Reference

Arga Jafino, Bramka. 2017. *Measuring Freight Transport Network Criticality: A Case Study in Bangladesh*. Delft, Netherlands: TU Delft (Delft University of Technology). http://resolver.tudelft.nl/uuid:0905337b-cdf7-4f6e-9cf6-ac26e4252580.

Chapter 4: Adaptation Strategy and Analysis

This chapter presents the adaptation options considered for national-scale and provinces-scale road network assets, evaluating each asset the ranges of adaptation options and the associated costs and benefits. Following this, the chapter discusses results of a detailed cost-benefit analysis for each network asset under different hazard scenarios.

Scope and Purpose of Adaptation Analysis

Adaptation planning is a much larger process than discussed in this study. Ideally, adaptation options should involve a wide range of measures including, among others, structural, institutional, and social changes. Also, the types of adaptation options depend upon the context of the specific country and the financing objectives, which govern the types of objectives outlined by different multidonor-funded development agencies (Ebinger and Vandycke 2015). This study recommends several proposed guidelines on the steps required for detailed site-specific adaptation options in Vietnam, neighboring Lao PDR, and other countries, based on an understanding of local conditions (ICEM 2017a and 2017b; MoPWT Laos 2008; CSIR et al 2011). The reader can refer to these studies to understand the step-by-step guidelines in the adaptation planning and implementation process.

Adaptation options explored in this study look specifically at measures intended to improve the structure reliability of road assets to make them more resilient to climate change impacts. *These can also be called climate resilience strategies*. The focus here is specifically on evaluating the benefits of structural engineering options to make the road assets structurally "climate proof." Therefore, the approach adopted here consists of exploring engineering options of adaptation targeted to improve or create climate-resilient engineering standards of design for various aspects of road assets—subsurface conditions, upgrading material specifications, cross section and standard dimensions, drainage and erosion, and protective engineering structures (ADB 2011). The levels of hazard exposures of road assets selected here are the most extreme based on their identified magnitudes: selected landslides and flashfloods susceptibilities are high and very high; selected river and typhoon flooding are greater than 1 meter. Hence, the study assumes these levels of hazards will potentially cause catastrophic failures to road assets, i.e., physically, the road assets will be damaged and lose their ability to provide service and will require rehabilitation. This assumption implies that the purpose of the adaptation option is to make road assets resilient to catastrophic failures in order to avoid rehabilitation and thus maintain the continuity of service flows.

The generalized evaluation of adaptation options presented here creates a high-level indicative assessment of transport systems and their climate resilience strategies; evaluation of adaptation options is a very site-specific problem, and depends on the detailed investigation of, among others, local terrains, structural dimensions of assets, conditions of assets, and specific failure mechanisms due to hazards. Estimating adaptation costs is a very site-specific problem and in particular different types of engineering-based adaptation options require detailed site investigation and structural design calculations of road asset design standards. At best, this analysis presents a first-order screening whereby the efficacy of different types of adaptation options can be compared and locations and assets with high (or low) adaptation benefits can be narrowed down for further investigation.

As discussed later, in Vietnam the vulnerability to slope stability of roads due to landslides and flashfloods is a major issue. Unfortunately, the underlying data in this study does not provide any information on road slopes inclines and areas, which would have been used to fully quantify adaptation options to build climate resilience to landslides and flashfloods.

Identifying Failures by Climate Change Driven Hazard Threats

Listed below are some of the types of failures of road assets due to hazards—landslides and flooding (river, flash, and typhoon)—in Vietnam. This is not an exhaustive list, but rather a list of main causes of failures that affect the continuity of road usage. In several instances two or more of these failure types could manifest simultaneously:

- Erosion of the road pavement;
- Embankment failures: slope erosion;
- Cut slope failure;
- Drainage failures: a) pavement drainage failure, b) cross drainage failure affecting dams, culverts and spillways, and c) river bank erosion;
- Structural failures: Collapse of any of the road asset, especially critical assets such as bridges and culverts.

While the several hazard mechanisms could trigger failures, the analysis identifies intense rainfall-induced landslides and flooding as the primary cause of road failures in Vietnam. For example, is the analysis recognizes that in Vietnam water is the single biggest trigger of slope movements, since saturation following heavy rain reduces pore suction, adds to the weight of the slope mass, and reduces both cohesion and friction (GITEC 2018).

Climate change can amplify the severity of failures due to increased levels of hazard threats. Table 4.1 lists some failure types that can intensify due to climate change.

Table 4.1. Potential Failure Types Due to Increased Hazard Threats Driven by Adverse Climate Change

Climate Change	Impacts
Increase in rainfall and intensity	• Damage to roads, under-ground and surface drainage systems due to flooding • Increase in scouring of roads, bridges, culverts, and support structures • Erosion of embankments and road infrastructure due to flooding • Triggering of roadside slope failures due to landslides • Overloading of drainage systems due to increased sedimentation for flooding • Deterioration of structural integrity of roads and bridges due to increase in soil moisture levels • Washout of gravel and earth roads due to flooding
Sea level rise	• General overtopping of roads, embankments and bridges • Damage to low-lying structures, and bridges due to flooding, inundation in coastal areas, and coastal erosion • Damage to embankments from land subsidence and landslides • Scouring of roads, bridges, and bridge supports
High winds	• Damage to road pavements and structures from trees and other debris • Damage to bridge decks and suspensions • Impact by wind driven wave action on embankments, bridge abutments
Increase in typhoon frequency	• Direct impact erosion of roads, slopes, and embankments from flash floods • All risks associated with increase in rainfall intensity due to increase landfall

Sources: Jasper Cook, ReCAP[1]; ADB 2011; Ebinger and Vandycke 2015; World Bank 2017.

Adaptation Options and Costs

In the Vietnam-specific context, the relevant adaptation interventions can be broadly described as a combination of the following:

1. *Pavement strengthening*: Unpaved roads made of earth and gravel are prone to rapid deterioration due to soil moisture saturation from excess water. Hence, the pavement strengthening option aims to create a more climate-resilient surface by investing in bitumen sealing or concrete paving, which increases the strength and protection of subsurface road conditions to prevent soil saturation. Periodic maintenance of the pavement to preserve its strengthening characteristics should be performed to prevent soil moisture saturation. *This intervention protects roads against flooding disruptions*.
2. *Improved pavement drainage*: To avoid disruptive pooling of water and sediments on roads (or even bridges), this investment option is aimed at improving the road surface crossfall, putting more side drains, turn-out drains, and scour checks. Periodic maintenance clears the drainage and prevent scour. *This intervention protects roads against flooding disruptions*.
3. *Earthwork protection*: To prevent structural collapse of sloped earthworks, this investment option works by adopting different climate-resilient slope strengthening measures, including improved masonry standards (ADB 2011) to enhance embankments and cut road slopes.

Periodic maintenance of the slopes should be performed to remove loose materials. *This intervention protects the roads against landslide disruptions*.

4. *Slope protection*: Aimed specifically at enhancing climate-resilience of road slope structures, this option includes installing gabions, block facing, bio-engineering of planted vegetation to strengthen slopes (ICEM 2017b), and improving face drainage against overtopping due to river flooding. Investment in slope strengthening can be undertaken with periodic maintenance. *This intervention protects the roads against landslide disruptions*.
5. *Improved cross drainage (culverts)*: This investment option builds more climate-resilient culverts and/or increases the size and protection standards of existing culverts (stream and relief), reflecting the increases in flood intensities due to climate change. Periodic maintenance of the culverts is performed to remove debris and sediments to prevent scouring. Flood vulnerability of culverts in Vietnam is a major issue, with several instances of culvert and small bridge failures recorded during major flood events (CSCNDPC 2017). *This intervention protects the roads against flooding disruptions*.

Implementation of the above options creates a climate-resilient road protected against all types of natural hazards risks. Hence, the study suggests a climate-resilient road design, which includes combinations of the five options as described above. In simplistic terms, this study suggests that building a climate-resilient road in Vietnam requires implementing one or more pavement upgrade options, enhancing the pavement drainage, constructing embankments and cut-slopes, increasing slope stability by investing in different measures, and improving cross-drainage by building more culverts.

For the purposes of this study, the analysis generalizes a set of fixed adaptation options across roads, depending on:

- *Road class*, either to the standard of a climate-resilient national road or to the standard of a climate-resilient district road.
- *Road terrain*, where a sample road is designed either for a flat terrain or a mountain terrain.
- *Bridge*, where a sample bridge is designed to represent any type of bridge in Vietnam.[2]

In order to enhance a road's climate resilience, the study selected *four climate-resilient road prototype designs*: *national mountain, national flat, district mountain, district flat, and bridge*, identifying every at-risk road associated with one of these prototype designs.

For each prototype road, the study designed a sample climate-resilient, 100-meter section by creating a bill of quantities, which specifies the amounts and unit costs of quantities needed to uplift the climate resilience of existing roads. The results of the study's climate-resilient design assumptions, summarized in table 4.2, arrive at unit costs of investment (CI) in US$ millions per length for upgrading existing national and district roads to prototype climate-resilient road standards.

Table 4.2. Cost Summary of Initial Adaptation Investment for Building Prototype Climate Resilient Roads in Vietnam

Prototype road	Terrain	Cost of adaptation investment (CI) (US$/km)
National road • Two-lane, 22.5 meters wide	Flat	1,535,000
	Mountain	1,828,500
District road • One-lane, 6.5 meters wide	Flat	808,000
	Mountain	1,439,000
Bridge	All	10,179,000

Source: World Bank calculations, with inputs provided by Dr. Jasper Cook, Research for Community Access Partnership (ReCAP): http://research4cap.org.

Results of Adaptation Analysis

In estimating the parameters of the adaptation net present value (NPV) calculations, the study assumed the following:

- All climate hazard scenarios models estimated hazard severity until the year 2050.[3] *Accordingly, the study considers a 35-year timeline of any adaptation intervention, from 2016 to 2050*.
- The study assumed a discount rate of 12 percent, based on the Vietnam Road Asset Management System (VRAMS) cost-benefit analysis tool assumption.
- The study assumed the adaptation options were implemented over the length of the network links affected by hazards. For example, if 10 percent of a road network link was affected by a hazard, then the costs were estimated for this 10 percent section.
- *The study assumed the freight flow volumes across the networks would grow as per the International Monetary Fund (IMF) forecasted 6.5 percent GDP growth for Vietnam.*[4] Thus, the study assumed economic impacts would grow by 6.5 percent every year over the timeline of the adaptation option.

For each road network under consideration, the study performed adaptation analysis on each link subjected to each hazard model assembled for the study. Thus, if a single road network link is at risk for typhoon flooding, river flooding, and landslides, the study estimates the costs and benefits of adaptation options for each type of hazard risk under each model scenario (current, or climate change RCP4.5 and RCP8.5, with the given time-horizon). For example, if a 1 km national road link is exposed to extreme river flooding over 100 to 500 m of its length, depending upon flooding return periods, then the study estimates the costs and benefits of adaptation for a chosen climate-resilient design for 500 m of this road. If the same road is exposed to extreme typhoon flooding over 100 to 200 m of its length, depending upon typhoon intensities, then the study estimates another set of costs and benefits for building climate resilience over 200 m of the road. Thus, the study estimates multiple climate-resilient designs for the same roads, depending upon their hazard exposures and risks. Table 4.3 lists the overall numbers of unique hazard exposure and adaptation options scenarios calculated for each type of road network.

Table 4.3. Numbers of Single-Link Failure and Hazard Exposure/Adaptation Options Scenarios Evaluated for Transport Networks in Vietnam

Selected transport network	Unique single-link failure scenarios	Unique hazard exposure/adaptation options scenarios
National-scale roads	968	6,010
Lao Cai province roads	1,299	5,049
Binh Dinh province roads	11,042	14,397
Thanh Hoa province roads	26,852	38,449

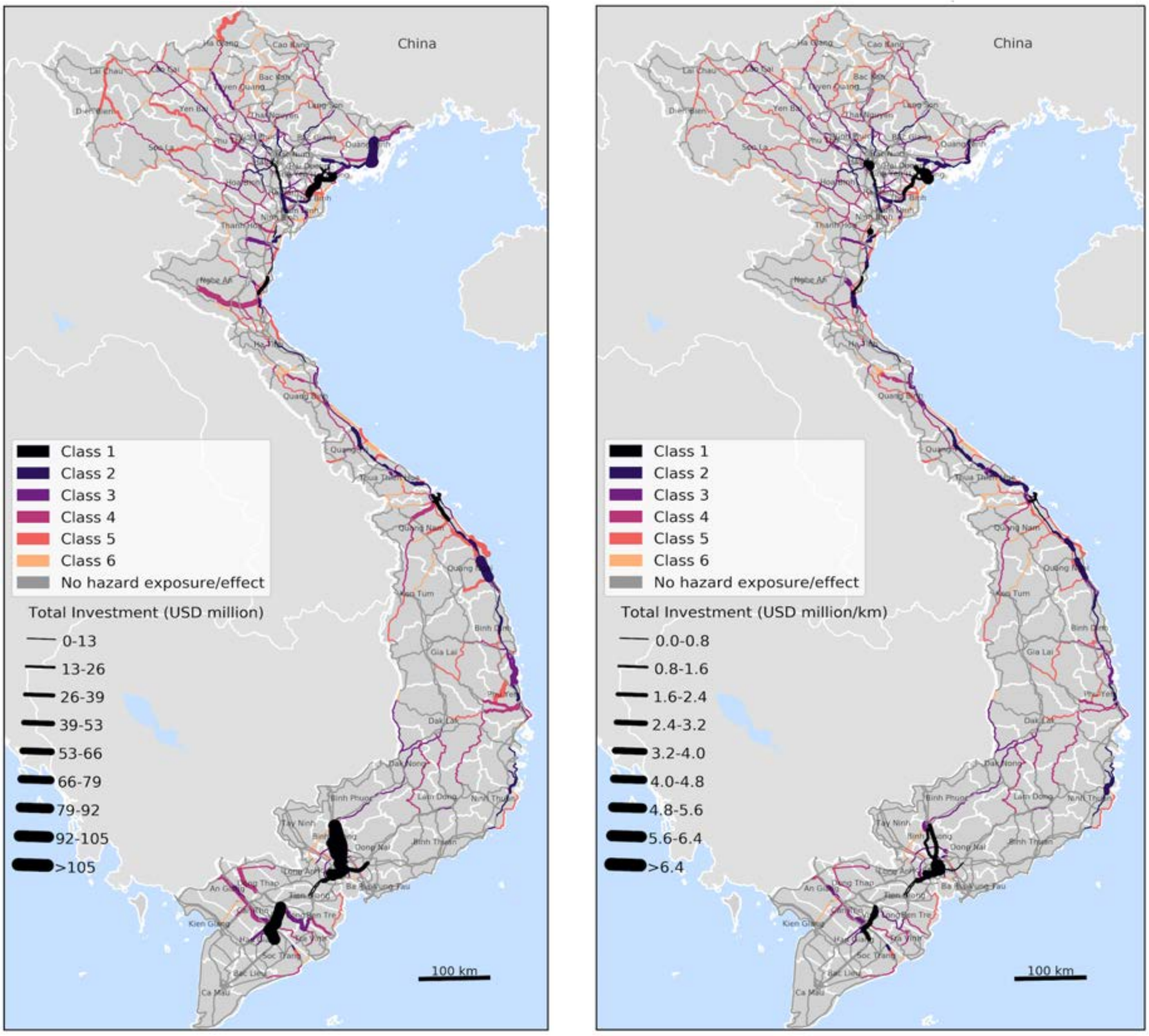
National-scale road network adaptation costs and benefits

This section presents a number of results at the national-scale road network level, discussing the adaptation metrics described in earlier sections.

Figure 4.1A shows the maximum initial investments (in US$ millions) required for individual road links to make them resilient to their worst levels of climate hazards. These estimates depend upon the length and width of the road links exposed to the extreme hazards, which implies that some roads require larger investments because of their very large hazard exposures. The results show particular roads links around Ho Chi Minh might requirement as high as an US$55 million investment to make them climate resilient. By adding the maintenance costs to the initial adaptation investments, the results also highlight particular road links around Ho Chi Minh that might require as high investments as US$105 million over 35 years to maintain climate resilience.

Figure 4.1B shows the adaptation investment costs per kilometers, which gives a sense of the comparative levels of investments required to uplift roads from current standards to climate-resilient standards. The spatial analysis shows the costs of investments per kilometer of national roads, which can reach as high as US$3.4 million for initial investments and US$6.4 million for investments over time. Due to the study's assumed chosen options for very high design standards meant to avoid any failures, these investment amounts compare to the construction of a new expressway,

Figure 4.1. Maximum Total Investment over 35 Years on the Climate Adaptation for Identified Links in the National-Scale Road Network in Vietnam

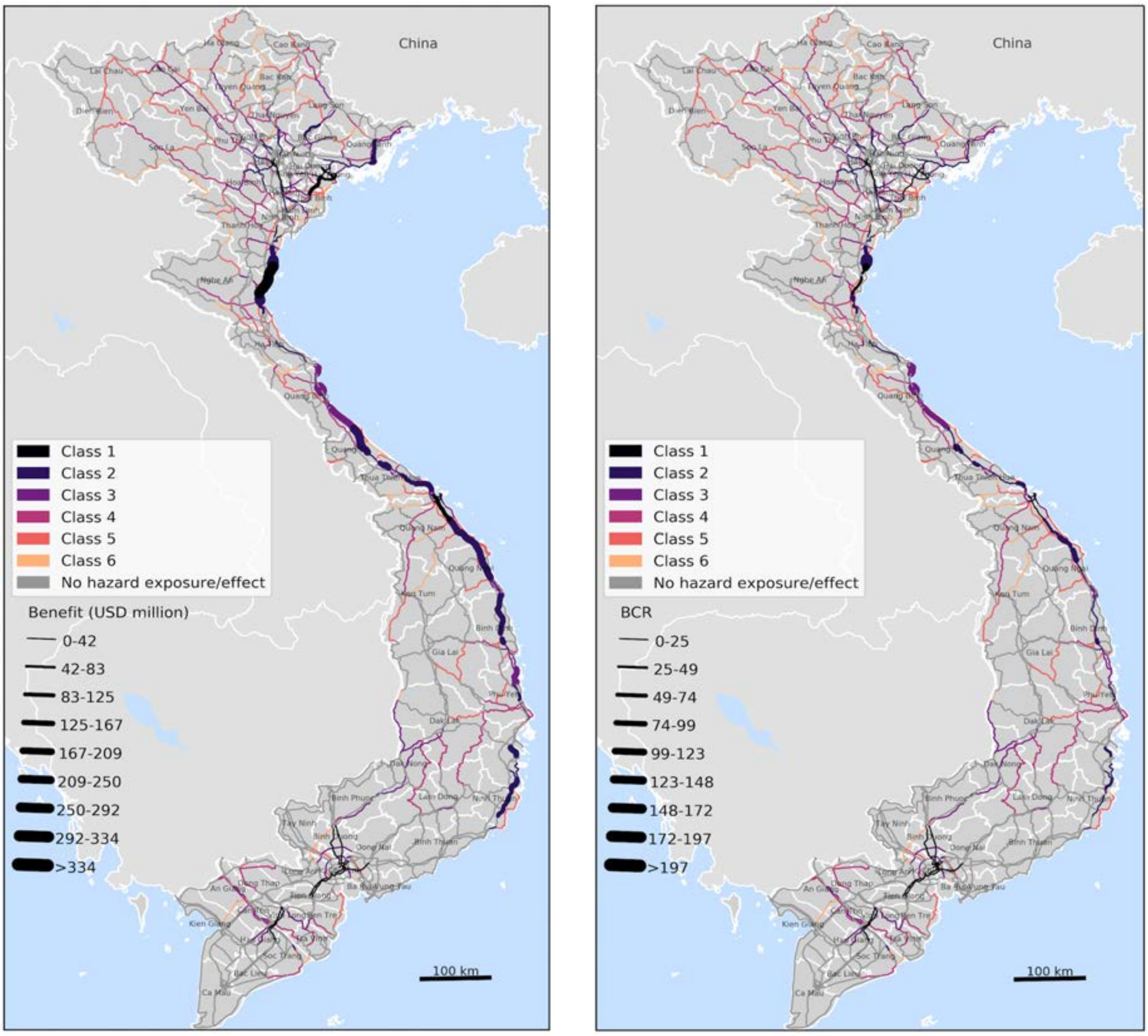


A. Maximum investment over time per section **B. Maximum total investment per km over time**

Figure 4.2A shows the maximum values of the estimated benefits over 35 years of investments in climate resilience of individual road links in the national-scale road network. These benefits represent the sum of the avoided annual expected rehabilitation costs over time for individual road links as well as the systemic expected annual economic losses (EAEL) over time from 10-day disruptions of transport freight flows caused by failures of individual road links. The results highlight the large benefits of investing into building climate resilience, particularly along the expressway sections toward the eastern coastline.

Figure 4.2B shows the maximum benefit-cost ratios (BCRs) of adaptation for all identified road links, derived from the results of figures 4.1A and 4.2A. The BCRs highlights where climate resilience investments could be prioritized—for road links with high BCRs, much greater than one. The results here show that the expressway link between Nghe An and Thanh Hoa has the highest BCR (197), which makes it a high priority link for climate resilience investments.

Figure 4.2. Estimated Maximum Benefits over 35 Years and Maximum BCRs of Adaptation Options for Identified Links in the National-Scale Road Network in Vietnam

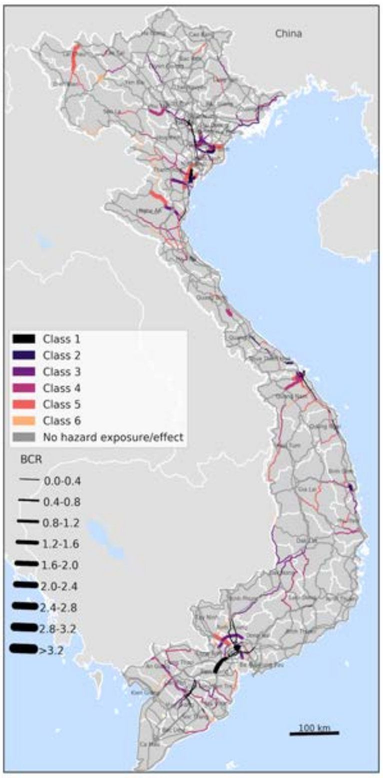


A. Maximum benefits over time **B. Maximum Benefit-Cost Ratio (BCR)**

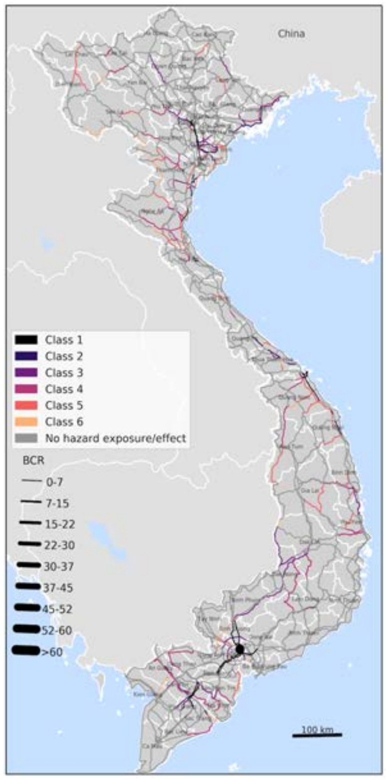
Another key insight from the adaptation analysis considers how BCRs might change under current and future climate hazard scenarios. This helps make a case for proactively investing in climate resilience for future levels of extreme hazards, rather than planning for current extreme hazard levels. For the national-scale road network links, such a comparison is made between current and future (RCP 4.5 and RCP 8.5) scenarios of river flooding. Figure 4.3A shows the maximum BCRs for current levels of river flooding, while Figures 4.3B and 4.3C show the maximum BCRs for future levels of river flooding under the RCP4.5 and RCP8.5 scenarios respectively. A substantial uplift in the BCRs in the future hazard scenarios makes a strong case for investing into building climate resilience to future hazards in Vietnam. The increase in BCRs is due mainly to the increase in the future river flooding risks under both emission scenarios, showing the greater benefits from investing in climate resilience to protect against potential future higher losses.

Table 4.4 provides the list of specific national road network links identified by their BCRs of adaptation. These links represent the top 20 assets ranked by maximum BCR values, and also report the minimum BCRs. If both the minimum and maximum BCR values are greater than 1, then the case for investing into such assets is quite robust, since every hazard scenario illustrates that investing in climate resilience is more beneficial than paying the adaptation costs. All 20 assets shown have a robust case for investing in climate resilience. The analysis shows that for these 20 assets a cumulative climate adaptation investment amounts to approximately US$95 million initially; over 35 years is the investments would amount to approximately US$153 million. However, the cumulative benefits of such investments over 35 years—estimated by adding together the benefits from individual links—are quite substantial, ranging between US$651 and US$3,656 million. Notably, the combined benefits of investing in all roads concurrently will not necessarily equal the sum of individual benefits because the avoided economic losses are not additive, but rather depend on the estimation of systemic network impacts.

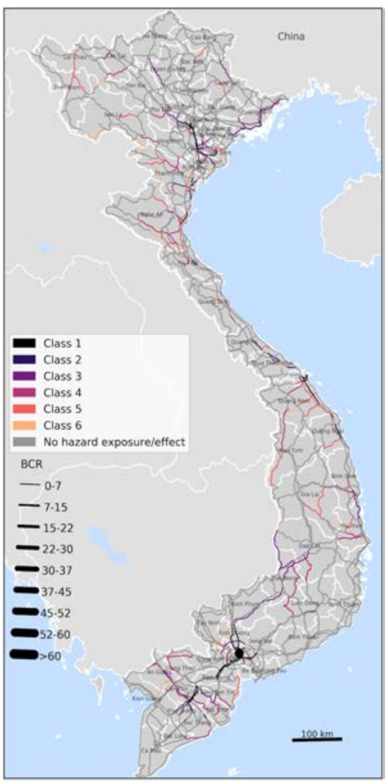
Figure 4.3. Comparisons of BCRs of Adaptation Options for National-Scale Road Network Links in Vietnam



A. Current 2016 river flooding



B. Future 2030 river flooding under RCP 4.5 emission scenarios



C. Future 2030 river flooding under RCP 8.5 emission scenarios

Table 4.4. Twenty National-Scale Roads Ranked in Descending Order of Maximum Adaptation BCRs

National highway	Route name	Road class	Maximum hazard exposure length (meters)	Initial investment (US$ millions)	Total investment (US$ millions)	Benefit (US$ millions)		BCR	
						Min.	Max.	Min.	Max.
1	NBH-THA border to TTH-DNG border	2	1,285	2.49	4.04	32.57	315.87	8	197
1	NBH-THA border to TTH-DNG border	3	1,943	3.00	4.73	36.33	320.16	8	149
1	NBH-THA border to TTH-DNG border	2	4,178	8.07	13.10	85.70	333.83	7	128
1	NBH-THA border to TTH-DNG border	2	1,414	2.74	4.45	50.30	203.75	11	119
1	NBH-THA border to TTH-DNG border	1	796	1.79	2.98	29.07	319.61	10	107
1	NBH-THA border to TTH-DNG border	3	2,303	3.56	5.61	11.21	137.31	2	104
1	NBH-THA border to TTH-DNG border	3	3,189	4.93	7.77	12.84	206.74	2	94
1	NBH-THA border to TTH-DNG border	2	2,688	5.19	8.43	23.44	171.94	3	85
1	NBH-THA border to TTH-DNG border	3	1,019	1.59	2.50	71.82	192.87	29	77
1	TTH-DNG border - KHA-NTN border	2	1,445	2.80	4.54	44.28	133.13	10	76
DBVB	**Đường bộ ven biển**	2	3,721	7.18	11.67	23.77	169.72	2	75
1	NBH-THA border to TTH-DNG border	2	9,609	18.53	30.12	82.20	189.73	3	72
1	TTH-DNG border - KHA-NTN border	2	1,298	2.52	4.08	16.15	131.75	4	70
1	TTH-DNG border - KHA-NTN border	2	1,849	3.57	5.80	9.33	127.84	2	62
1	TTH-DNG border - KHA-NTN border	2	2,746	5.30	8.61	23.68	170.44	3	62
1	TTH-DNG border - KHA-NTN border	3	6,414	9.90	15.62	35.78	113.90	2	61
1	NBH-THA border to TTH-DNG border	1	55	0.15	0.23	6.50	13.68	28	60
1	NBH-THA border to TTH-DNG border	2	1,080	2.10	3.40	11.02	159.09	3	57
1	NBH-THA border to TTH-DNG border	2	4,055	7.84	12.72	31.62	134.68	2	55
1	NBH-THA border to TTH-DNG border	2	1,052	2.05	3.32	14.14	110.81	4	55
		Total		**95.30**	**153.72**	**651.76**	**3,656.85**		

Province-scale road network adaptation costs and benefits

The study also performed an adaptation analysis for each of the three province-scale road networks. In all map figures that follow, an adaptation analysis was performed for each of the links highlighted in black or shades of red—signifying an exposure to hazard. As indicated in the maps, black highlighting represents a failed link with no alternative routes to nearby commune centers, which impairs economic activity. Red highlighting indicates failed links with alternative routes, which maintain access to the nearest commune centers.

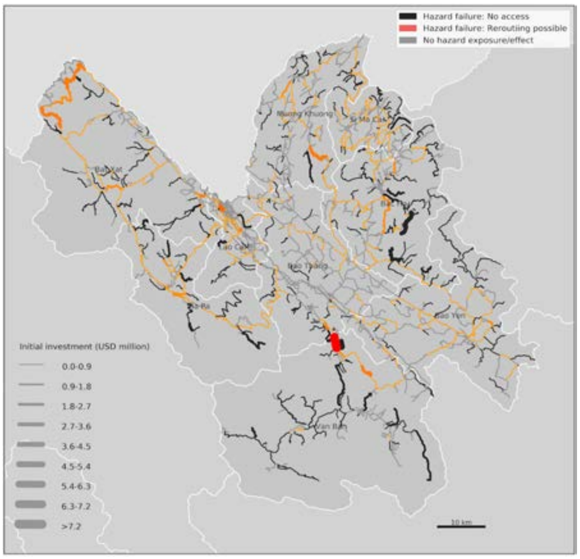
On the province-scale, identifying some specific assets with high BCRs would help provide a sense of which kinds of assets—national roads, provincial roads, local (commune or district) roads, or bridges—are key to the accessibility province-scale economic activities. The following sections present lists specific assets—showing the asset types, the commune and districts they are located in, their maximum lengths of hazard exposures, the initial and total investments required to achieve climate resilience, and the minimum and maximum benefits and BCRs from investing in those assets.

Lao Cai province-scale roads network

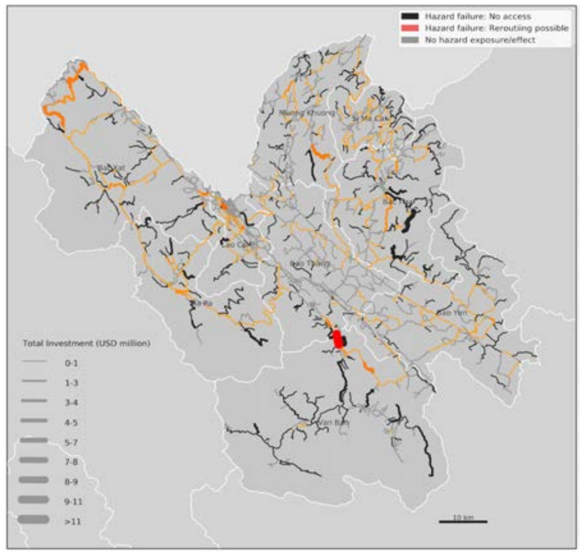
Figures 4.4A through 4.4D show, respectively, the maximum initial investment, the maximum investments over 35 years, maximum values of the estimated benefits over 35 years, and maximum BCRs of adaptation for all identified road links exposed to extreme hazard. The key highlights from these results identify several road links in the province—prominent candidates for adaptation investments—whose failures cut off access to commune centers and hence economic activities. Figure 4.4D shows several such links in the south of the province have BCR > 1, and include significant points in the network (possibly bridges) where the BCRs are highest.

Table 4.5 gives the list of the specific road network assets identified by their adaptation of BCRs. The table ranks the top 20 assets by maximum BCR values, while also reporting their minimum BCRs. The results indicate that some local (commune or district) roads and bridges in the provinces have the highest BCRs, making them most significant to the provision of economic activities; consequently, building their climate resilience should be prioritized. In addition, several road links in Lao Cai important for gaining access to economic activities also emerge as priority assets for climate adaptation investments. The analysis shows that for these 20 assets a cumulative climate adaptation investment amounts to approximately US$9 million initially, with a total investment over 35 years of approximately US$12.9 million. The cumulative benefits of such investments over 35 years, estimated by adding the benefits from individual links, range between US$16.4 and US$22.5 million.

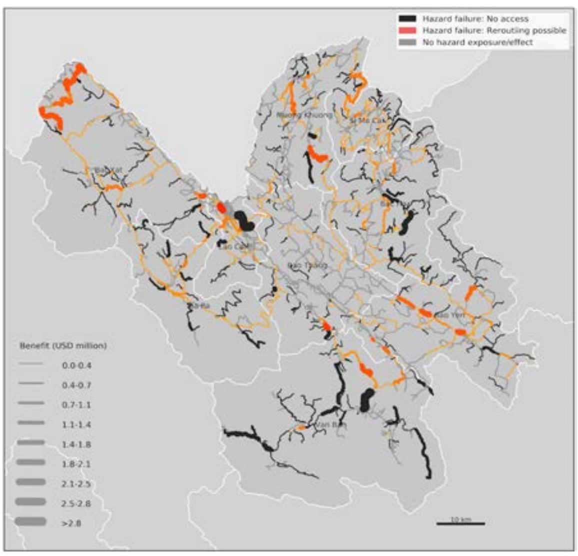
Figure 4.4. Investments, Benefits, and Adaptation BCR Options for Identified Links in the Lao Cai Road Network



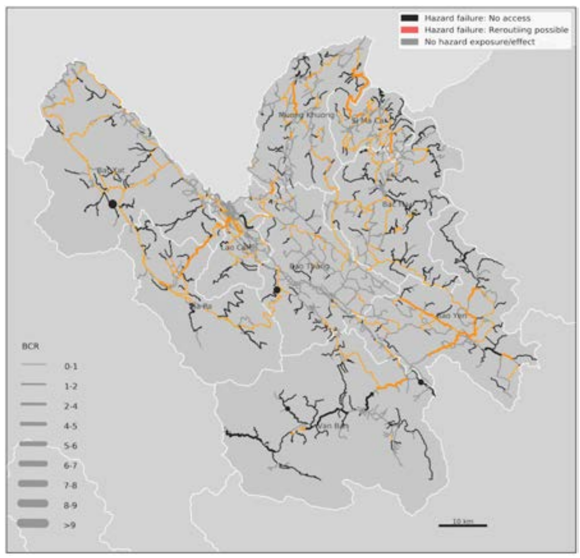
A. Maximum initial investment



B. Maximum investment over time



C. Maximum benefit over time



D. Maximum BCR

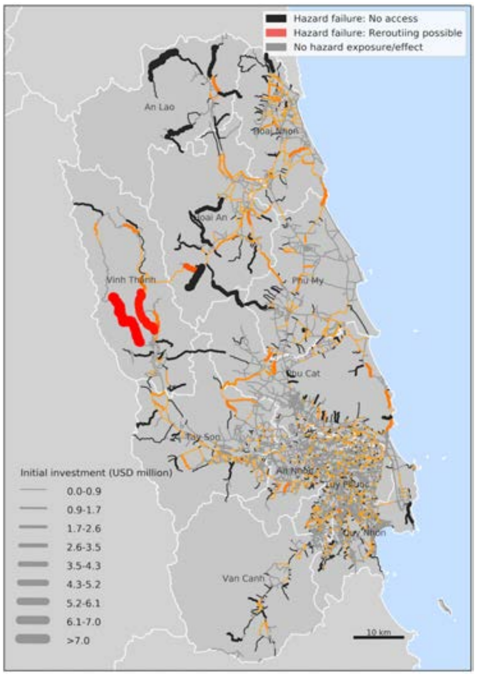
Table 4.5. Top 20 Lao Cai Road Assets Ranked in Descending Order of Maximum Adaptation BCRs

Asset type	Commune name	District name	Maximum hazard exposure length (meters)	Initial investment (US$)	Total investment (US$)	Benefit (US$)		BCR	
						Min.	Max.	Min.	Max.
Bridge	Nam Pung	Bat Xat	15	50,122	59,824	524,009	565,302	8.8	9.4
Local road	Gia Phu	Bao Thang	93	161,241	222,337	392,406	1,758,052	1.8	7.9
Bridge	Tan An	Van Ban	28	90,263	110,696	543,361	712,690	4.9	6.4
Local road	Dan Thang	Van Ban	32	60,139	81,388	87,584	431,644	1.1	5.3
Expressway	Tan An	Van Ban	100	365,277	570,972	1,156,642	1,342,008	2.0	2.4
Local road	Gia Phu	Bao Thang	146	249,353	345,176	231,463	766,128	0.7	2.2
Local road	Van Hoa	Lao Cai	593	999,203	1,388,596	654,402	2,827,630	0.5	2.0
National road	Son Thuy	Van Ban	653	957,339	1,387,381	1,815,881	2,668,361	1.3	1.9
Local road	Khanh Yen Ha	Van Ban	90	155,697	214,609	139,489	375,268	0.6	1.7
Bridge	Ban Lien	Bac Ha	24	77,235	92,928	48,905	140,403	0.5	1.5
Bridge	Nam Pung	Bat Xat	15	50,847	60,709	55,871	80,054	0.9	1.3
National road	Hoa Mac	Van Ban	483	710,312	1,028,267	1,326,067	1,337,024	1.3	1.3
National road	Minh Luong	Van Ban	566	827,091	1,199,299	1,551,401	1,555,555	1.3	1.3
National road	Thuong Ha	Bao Yen	553	809,385	1,173,367	1,516,086	1,518,548	1.3	1.3
National road	Pho Rang	Bao Yen	530	776,177	1,124,731	1,451,507	1,451,825	1.3	1.3
National road	Muong Khuong	Muong Khuong	151	228,832	328,453	421,722	423,483	1.3	1.3
National road	Xuan Hoa	Bao Yen	394	578,966	838,576	1,081,134	1,081,185	1.3	1.3
National road	Nam Xe	Van Ban	392	575,960	834,174	1,075,350	1,075,376	1.3	1.3
National road	Thanh Binh	Muong Khuong	493	724,721	1,049,370	1,352,037	1,352,103	1.3	1.3
National road	Muong Khuong	Muong Khuong	368	541,065	783,067	1,007,730	1,007,735	1.3	1.3
Total				**8,989,225**	**12,893,921**	**16,433,046**	**22,470,373**		

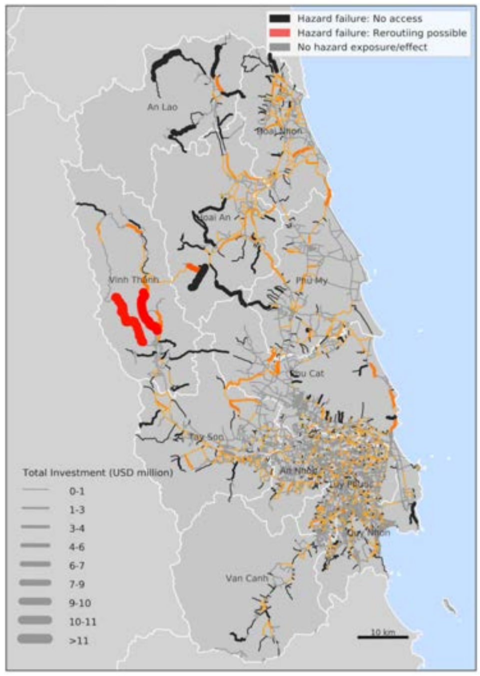
Binh Dinh province roads

The analysis shows that for these 20 assets a cumulative climate adaptation investment amounts to approximately US$1.2 million initially, and over 35 years reaches approximately US$1.6 million (figure 4.5). The cumulative benefits over 35 years, estimated by adding the benefits from individual links, of such investments range between US$14.2 and US$31.4 million (table 4.6).

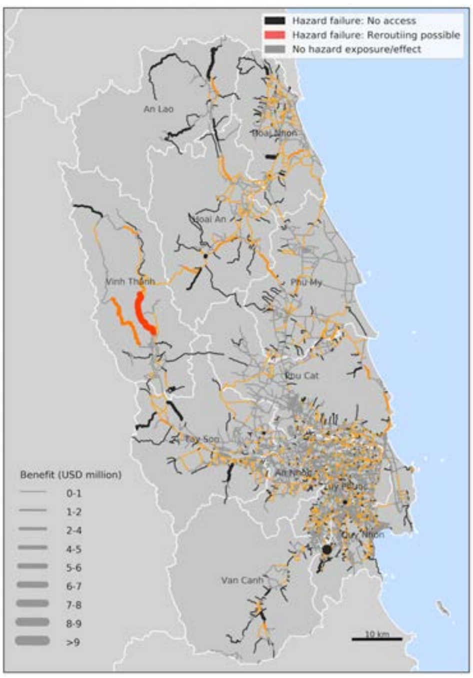
Figure 4.5. Investments, Benefits, and BCRs of Adaptation Options for Identified Links in the Binh Dinh Road Network



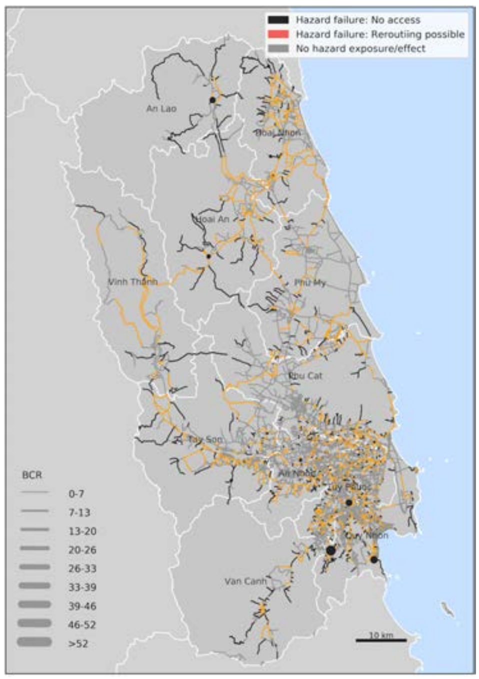
A. Maximum initial investment



B. Maximum investment over time



C. Maximum benefit over time



D. Benefit-cost ratio

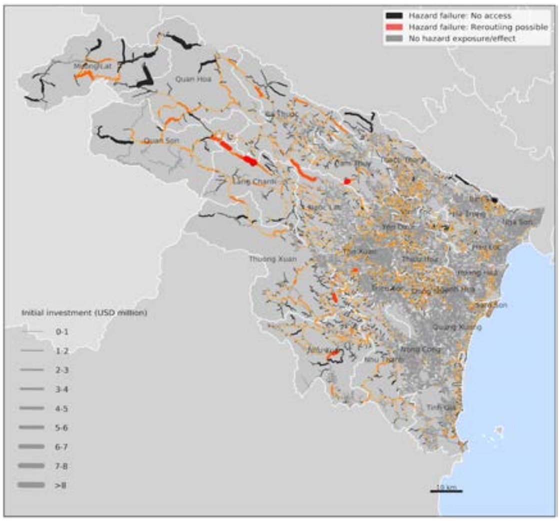
Table 4.6. Top 20 Binh Dinh Road Assets Ranked in Descending Order of Maximum Adaptation BCRs

Asset type	Commune name	District name	Maximum hazard exposure length (meters)	Initial investment (US$)	Total investment (US$)	Benefit (US$)		BCR	
						Min.	Max.	Min.	Max.
Local road	Phuoc My	Quy Nhon	108	114,594	179,470	2,670,602	9,413,243	15	52
National road	Ghenh Rang	Quy Nhon	8	8,917	10,436	124,418	428,047	12	41
Bridge	An Tan	An Lao	8	29,163	34,232	683,481	1,203,717	20	35
Local road	Tuy Phuoc	Tuy Phuoc	63	69,542	107,448	3,496,164	3,629,342	33	34
Local road	An Nghia	Hoai An	122	128,485	201,678	1,271,253	4,114,864	6	20
Local road	Nhon Hau	An Nhon	7	13,555	17,944	95,993	325,041	5	18
Bridge	Hoai Son	Hoai Nhon	11	39,739	47,145	232,847	771,422	5	16
Bridge	Hoai Tan	Hoai Nhon	45	139,971	169,528	2,487,608	2,753,177	15	16
Bridge	Phuoc My	Quy Nhon	20	66,165	79,412	368,444	1,260,278	5	16
Bridge	Tay Xuan	Tay Son	11	38,456	45,579	203,829	640,231	4	14
Bridge	An Hao Tay	Hoai An	13	45,480	54,155	383,299	708,861	7	13
Bridge	Nhon Hau	An Nhon	5	22,483	26,076	98,772	327,819	4	13
Local road	Tay Xuan	Tay Son	31	37,516	56,250	204,282	640,684	4	11
Bridge	Phuoc Quang	Tuy Phuoc	6	24,850	28,967	97,273	324,475	3	11
National road	Ghenh Rang	Quy Nhon	81	40,850	56,983	188,705	523,325	3	9
Local road	Tay An	Tay Son	168	173,697	273,955	918,272	2,462,332	3	9
Bridge	Tay Giang	Tay Son	18	60,388	73,557	288,159	609,252	4	8
Local road	Cat Chanh	Phu Cat	56	62,045	95,463	222,854	708,369	2	7
Bridge	Binh Nghi	Tay Son	5	21,950	25,425	55,223	168,167	2	7
Local road	Phuoc Thuan	Tuy Phuoc	36	42,295	63,890	139,776	416,993	2	7
Total				**1,180,139**	**1,647,594**	**14,231,253**	**31,429,640**		

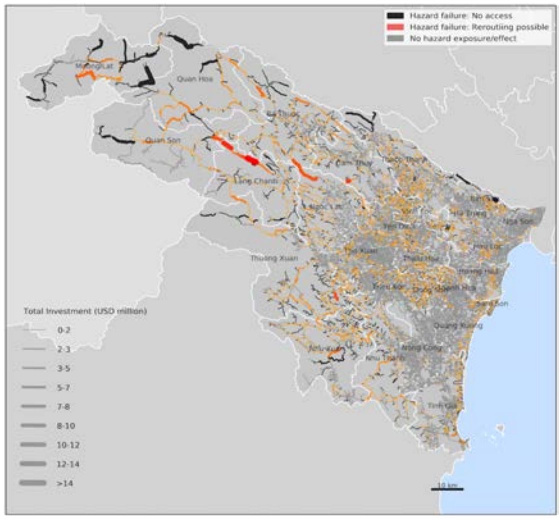
Thanh Hoa province roads

Figure 4.6 illustrates and table 4.7 lists the top 20 specific road network assets identified by their BCRs of adaptation. All assets have minimum and maximum BCRs > 1, which makes a robust case for investing in their climate resilience. For these 20 assets, a cumulative climate adaptation investment amounts to approximately US$1.5 million initially, with a total of US$2.3million over 35 years. The cumulative benefits of such investments over 35 years, estimated by adding the benefits from individual links, range between US$7.8 and US$23.4 million.

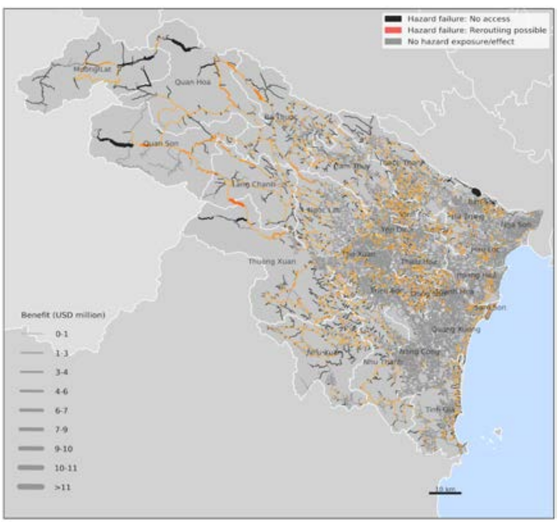
Figure 4.6. Investments, Benefits, and Adaptation BCRs Options for Identified Links in the Thanh Hoa Road Network



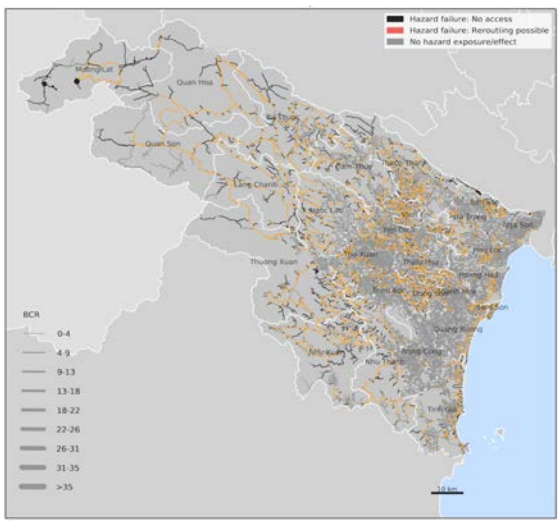
A. Maximum initial investment



B. Maximum investment over time



C. Maximum benefit over time



D. BCR

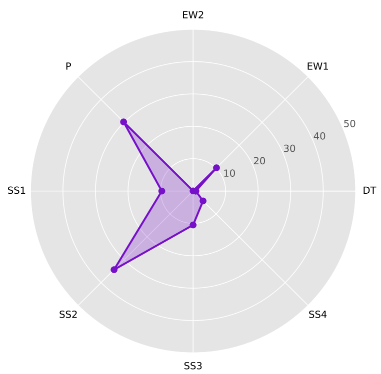
Table 4.7. Top 20 Thanh Hoa Road Assets Ranked in Descending Order of Maximum Adaptation BCRs

Asset type	Commune name	District name	Maximum hazard exposure length (meters)	Initial investment (US$)	Total investment (US$)	Benefit (US$)		BCR	
						Min.	Max.	Min.	Max.
Local road	Pu Nhi	Muong Lat	44	50,062	76,306	771,381	2,678,809	10	35
Bridge	Quang Chieu	Muong Lat	2	12,265	13,600	135,066	451,068	10	33
Bridge	Xuan Cao	Thuong Xuan	6	23,849	27,744	162,858	576,843	6	21
Bridge	Pu Nhi	Muong Lat	2	12,182	13,499	74,402	257,194	6	19
Bridge	Quang Chieu	Muong Lat	6	23,790	27,673	131,301	444,398	5	16
Local road	Nga Dien	Nga Son	26	31,724	46,990	164,642	559,082	4	12
Bridge	Muong Ly	Muong Lat	7	28,290	33,167	176,400	364,716	5	11
Local road	Quang Chieu	Muong Lat	27	32,997	49,026	159,503	514,015	3	10
Local road	Bac Son	Bim Son	712	724,512	1,150,046	3,981,353	11,480,906	3	10
Bridge	Quang Chieu	Muong Lat	5	22,011	25,500	75,491	251,168	3	10
Bridge	Hai Van	Nhu Thanh	29	91,084	109,837	261,960	864,780	2	8
Local road	Nga Dien	Nga Son	42	48,101	73,172	170,467	564,906	2	8
Bridge	Quang Chieu	Muong Lat	54	165,715	200,961	483,486	1,501,439	2	7
Urban road	Trung Son	Quan Hoa	20	51,807	81,247	393,965	522,847	5	6
Local road	Xuan Khang	Nhu Thanh	37	42,854	64,783	133,467	411,658	2	6
Local road	Luan Thanh	Thuong Xuan	32	37,903	56,869	105,024	355,646	2	6
Bridge	Quang Chieu	Muong Lat	9	33,924	40,046	76,539	244,625	2	6
Local road	Thanh Tan	Nhu Thanh	52	57,897	88,832	154,620	502,973	2	6
Local road	Xuan Khang	Nhu Thanh	11	16,947	23,368	38,255	122,988	2	5
Local road	Hai Van	Nhu Thanh	40	46,325	70,332	109,882	356,369	2	5
Total				**1,554,239**	**2,272,999**	**7,760,062**	**23,026,429**		

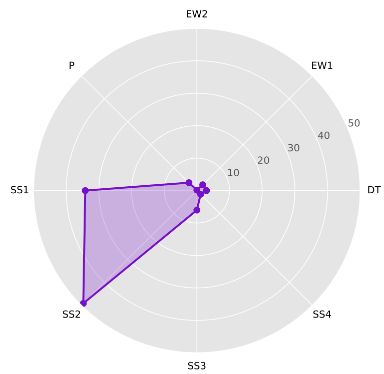
Decision-Making under Uncertainty: Sensitivity of Costs of Adaptation

The global sensitivity analysis shown in figure 4.7 demonstrates that the variations in initial investment cost estimates for national roads are most sensitive to the costs of pavement upgrades and improvements in slope stability, accomplished by installing embankment-retaining gabions (figure 4.7A). The initial climate resilience investment costs in the mountainous terrain of Lao Cai (figure 4.7B) are most sensitive to the investment costs of upgrading and protecting embankments, while Binh Dinh (figure 4.7C) and Thanh Hoa (figure 4.7D) are most sensitive to the investment costs of improving slope stability through road embankments, building embankments, and upgrading pavements. The numbers in figure 4.7 show what percentages of costs are driven by variations in different types of investments.

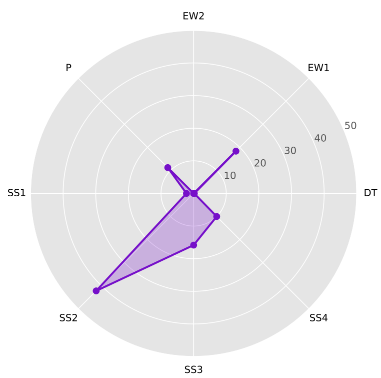
Figure 4.7. Parameter Sensitivity for National- and Province-Scale Roads



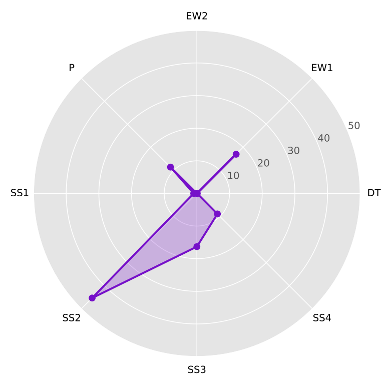
A. Parameter sensitivity for national roads



B. Parameter sensitivity for Lao Cai



C. Parameter sensitivity for Binh Dinh



D. Parameter sensitivity for Thanh Hoa

Code	Item	Code	Item	Code	Item
P	Gravel	DT	Line Drain L & R	SS3	Concrete/block Face
	Sealed	EW1	Embankment Construction	SS4	River bank
	Concrete	EW2	Cut slope Formation		
	Concrete FW	SS1	Cut slope Toe Retaining Gabions		
SS2	Embankment Retaining Gabions	SS6	Bioengineering		

Ranges and uncertainties in adaptation estimates

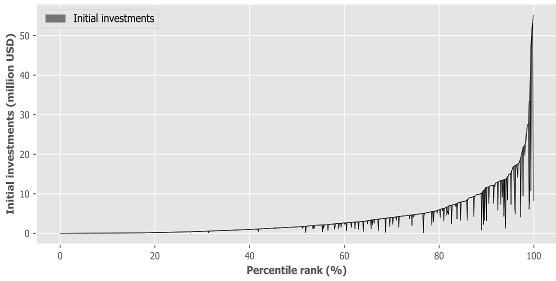
National-scale roads

This section discusses the ranges and uncertainties in the estimation of adaptation costs and benefits. Figures 4.8A through 4.8D show for individual national-scale road network links the ranges of: (a) initial investment costs, (b) the NPV of total investments over the 35-year planning horizon; (c) the NPV of adaptation benefits due to losses avoided over the 35-year planning horizon, and (d) the BCRs.

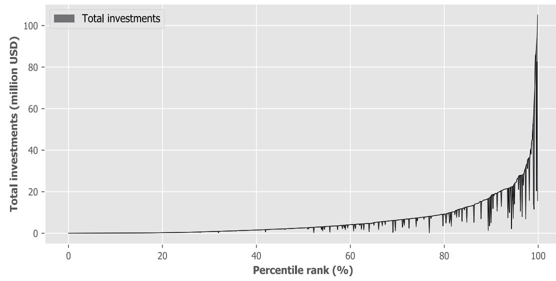
The variations in cost estimates for links in figures 4.8A and 4.8B are evident because of their exposure to multiple hazards; thus, the analysis estimates costs depending upon the extent of exposure to each hazard. As discussed in the previous section, the variations in initial investment cost estimates are most sensitive to the costs of pavement upgrades and improvements in slope stability through the installation of embankment-retaining gabions. Total investments costs over time are most sensitive to the increases in pavement maintenance costs; in the model, most pavement maintenance costs are far more than other maintenance costs. The results show the highest estimated initial investments for building climate-resilient national-scale road network range from US$52 to US$55 million, with the NPV of total investment over time going up from US$87 to US$105 million. However, these investments might not necessarily be for the same road links.

Variations in NPVs of the adaptation benefits shown in figure 4.8C are sensitive generally to the avoided economic losses, and to some extent the costs of rehabilitation. For links with very high NPVs, the benefits are driven mainly by the values of avoided economic losses. The importance of these links to the wider network makes the case for investing in climate resilience. The analysis shows that the highest NPVs of adaptation benefits range from US$118 to US$334 million, substantially larger than the NPVs of total investments. As shown in figure 4.8D, for several links this leads to generally high benefit-cost ratios (BCR >> 1). Significantly, the analysis shows that from the 60th percentile onwards, the minimum and maximum BCRs of several links are both greater than one, indicating that under every extreme climate hazard scenario, investing in the climate resilience of a significant proportion of national-scale roads would be beneficial.

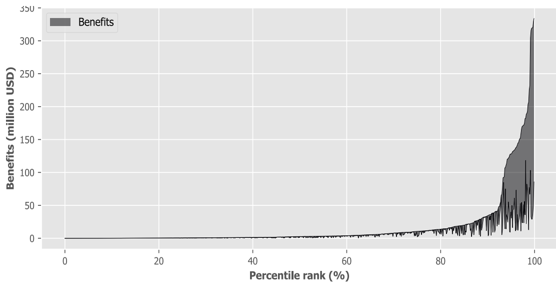
Figure 4.8. Adaptation Analysis Results for the National-Scale Road Network in Vietnam



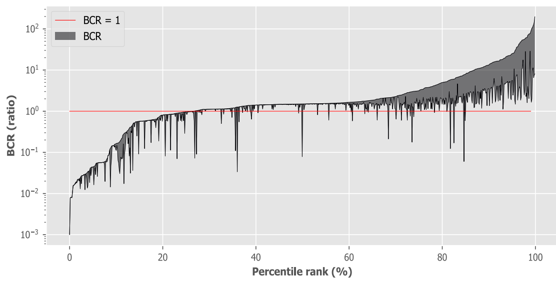
A. Range of initial adaptation investments



B. Range of total adaptation investments



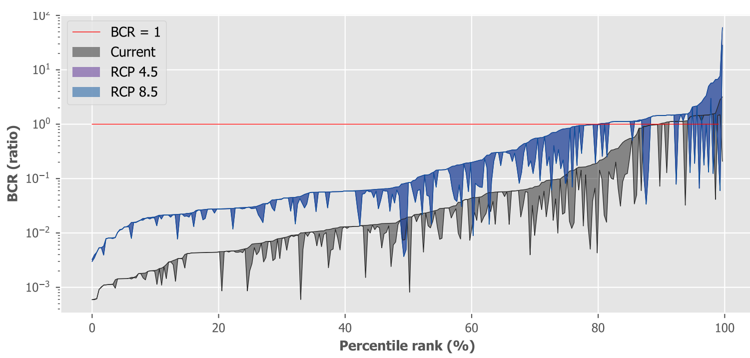
C. Range of adaptation benefits



D. Range of adaptation BCRs

Comparing hazard-specific adaptation BCRs across different scenarios of the same hazard type shows how the hazard uncertainties influence the adaptation analysis outcomes. Such a comparison is made for the case of national-scale road network risks due to river flooding in current conditions and for the future under RCP4.5 and RCP8.5 emission scenarios, as shown in figure 4.9. The results show a significant uplift of BCRs of adaptation when climate resilience investments are made to avoid future levels of extreme river flooding driven risks. The analysis mostly does not show any difference between BCRs of adaptation when evaluated for RCP4.5 and RCP8.5 climate scenario driven river flooding risks, which is reflected through the complete overlap of the curves for these two scenarios. Significantly, in comparison to the current scenarios, large percentiles of road links have BCRs > 1 when adapting to future climate scenarios. *This result provides a very compelling case for a need in Vietnam to plan climate resilience investments in anticipation of future climate change driven hazards, when the risks and therefore benefits of avoiding those risks will be much higher.*

Figure 4.9. Ranges of Adaptation BCRs for the National-Scale Road Network in Vietnam, Evaluated for Current and Future Extreme River Flooding Scenarios



Province-scale roads

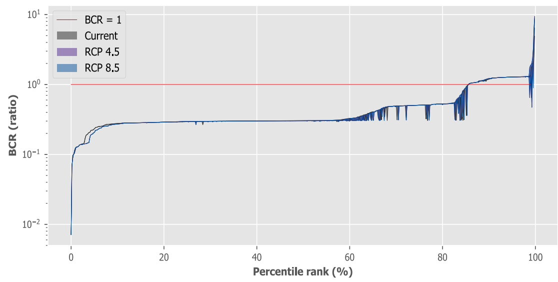
The province-scale analyses show, in comparison to most road assets, a relatively small percentile of road assets have significantly higher adaptation costs. Initial climate-resilience investments for individual road assets reach in excess of US$2 million for 1) approximately the top 10 percentile assets in Lao Cai; and 2) approximately the top 2 to 3 percentile assets in Binh Dinh and Thanh Hoa. Some of these very high value assets might potentially have high benefits; hence, their costs might be justified. The analyses show very little variations of initial and total investment costs in both Lao Cai and Binh Dinh, while the variability is more apparent in Thanh Hoa. The lack of variations in Lao Cai and Binh Dinh stems from the road network assets in both provinces having similar exposure lengths to the various hazards scenarios; therefore, since the costs, which depend upon the lengths of road assets exposed to hazards, are also similar. As discussed in the previous section, the sensitivity of initial climate resilience investment costs in each province are as follows: a) Lao Cai is most sensitive to the investment costs for upgrading and protecting embankments, due to its mountainous terrain; and b) Both Binh Dinh and Thanh Hoa are most sensitive to investment costs for improving slope stability of roads embankments, building embankments, and upgrading pavements.

The ranges of adaptation benefits in the three province-scale analyses also show that for a relatively small percentile of road assets, the benefits of adaptation are much higher than for the rest of the network assets. Initial climate resilience investments for individual road assets exceed US$2 million for: a) approximately the top 5 percentile assets in Lao Cai; and b) around the top 2 to 3 percentile assets in Binh Dinh and Thanh Hoa. The variations in the ranges of benefits of adaptation in the three province-scale analyses arise are mainly sensitive to the changes in the avoided economic impacts of disruptions. For such assets the case for investing in climate resilience is compelling, because the benefits outweigh the costs, as is evident from the BCR plot for the three provinces.

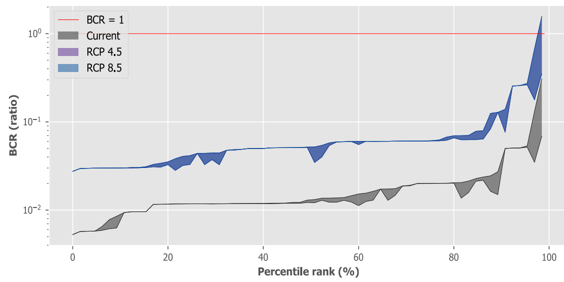
Figure 4.10D shows that in Lao Cai approximately the top 15% percentile of assets (roughly 190 in the Lao Cai network) at risk of hazard have maximum BCR > 1. In Binh Dinh (figure 4.10C) again assets in the top 2 to 3 percentile have maximum BCRs > 1, which amount to roughly 220 to 330 assets in Binh Dinh and 530 to 800 assets in Thanh Hoa. Though a relatively small proportion, these numbers of assets are significant when it comes to prioritizing climate investments. The next section provides more evidence of where and which assets could be further prioritized, based on identifying the locations and types of specific assets.

The results show a clear case of increased BCRs in Lao Cai when comparing current and future river flooding scenarios, as shown in figure 4.10B, where maximum BCRs become greater than one only for future extreme river flooding scenarios. In Binh Dinh and Thanh Hoa, the number of assets with maximum BCRs > 1 in the future river flooding scenarios also show an increase. As presented earlier in the report, all increases arise from increases in future river flooding risks, which avoided economic loss. Landslide susceptibility in Lao Cai is included here as a prominent hazard in the province, for which the underlying hazard data offered some climate change scenario-based information. In the absence of any probabilistic hazard information on the landslide susceptibility much of the current and future adaptation options show similar outcomes. But, significantly, several assets with BCR > 1 create a compelling case for investing in climate resilience.

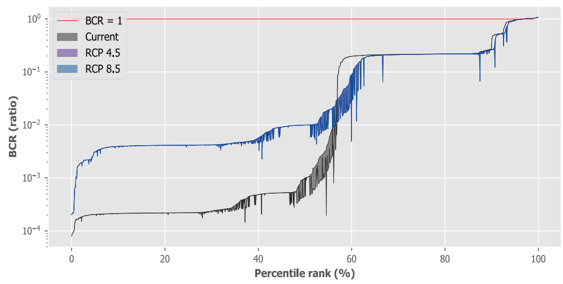
Figure 4.10. Adaptation BCRs for Province-Scale Road Networks



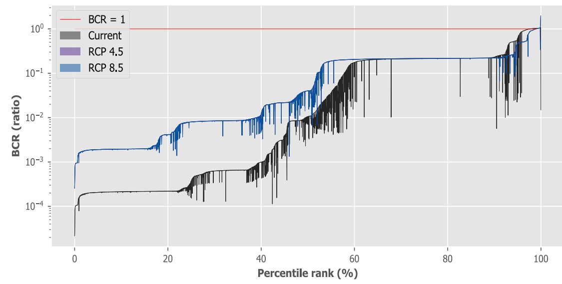
A. Range of BCR adaptation to landslide risks (Lao Cai)



B. Range of BCR adaptation to river flooding risks (Lao Cai)



C. Range of BCR adaptation to river flooding risks (Binh Dinh)



D. Range of BCR adaptation to river flooding risks (Thanh Hoa)

Notes

1. Dr. Jasper Cook, a civil engineer, serves as infrastructure research manager for the Africa Community Access Partnership (AfCAP) and the Asia Community Access Parternship (ASCAP), research programs under the umbrella of the UKAid-funded Research for Community Access Partnership (ReCAP). For more information, visit: http://research4cap.org.

2. Costs estimates for bridges are highly uncertain and depend heavily on the particular bridge being studied. Hence no claim is made here that the bridge costs considered in this study will apply to each and every bridge in Vietnam. The costs are more an indicative of the order to investment that might be required into bridges.

3. The GLOFRIS models estimate the average maximum flood depths from 2010 to 2049, which is used as a representative of a 2030 event. However, these models essentially estimate hazard scenarios to 2049.

4. Data accessed via the International Monetary Fund DataMapper: http://www.imf.org/external/datamapper/NGDP_RPCH@WEO/OEMDC/ADVEC/WEOWORLD/VNM.

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Chapter 5: Exploring Multimodal Options for National-Scale Transport

This chapter explains how the multimodal transport system was created for this study. Following this, the chapter evaluates the effect of multimodality on failures by exploring modal shifts from road and rail networks.

In the analysis presented to this point, each mode of transport has been assessed individually to understand the impacts of failures. In reality, failures may result in exploring multimodal options for maintaining transport service continuity. Based on the study's understanding, multimodal switching options have not been well explored in Vietnam. Hence, this chapter explores the possible changes in network failure effects if multimodal options were always available to accommodate for failures along individual modes.

The chapter explores the following key questions:

- What are the multimodal transport networks options available in providing continuous service when individual transport modes are damaged or disrupted by external natural hazard shocks?
- Are there any gains in terms of decreasing losses due to multimodal options?

Switching from one mode to another during failure, via a multimodal connection, presents a potential adaptation option, and where modal switching is a preferred option, its benefits should be compared with the costs involved in facilitating and improving multimodal links and upgrading transport modes. The analysis presented here explores the benefits of multimodality in making informed decisions.

The analysis quantifies impacts of multimodality through two metrics:

- *Total economic impact metric*: The overall economic criticality of network links measured as the sum of their macroeconomic losses and the freight redistribution costs incurred due to their failures
- *The AADF tonnage shift*: The overall systemic shift of tonnage from a disrupted mode to other modes due to multimodal options

The key steps in undertaking a multimodal analysis involve:

- Identifying and creating links at all locations where multimodal transfers might be inferred
- Estimating the costs of multimodal shifts
- Performing the failure analysis, as previously outlined in the criticality analysis, with the change, now that the entire multimodal transport network-of-networks is considered a rerouting option
- Estimating the multimodal metrics

The multimodal analysis presented here considered only the failures scenarios for the national-scale road and the railway networks.

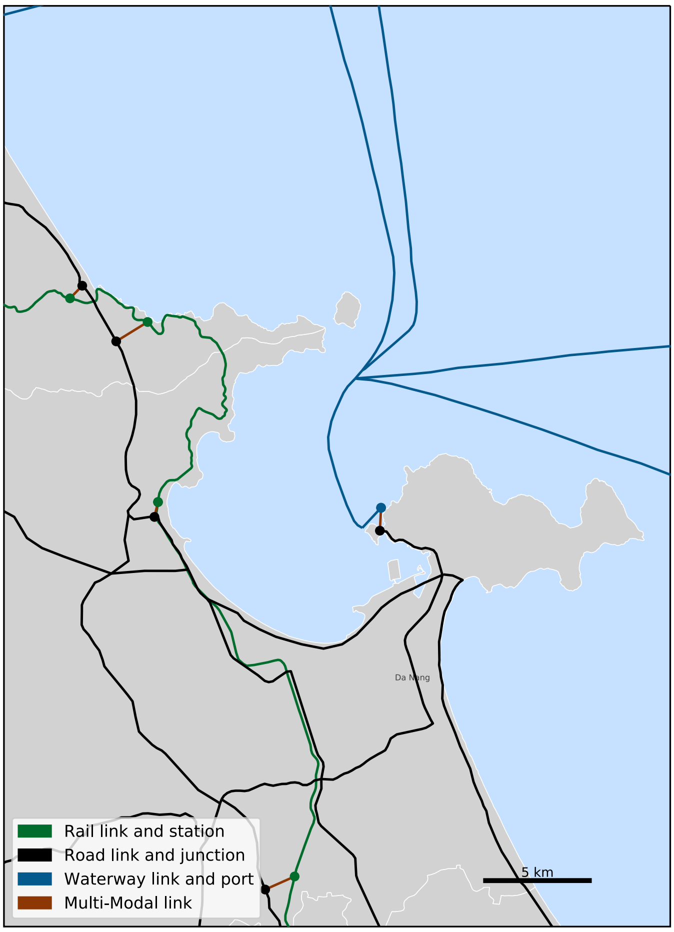
Including Multimodal Links and Costs

The study created the physical topology of multimodal network for the national-scale analysis, using the national-scale road, railway, inland waterway, and maritime network models. The study assumed the following while creating the multimodal network links:

- To create the port-road and port-rail links, all identified inland and maritime ports were selected as multimodal points and joined to their nearest road and rail nodes.
- To create the road-rail multimodal links, all rail stations were selected as multimodal points and joined to the nearest road nodes.
- To create a more realistic spatial mapping, only those multimodal links with lengths < 3 kilometers were selected.

The multimodal network links represent a notional connectivity between modes, and at best represent the nearest possible accessibility point from one transport mode to another. A sample of the network, zoomed in at a selected location, is shown in figure 5.1.

Figure 5.1. Multimodal Links Created in the Network Model



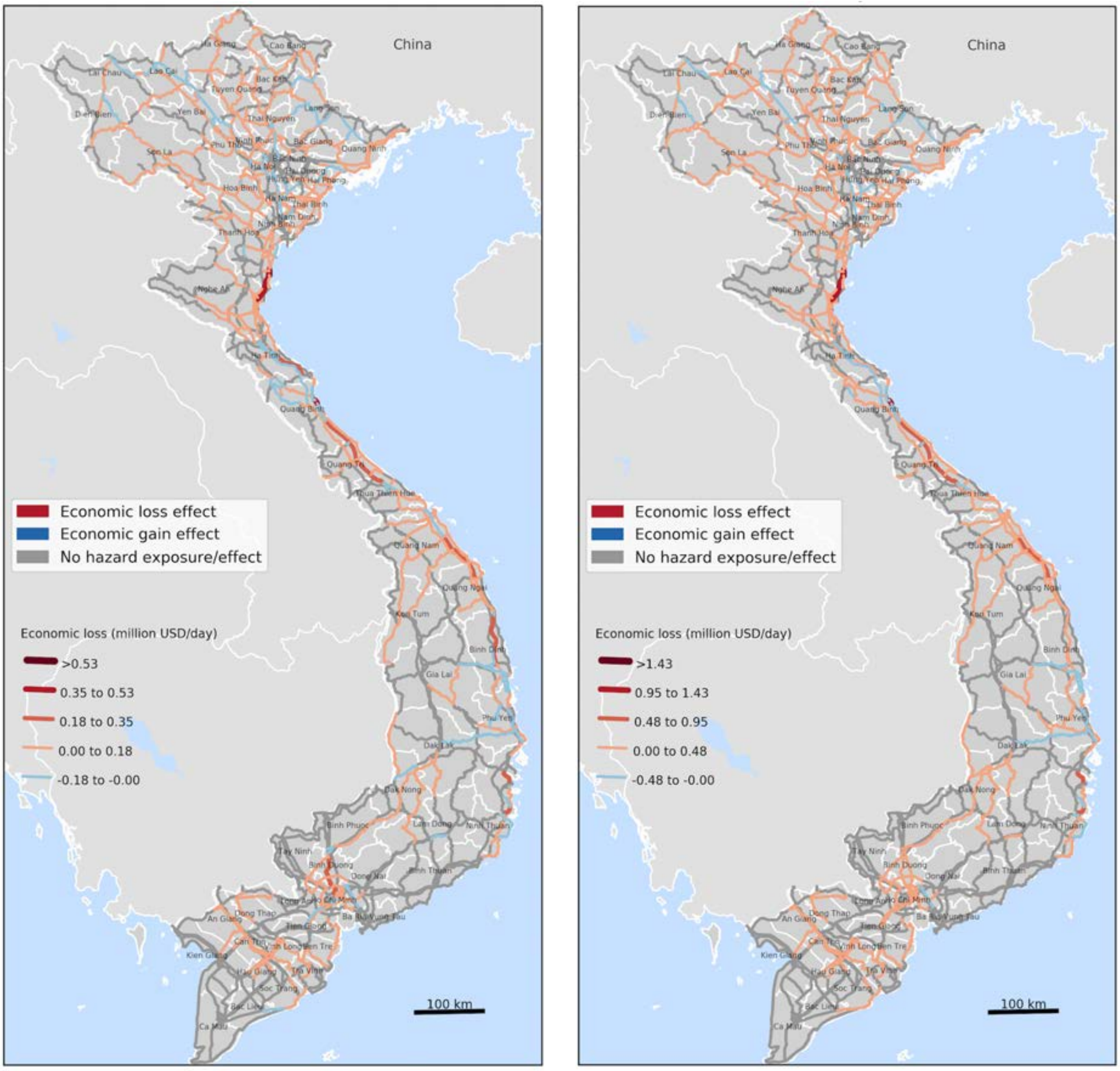
Results of Partial Multimodal Shifts in Road Failure Analysis

The 968 cases of individual road failures identified in the road criticality analysis were again tested with the multimodal networks. For each failure scenario, the analysis estimated the AADF disruptions, the macroeconomic losses, the rerouting losses, and the overall economic impacts. The results showed quite evidently that because of multimodality, the main effect was seen in terms of the changing redistribution costs, as most cases of single-point failure were eliminated. Hence, understanding the net economic impacts, due to changing rerouting costs, represents the main result here.

To assume a complete shift of road freight toward other modes via multimodal linkages is unrealistic, because networks such as railways have no capacity to accommodate the large volumes of road tonnages. A more feasible and realistic analysis would be to understand cases that explore options for rerouting a small percentage of the disrupted flows from the road to multimodal networks, while rerouting the remaining freight to undamaged roads. In discussing this option here, the study assumes that for each road failure scenario, 90 percent of freight is rerouted along the road network, with the remaining 10 percent rerouted to the least-cost multimodal option—which could be the road network.

The result in figure 5.2 shows that even a 10 percent modal shift can help reduce the economic impacts of road failure. For example, key sections of roads show gains, attributed to modal shifts, ranging from US$0.18 to US$0.47 million per day. Also, across the minimum and maximum flow scenarios, the highest losses along the highest flow routes get reduced to US$0.53 to US$1.43 million per day, in comparison to no multimodal rerouting option loss values of US$0.67 to US$1.9 million per day. Notably, this 10 percent shift from road to other modes reduces economic losses by approximately 20 to 25 percent.

Figure 5.2. Total Economic Impacts of National-Scale Road Links Failures When Considering 90 Percent Flow Rerouting on Roads and 10 Percent Rerouting along Other Networks via Multimodal Links



A. Minimum economic impact **B. Maximum economic impact**

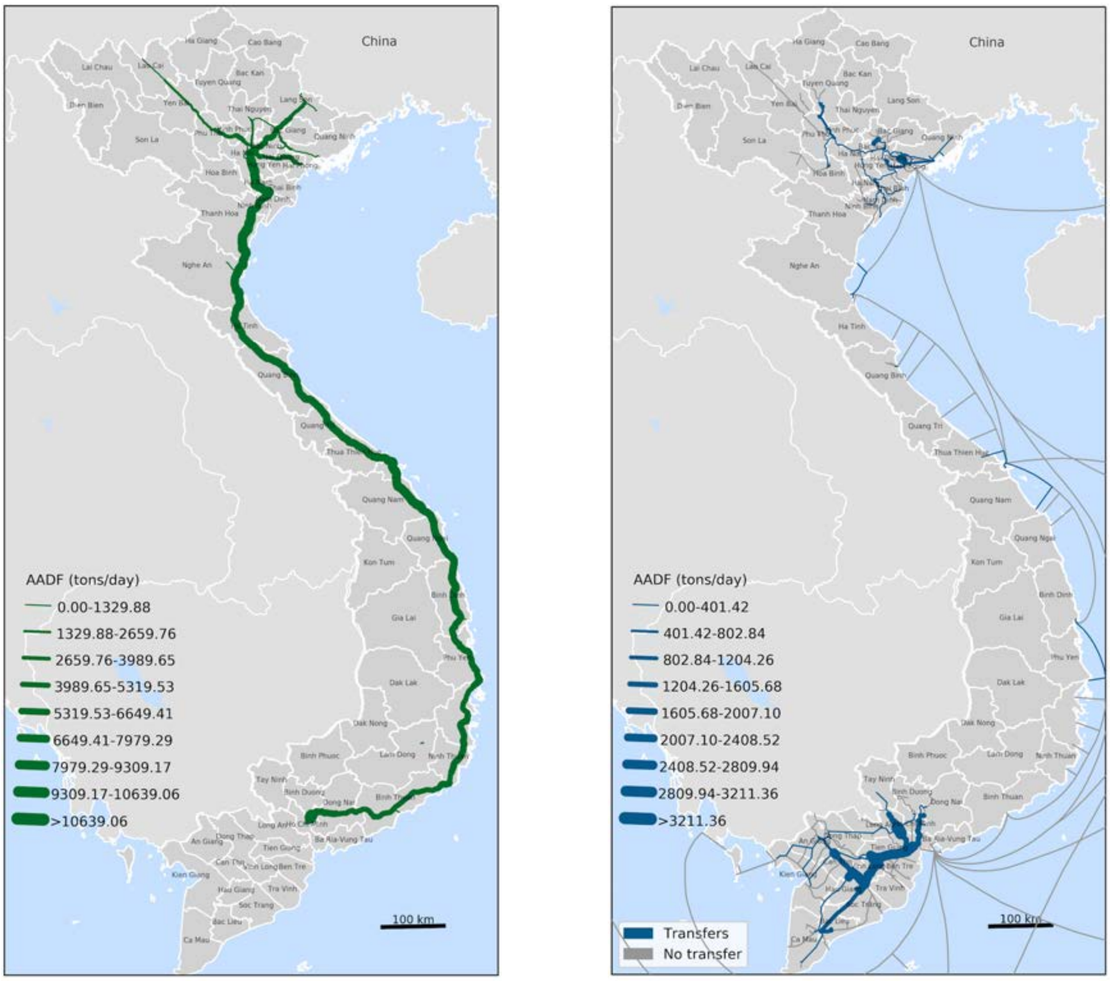
The chapter next presents the causal effects of the economic gains and losses due to multimodality indicate where the systemic modal shifts take place. Figure 5.3 shows the combined effects of redistribution of 10 percent of flows in terms of AADF tonnages shifts from national-scale roads to other modes—railways, inland waterways, and maritime. In each figure, panel A shows results for the railways and panel B shows the combined inland waterways and maritime. The results reveal that a predominant number of disrupted road failures prefer to be, rerouted via railways because it is often the cheapest and closest option to high-flow road links. The original VITRANSS study estimated railway transport costs in Vietnam to be lower than costs for road transport (JICA et al 2000), and this finding is reflected in this study. Consequently, if transportation assignments were based only on transportation costs, railways would be preferred over roads. For the minimum to maximum flow scenarios, the railways witness an added maximum of approximately 8,500 to 10,600 tons per day in systemic flow rerouting. This can lead to an almost doubling of rail tonnage volumes, based on the estimated tonnages in this study. According to existing analysis (Systra 2018), most of the railways currently operate under capacity, for example:

- Along the Hanoi–Ho Chi Minh line, freight uses only 35 to 41 percent of network capacity, with an estimated leftover capacity between 0 and 29 percent, with 0 percent around Saigon.
- Along the remaining lines in the north (radiating from Hanoi), freight uses only 11 to 30 percent of network capacity, with an estimated leftover capacity between 48 and 85 percent.

Based on the above it would be quite feasible to redistribute road freight toward railways, especially along the northern routes. Moreover, the figure 5.2 result indicates gains in transferring even 10 percent of disrupted freights from road to rail along the Hanoi to Lao Cai route.

Between railways and waterways, the preference for railways outweighs that of waterways, except in a small area in the north and a predominant preference in the southern areas that have no railway networks. Given the high volumes transported on southern waterways, the tonnages shown here can be accommodated by their preferred modes without exceeding capacities.

Figure 5.3. Redistribution of 10 Percent of Maximum Road Tonnage Flows as Added Tonnages onto Rail and Waterway Networks following Road Network Link Disruptions



A. Maximum total tonnage of road transfers (Railways)

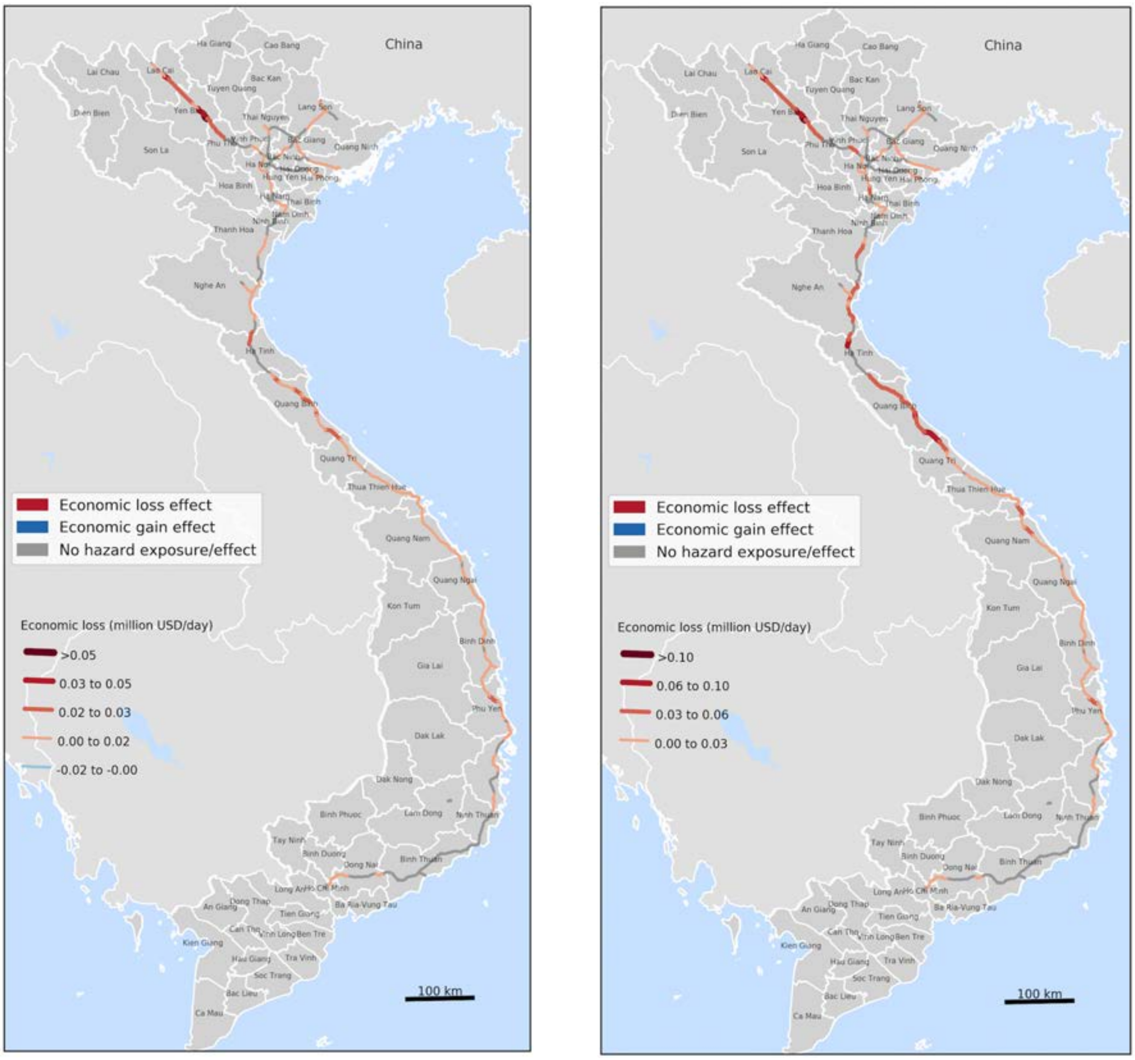
B. Maximum total tonnage of road transfers (Waterways and Maritime)

Rail Failure Analysis Results

The 164 cases of individual rail failures identified in the rail criticality analysis were also tested, and for each failure scenario, the study estimated the AADF disruptions, the macroeconomic losses, the rerouting losses, and the overall economic impacts. Again, multimodality quite evidently exerted influence in terms of the changing redistribution costs, as mostly cases of single-points failure were eliminated. The model did not find any substantial cases of macroeconomic losses. Accordingly, the analysis demonstrates the net economic impacts, mainly due to changing rerouting costs.

Figure 5.4 shows the economic impacts of individual railway link failures corresponding to the minimum and maximum tonnages flows and generalized costs scenarios, where the economic impacts for a link are represented on that specific link. The biggest change here—in comparison to the result in figure 3.2—is that the elimination of all single failure scenarios significantly reduces the economic losses. Also, large sections of the railway network closer to the southern end of Hanoi–Ho Chi Minh line demonstrate several instances where multimodal options result in economic gains, shown as negative values and in the color blue on the maps. In particular, the economic gains can reach as high as US$0.02 to US$0.06 million per day, based on the minimum to maximum flow scenarios. In addition, the highest economic losses fall to US$0.05 to US$0.10 million per day, contrasting with the figure 3.2 result, where these links showed economic losses ranging from US$2.3 to US$2.6 million per day for the same failure scenarios. However, in agreement with the result in figure 5.2, as a cheaper option than roads, the multimodal shift along the Hanoi–Lao Cai railway line shows a loss.

Figure 5.4. Total Economic Impacts of Rail Link Failures when Considering Rerouting Options along National-Scale Roads, Inland Waterways and Maritime Networks via Multimodal Links

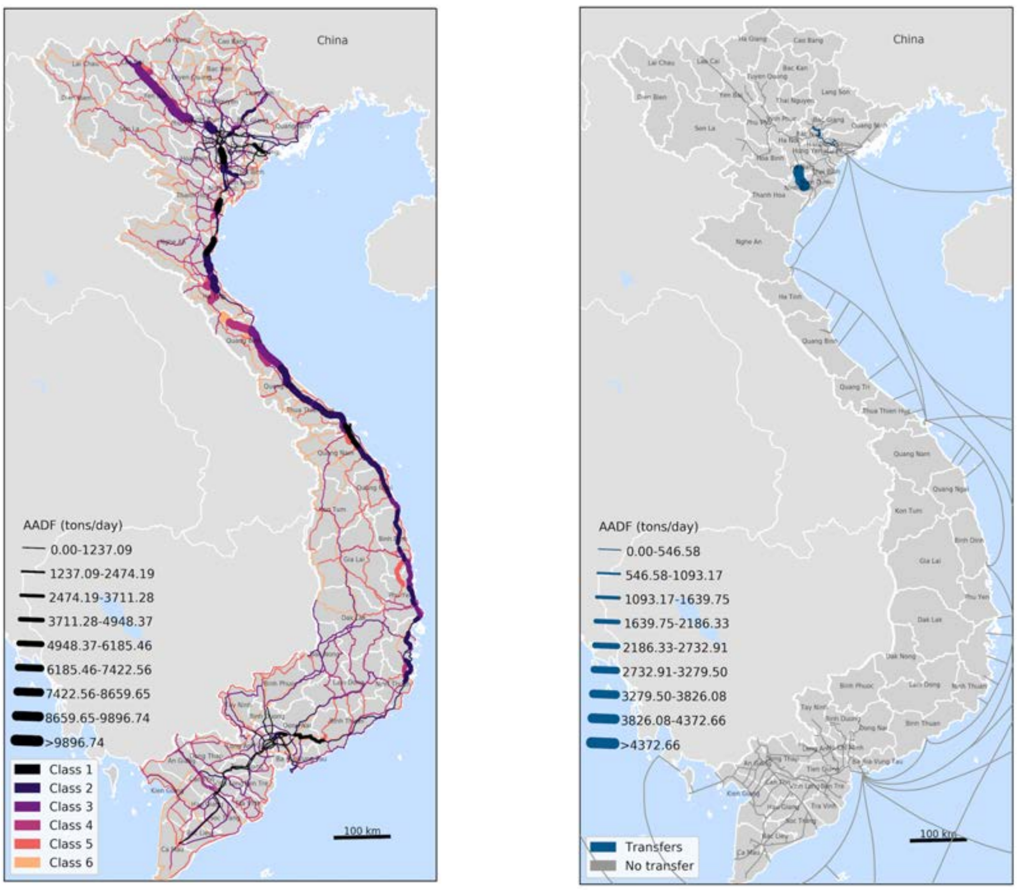


A. Minimum economic impact **B. Maximum economic impact**

Figure 5.5 shows the combined effects of flow redistribution in terms of AADF tonnages shifts from railways and roads to other modes—national-scale roads, inland waterways, and maritime. In each figure, panel A shows the results for the national-scale roads and panel B shows the combined inland waterways and maritime. The results demonstrate that a predominant number of disrupted railway failures would prefer to be rerouted via national-scale roads as the closest option around high-flow railway links. The national-scale roads witness an added maximum of approximately 8,300 to 9,900 tons per day in systemic flow rerouting for the minimum to maximum flow scenarios, largely due to transfers along the Hanoi–Lao Cai route. The waterway networks witness an added maximum of approximately 3,200 to 4,300 tons per day in systemic flow rerouting for the minimum to maximum flow scenarios, mainly along a small northern section.

Since railway flows are much lower when compared to the roads, these transfer volumes can be accommodated by the other networks. Even though the modal shifts from railways to other modes reduce losses, the frequent traffic congestion along alternative road networks could cause costly delays. The road network failure analysis presents a strong case for the benefits of investing in a reliable railway and stronger multimodal options rather than a continued reliance on roads alone.

Figure 5.5. Redistribution of Maximum Tonnage Flows as Added Tonnages onto National-Scale Roads and Waterway (Inland and Maritime) Networks following Rail Network Link Disruptions



A. Maximum total tonnage (National-Scale Roads)

B. Maximum total tonnage (Inland Waterways and Maritime)

References

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Chapter 6: Conclusions and Policy Recommendations

As previously stated, this report aims to create a methodological and computational framework for transport risk analysis in Vietnam. Through the successful demonstration of this framework, the study delivered a novel system-of-systems tool for analyzing and prioritizing transport resilience based on spatial criticalities, risks, and adaptation benefits. *Hence, for Vietnam stakeholders, the report's primary recommendation is to recognize the investment value in a detailed spatial risk analysis approach and building on the existing and new knowledge compiled and created through this project*.

Based on the analysis results and insights of this project, several other recommendations for stakeholders emerge from this study, as discussed below:

Increasing Vulnerabilities Due to Climate Change

Recommendation: Vietnam's transport sectors need to be prepared for the increasing intensity and frequency of extreme hazards due to climate change.

The analysis demonstrates that for all transport sectors in Vietnam, extreme hazard exposures to similar hazards over the same spatial scales increase under climate change scenarios. The overall maximum kilometers of national-scale roads, railways, and province-scale road networks exposed to extreme hazard levels increase under all climate scenarios. All major inland, coastal, and air ports are vulnerable to river flooding with increasing frequency, when extreme levels of flooding seen in 1,000-year events could start occurring in five-year events.

Prioritizing Transport Network Resilience for Systemic Economic Benefit

Recommendation: The systemic understanding of locations whose failures create increasing economic risks presents a strong economic case for investing in building climate resilience of Vietnam's transport networks.

The model and analysis results most usefully highlight systemic criticalities and hazard-specific, high-risk network locations, which can be prioritized for further detailed investigations into climate resilience. The model results show locations of road networks whose failures can result in very high daily losses of up to US$1.9 million per day, while railway failures can result in losses as high as US$2.6 million per day. The wider implications of macroeconomic losses due to transport disruptions are quite crucial when factoring such losses. Generally, transport analysis ignores such effects, which result in underestimating the impacts of transport disruptions.

Comparisons of current and future hazard risks prominently highlight the strong case in Vietnam to invest in building climate-resilient national-scale roads and railways. In addition, the comparisons strongly indicate that access to economic opportunities in several areas of provinces will be severely affected without investment in building climate-resilient roads. The expected annual economic losses—a measure of risks due to transport failures from future climate change-driven river flooding— all significantly increase by at least 100 percent across national-scale roads, railways, and province-scale road networks. All network links with high impacts show these increases.

Making the Case for Investment in Adaptation to Build Transport Network Resilience

Recommendation: Vietnam's road networks require investments to overhaul existing road assets to higher climate-resilient design standards. Though such investments could be costly, their benefits outweigh the costs for priority network assets, making adaptation investments viable options for roads.

The analysis has demonstrated that the national-scale and province-scale road networks all need adaptation planning to protect against future climate-related hazards. In the Vietnam specific context, the relevant adaptation interventions for roads considered in this study include:

- Pavement strengthening;
- Improving pavement drainage;
- Earthwork protection;
- Slope protection; and
- Improved cross drainage (culverts). To build a 'climate proof' road, a climate-resilient road design is suggested in this study, which includes combinations of all options.

Prioritization of investments in transport network resilience should be based on evaluation of the costs of investments in the transport network and the benefits yielded by these investments through avoided disruptions. Analysis of costs and benefits of interventions in the transport network should be risk-based, i.e., should consider both the probability and the consequences of transport network failure. This study has provided evidence of all these steps, providing essential evidence for prioritizing interventions.

The analysis shows that the Benefit-Cost Ratios (BCR) of adaptation investments into national-scale roads are mostly greater than one. The analysis suggests that, for some national-scale roads, upgrading to climate-resilient designs could cost up to US$3.4 million per kilometer, compared to the US$1.0 million per kilometer costs of building roads to existing standards. But the high economic benefits of such investments justify the high costs. Similarly, for province-scale road networks a relatively small—but significant—number of assets have BCRs > 1. Many of these are bridges and local roads, crucial for accessing locations of economic activities. For road networks, the increasing BCRs under future climate-hazards scenarios strengthen the case for investing in climate resilience to protect again future climate risks.

However, in some cases, the selected and analyzed adaptation options might not be the best for climate change adaptation, suggesting a need to investigate several other suitable technologies for increasing the resistance of transport infrastructures to hazards. To some extent, options are location specific. For example, two other adaptation options worth considering could include the following:

1. Scour protection of bridge foundations and abutments, and
2. Forecasting and warning systems, which help to avoid vehicle accidents and train-derailing incidents that exacerbate disruptions.

Given that this report has demonstrated how adaptation options can be considered and has shown in detail how to evaluate their benefits, a similar process can be followed for other types of options not assessed in this study. For example, beyond direct investment in suggest and new climate resilience technologies, adoption of appropriate operation regimes is central to ensuring their effectiveness in the long-term. The costs of operations should be incorporated within the lifetime cost of the asset, ensuring robust cost-benefit adaptation decision appraisal.

Strong Case for Improving Multimodal Transport Linkages and Enhancing Efficiency across Modes

Recommendation: Vietnam's transport networks need to function as integrated multimodal systems, which can be achieved by improving existing multimodal linkages and creating new ones.

This study has shown that the economic impacts of disruptions can be reduced by building additional transport multimodal connectivity. Often known as increasing "redundancy" in the network, this phrase might be interpreted as being wasteful and inefficient, when in fact, providing extra connectivity and capacity will assist the everyday flow of goods and people as well as providing new rerouting opportunities when major disruptions occur.

This study shows a very clear benefit of redistributing flows from the road network to the railways and inland and maritime networks. Even a 10 percent shift of road freights, especially to railways, can reduce economic impacts by 20 to 25 percent. Improvements in enhancing railways and waterways efficiency can reduce risks for already congested roads and take advantage of unused capacity in the railways to accommodate the additional modal shift from roads. The availability of multimodal options would significantly reduce potential losses on the railways, and such options should be considered in the future.

Improving Existing Data Gaps for Further Studies

Recommendation: Under this study, Vietnam's transport resilience planning benefits from a system-of-systems transport risk analysis. The study recognizes the extreme importance of increasing capacity through cross-sector, cross-organization collaborations, which will enable the pursuit of further studies and continued efforts to improve the underlying datasets.

As highlighted throughout the report, the study has coped with severely limited data. Some of these limitations exist in assembling and standardizing the following:

- Topological representations of infrastructure networks with proper attributes
- Transport flows that represent the latest conditions and trends
- Transportation cost assignments reflective of existing conditions
- Economic flows data showing current structure of the country and regional economies
- Probabilistic hazards at similar spatial resolutions and with Vietnam-specific climate scenarios
- Seasonality information of extreme hazards levels and transport network flows
- Information on disruption durations and response behaviors
- Costs of various adaptation options most relevant to Vietnam

The study recommends that effort is invested in improving these data gaps in order to improve future studies and more robustly make the economic case for investment in the transport network.

For increasing capacity to standardize and share data, the study notes the extreme importance or creating a cross-sector and cross-organization collaboration, which involves MoT, DRVN, PDoT, CAAV, VINAMARINE, VIWA, TDSI, MARD, MoNRE, General Statistics Office, among other departments.

The study team has set out the process of improving gaps by providing the study model as an open-source resource (https://github.com/oi-analytics/vietnam-transport), and creating a user document that shows the standardized data requirements (https://vietnam-transport-risk-analysis.readthedocs.io/en/latest/). Gaining the most benefit from these innovative new capabilities will require trained personnel in Vietnam.

The model developed in this study can be readily adapted to accommodate further improvements. The study has only addressed some of the economic and social functions of transport infrastructure. Notably, the study has not explored the role of transport infrastructure in enabling passenger travel for work or other purposes, or its role in labor market participation. These should be included in future studies, alongside other wider economic and social benefits of transport infrastructure. In these recommendations the study has already identified that the investment prioritization needed to improve resilience of the transport network would require consideration of the costs and effectiveness of alternative interventions, and recommend these studies serve as the next step after this study of transport network vulnerability and risks.

Appendix A: Methodology for Transport Risk and Adaptation Assessment

Methodological Framework and Implementation Structure

Figure A.1 provides a graphical overview of the system-of-systems methodological approach, which consists of the following components explained below. The report chapters present details on the data and models for the following components:

A. ***Hazard assembly***: (A-1) Assembling current and future hazard datasets with the spatial extent, magnitudes, and return periods (or probabilities), and extracting those hazards with values above certain thresholds.

B. ***Multimodal transport networks assembly***: The aim is to assemble the multimodal transport system-of-systems. The steps toward creating this system-of-systems include (B-1) Collecting Geospatial Information Systems (GIS) data and creating connected network models from such data; (B-2) Identifying locations on the networks and assigning them attributes (e.g., road conditions, type of port, rail station, etc.); (B-3) Identifying key network nodes where freight transport starts (origins) and ends (destination); (B-4) Collecting freight data and integrating it with the network locations; (B-5) Assembling information on modal split options and generalized cost based performance measures for the multimodal networks; (B-6) Assigning OD flows on the networks based on a least generalized cost criteria to create average annual daily freight (AADF) estimates; and (B-7) At the provincial scales assigning areas of population concentrations to locations of interest via the road network.

C. ***Failure and flow disruption analysis***: Following from A and B, the flow disruption analysis involves: (C-1) Intersecting the hazards with the networks to initiate network edge failure conditions; (C-2) Finding all existing disrupted origin-destination (OD) routes; (C-3) Finding rerouting options and redirecting flows toward alternative routes; (C-4) Estimating flow disruptions in terms of freight tonnage lost or passenger counts lost when there are no rerouting options; and (C-5) Estimating changes in performance measures such as generalized cost changes for freight transport or for changing access for to important location in provinces.

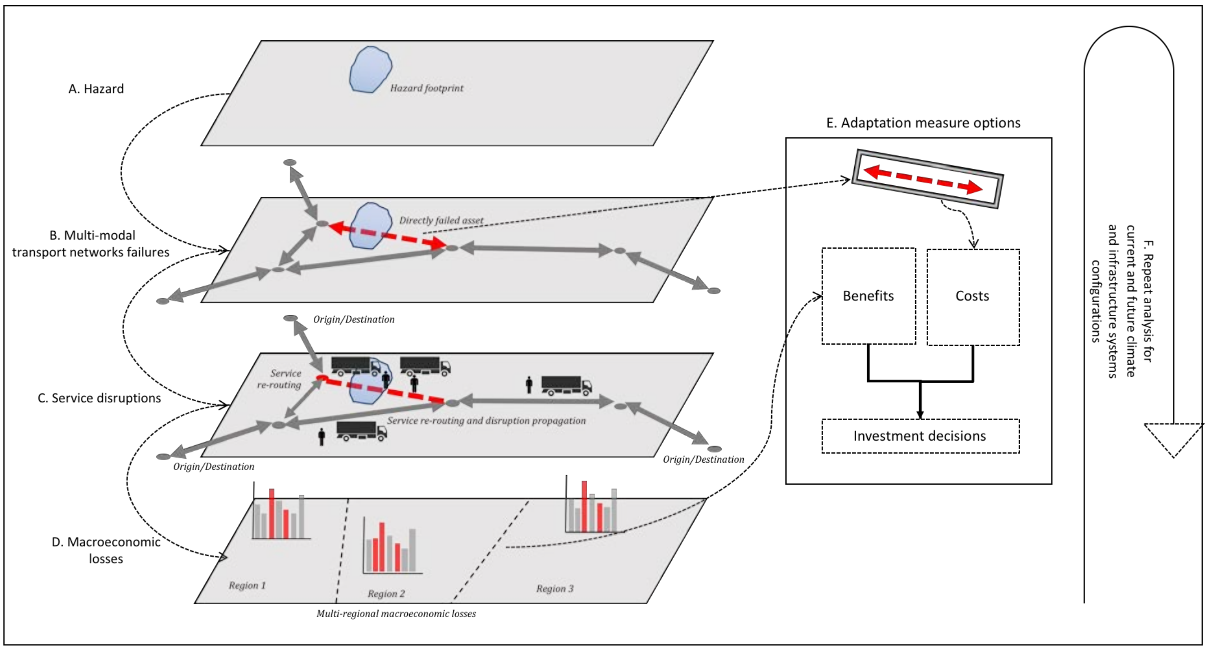
D. ***Macroeconomic loss analysis***: Following from C, macroeconomic loss involves (D-1) Assembling the regional input-output (IO) datasets to map the trading relationship between provinces; (D-2) Converting the freight tonnage losses to economic flow losses as US$ per day direct economic supply losses and direct economic demand losses; and (D-3) Estimating the indirect economic losses over the multi-regional system.

E. ***Adaptation options analysis***: Estimation of Net Present Values (NPVs) of adaptation, which follows D, involves (E-1) Selecting a list of investment strategies for adaptation; (E-2) Assembling data on the costs of damages of assets, the one-time costs and period maintenance costs of different adaptation options; (E-3) Assembling estimates of the discount rates and timelines of adaptation planning; and (E-4) Calculating the NPVs (BCRs) given by Equations (3) through (6).

F. ***Creation of future scenarios***: To understand future transport failures and losses, the steps include (F-1) Assembling statistics on future OD growth scenarios based on projected national or regional Gross Domestic Product (GDP) growth; (F-2) Incorporating structural changes to the networks (if possible) in terms of changing conditions of links (e.g., increase in paved roads, upgraded rail lines); (F-3) Assembling statistics and estimating the changes in performance measures that determine generalized cost functions in the future; (F-4) Creating modal options for new flow assignments. To understand the systemic nature of disruptions and losses, the analysis is repeated several times for different hazard events. It can also be updated for current and future infrastructure network configurations and climate change driven hazard events to perform several vulnerability, risk, and adaptation assessments.

The above methodological framework is consistent with those previously applied to The United Republic of Tanzania (Pant et al 2018b) and United Kingdom (Thacker et al 2017a), to inform infrastructure vulnerability and extreme hazard risk assessment at regional (Pant et al 2018b) and national (Thacker et al 2017b) scales.

Figure A.1. Graphical Representation of Infrastructure System-of-Systems Risk Assessment Framework



Key definitions

The framework presents different types of system-of-systems assessments useful for decision-making:

- **Criticality assessment**: *Criticality* here is defined *as a measure of the transport link's importance and disruptive impact on the rest of the transport infrastructure* (Pant et al 2015). Criticality assessment results in ranking network assets based on their relative impacts on the serviceability of the transport networks (Arga Jafino 2017).
- **Vulnerability assessment**: *Vulnerability* is defined *as the measure of the negative consequences due to failures of transport links from external shock events* (Pant et al 2016). Vulnerability assessment is done in the context of natural hazards and results in understanding the relative impacts of hazards on the continued transport availability.

- **Risk assessment**: *Risk* is defined *as the product of the probability of a hazard and the consequences of transport link failures*. Risk assessment results in understanding the comparative impacts on different hazard frequencies and assigning composite scores to most disrupted transport links.
- **Adaptation planning**: Planned adaptation refers to measures taken to reduce risks. In the context of climate change the *planned adaptation seeks to capitalize on the opportunities associated with climate change* (Füssel 2007). For transport systems, adaptation planning seeks to identify the assets and locations that could be prioritized for targeted investments to provide maximum benefits in reducing risks.

All the above assessments are done with the aim of understanding the impacts of transport network service flow disruptions due to natural hazards. Network service *flow* is defined as the *general measure of volumes of mobility between network locations over a suitably chosen time frame*. The locations between which service flows are measured are called origin-destination (OD) pairs, with the flow being directed from an origin toward a destination. In this study network flows are modeled and measured in terms of:

- *Average annual daily freight* (AADF) volumes: The estimated tonnage of freight moving on an average day between different network locations. These measures are derived from a model.
- *Average annual vehicle traffic* (AADT) counts: The estimated numbers of commercial vehicles on an average day between different road network locations. These measures are derived from observed data.[1]
- *Net revenue measures*: The estimated daily net revenue of goods and services with access to an important location via a transport network. These measures are estimated for understanding local road access to important locations at the province scale.

The estimates for network flows are based on *performance measures* that *quantify the criteria used for assigning flows on the networks*. In this study, key network performance measures for freight and net revenue flow assignment depend on:

- Identification of key locations and knowledge of spatial patterns of freight transport, for example, mapping and tracking of freight routes between provinces;
- Modal splits that indicate how freight transport mode choices are made; and
- *Generalized cost*, which is a composite measure of the transport costs (in US$), expressed as a function of travel time, transport prices, and variability of service.

The estimation of network flows disruptions is done via failure analysis. *Failure* here is defined as the *condition where a network node or link has lost complete functionality*. ***This study does not consider the cases where failed network nodes or links might function partially***. The rationale for considering complete loss of functionality is that: a) The main goal is to understand how important the uninterrupted functionality of individual links is to the rest of the networks; and b) The interest here is in simulating catastrophic event conditions where there are instances of complete loss of network functionality along affected nodes or links.

This study performed failure analyses based on spatially intersecting hazards with network nodes and links, to infer hazard exposures. A *hazard* signifies an *external shock event that initiates failure in the transport networks*. Inferring the asset failures criteria due to hazard exposure requires detailed physical process-based models of fragility curves[2] of assets for given hazard magnitudes, which generally is not possible. For example, the flood fragility of a road will depend upon its physical dimensions, construction standards, material types, scour to flooding, etc. *To select sets of failed nodes and links, simplified failure criteria are chosen, where hazard levels above a threshold are catastrophic enough to cause failures*.

The characterization of failures within the transportation networks leads to characterizing the *disruptions* to network flows. Disruptions refer to the *change in network flows and performance measures due to the failures of network links*. The disruption estimation consists of the following steps: a) Each OD route through failed links is assumed to be no longer available; b) A flow rerouting option for the disrupted OD route is chosen based on the next best route option that gives the least generalized cost estimate; c) The redistributed flows and performance measures are compared with the pre-disruption values.

In some instances, no flow-rerouting options exist because physically the OD route through the failed links is the only available option. Such instances are called *complete failure scenarios*, and individual links causing such scenarios are called *single points of failure*. The general term a *point of failure* is defined to signify a *location on the transport routes whose failure significantly threatens the flow of essential services*. In this study, points of failures' disruptive impacts are measured as: a) AADF flow losses; and b) daily losses of net revenue.

In instances where flow-rerouting options are available, disruptive impacts are measured in terms of the *freight redistribution costs*, or the difference between the post-disruption and pre-disruption generalized cost estimates of an OD flow. The study assumes the rerouting options are fully utilized, irrespective of the increase in travel distance, time, and cost of rerouting.

For the national-scale analysis, the points of failure scenarios may further result in *macroeconomic flow* losses, due to the AADF flow losses. These macroeconomic losses are estimated through a multi-regional economic input-output (MRIO) dataset for disaster loss estimations (Koks and Thissen 2016). By tracking the flow type and industry type of each disrupted OD route, the economic losses from AADF flow losses result in:

- *Macroeconomic supply losses* occur when the production capacities of industries are diminished due to unavailability of commodities required for production.
- *Macroeconomic* demand *losses* occur when the final demands for goods of the disrupted industries are diminished, as they cannot reach the markets.

The above economic flows losses are considered *direct (output) losses* that can be described as the economic flow losses which occur to industry sectors directly affected by the disruption of transport flows. In the economic input-output (IO) system these industry sectors are trading with several other industry sectors across regions, which together make up a multi-regional economic system. These trade relationships create backward (supply) and/or forward (demand) linkages, which get disturbed due to direct losses. This results in *indirect (output) losses* that can be described as the system-wide effects to other firms and industries via backward and/or forward linkages, proceeding to become the ripple effect of the original direct loss (Okuyama and Santos 2014). In this study, the direct and indirect economic losses points of failure scenarios are estimated in US$ per day values, to account for the impact of an AADF tonnage worth of freight flow losses.

Estimation of adaptation options

Adaptation options are defined as the array of strategies and measures available and appropriate for addressing adaptation needs (CSIR et al 2016). Ideally, we should consider several types of adaptation measures, including structural, institutional, and social changes, among others. *In this study, adaptation options involve making investments to improve the structural reliability of transport links*. The effectiveness of different adaptation options is evaluated and compared through a cost-benefit analysis (CBA), which is a well-established technique to compare the costs of an option with its benefits (OECD 2006). When the adaptation options involve investments to improve the structural reliability of the transport links, then:

1. The benefits of adaptation are the sum of the avoided Expected Annual Damages (EAD) and the Expected Annual Economic Losses (EAEL). EAD signify the direct damage costs incurred due to physical collapse of transport links, while EAEL signify the costs incurred due to transport flow disruptions as described in the previous section.
2. The *costs of adaptation* are the sum of the capital costs, CI, of an initial investment to implement a chosen option, and further maintenance costs, CP, to preserve the quality of the asset over its lifetime.
3. The value of the adaptation options is estimated as the difference between the benefits and the costs.
4. The benefits of adaptation are assumed to last over a long time period; thus, the actual value of an adaptation option is estimated over an annual time-scale $t0,\ldots,tT,$ starting at the time $t0$ when the option is implemented and continues over its planned time horizon T. This leads to the Net Present Value (NPV) of adaptation given as:

$$NPV= j=0j=TEADtj+EAELtj-CPtj1+rj-CIt0 \qquad (3)$$

Where $EADtj$ is the expected annual damages for year tj, $EAELtj$, is the expected annual economic loss for year tj, $CIt0$, is the adaptation investment made at the start year $t0$, $CPtj$, is the cost of periodic investment needed,[3] r is the discount rate, and j is the count for the years over which the value of adaptation is evaluated.

5. The metric of benefit-cost ratio (BCR) can similarly be estimated to evaluate the effectiveness of the adaption options:

$$BCR=j=0j=TEADtj+EAELtj1+rjj=TCPtj1+rj+CIt0 \qquad (4)$$

The practical steps in estimating the Net Present Value (NPV) of adaptation involve:

- Having a sample of probabilistic hazard events;
- Getting data on the costs of asset damages, the one-time costs of the adaptation option, and the periodic costs of maintenance; and

- Estimating the economic losses due to transport link failures in two ways, depending upon the scale of the analysis. In both cases the economic loss estimates are daily estimates, which are multiplied by an assumed duration of disruption:
    a. For the national-scale network analysis, the economic losses are given as sum of the daily macroeconomic losses and the total costs of rerouting.
    b. For the province-scale network analysis, the economic losses are given as sum of the loss of daily net revenue and the total costs of rerouting.

The process of estimating the NPV (or BCR) of an adaptation option is undertaken for all the failed transport links, following which all NPV (and BCR) estimates can be ranked. The links with the highest BCR values should be prioritized for investments, as they provide the highest benefits toward maintaining the network reliability.

A similar process can be repeated for a set of adaptation options, as there are potentially several different adaptation options worth considering. Hence, the NPVs could be compared across all assets and all options to select the ones with high benefits for the system. When considering climate change, the effectiveness of the same set of adaptation options can be further compared between current hazard scenarios and future climate change-driven scenarios.

Uncertainty analysis

Previous sections outline several sources of uncertainty throughout the whole process of the criticality, vulnerability, risk and adaptation assessments. Some of these, among others, include:

- Uncertainties associated with the estimation of the projected natural hazards under different climate change scenarios;
- Aleatory uncertainties (Bae et al 2004) in the network model structures due to lack of proper topological network data;
- Epistemic uncertainties[4] in the transport flow estimation models, due to imprecise information on the network speeds, costs, and tonnages; and
- Uncertainties in the estimation of the costs of asset damages, costs of the adaptation option and the periodic costs of maintenance.

To overcome the challenges of accounting for the different types of uncertainties, this study adopts a robust decision-making approach by simulating hundreds to thousands of different sets of transport link failures under different current and future hazards to describe how adaptation options might perform under many plausible failure scenarios (Lempert et al 2013). At every step the sensitivity of the model outputs to input parameters are analyzed to understand which parameters might influence the estimates the most. This approach aligns with the Decision Making Under Deep-Uncertainty (DMDU) methods, which are gaining popularity among decision-makers (Hallegatte et al 2012; Espinet et al 2018).

The robust estimates of the NPVs (or BCRs) of different adaptation options for different transport link failures are created by calculating the minimum and maximum NPV for each type of option for each type of failure scenario.

To arrive at these estimates, the study assumes that:

- For every adaptation option, the costs of adaptation and maintenance are given or estimated over a range;
- The damage costs of assets are given or estimated over a range; and
- The economic losses are estimated by accounting for the range of possible tonnages, speeds, and costs along the networks.

The study concludes that transport links for which adaptation options give both $NPVmin>0$ (or $BCRmin>1BBCR\mathrm{m}$) and $NPV\mathrm{max}>0NPVmax>0$ (or $BCRmax>1BCR\mathrm{max}>1$), should be treated as no-regret options and prioritized for investments. Further prioritization of such transport links can be done by ranking BCRs and selecting those with the highest values as these give the highest benefit in terms of improving transport reliability.

Notes

1. No AADT measures are available for other modes of transport.

2. Fragility curves quantify the conditional probability of failure of an asset for a given level of hazard. Fragility curves that are derived from statistical analysis of historical failure data that record the condition of an asset, 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.

3. Maintenance could be considered to be part of the benefits as well, if we were considering partial failures. However, used here, maintenance represents a cost option undertaken to prevent the catastrophic failure of an asset.

4. See note no. 3.

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Appendix B: Overview of Datasets

Each transport mode in this study first represented as a *network,* which is the *collection of nodes joined together by a collection of links*. The *physical network topology* defined as *the structure that encodes the physical placement of nodes and their connecting links* describes the network structure. The existence of physical links with information about their connecting node locations is a necessary and essential condition for the creation of the transport network models, because of the geospatial nature of the transport systems. In the absence of such information the underlying infrastructure data has to be processed further by either adding new link geometries to connect nodes or by filling gaps in missing physical link geometries to connect nodes and thereby complete the physical network topology.

All network models were created from geospatial data that needed post-processing to fill gaps in the underlying raw datasets (table B.1). Depending upon the quality of the received raw datasets, the network models represent the physical properties such as the lengths, conditions, and widths of transport network assets as approximations of the equivalent real-world systems.

Table B.1. Raw Datasets Collected from Different Data Sources for the Transport Risks Analysis Modeling in Vietnam

Dataset	Data scope	Source	Year
Administrative boundary and statistics	Commune, district and province levels	GSO, WHO	2016
Economic input-output data	National scale	GSO	2012
National roads	National, province (roads only)	TDSI	2018
Province roads		Vietbando	2018
Rail		VITRANSS II and MoT	2009–2016
Inland waterway		VIWA	2018
Maritime		Ports – VINAMARINE Routes – WHO	2018
Airports		Airports – CAA Routes – OIA modeled	2018
OD flows	Inter-province ODs	VITRANSS II	2009
	Crop production locations	IFPRI	2016
Transport Costs	National	VITRANSS II reports (projected to 2016 values)	2009–2016
Adaptation costs	Roads	Jasper Cook, VRAMS, PMU6	2018

Natural hazards dataset

Table B.2 provides the list of all assembled natural hazard datasets used in this study. From left to right, the table gives the:

- Names of the hazard types;
- Shorthand model names, either given in the data source or created for the study;
- Assumed year of hazard represented by the model;
- Climate scenarios;
- Hazard probabilities (if any);
- Selected banded values for banded hazard datasets for sampling hazard extremes;
- Selected flood-depth threshold for all flood datasets for sampling extreme flooding scenarios;
- Spatial resolution in terms of the grid size unit areas in the model;
- Provinces covered by the hazard maps; and
- Source of the datasets.

Ideally, for a natural hazard risk assessment the hazard datasets should contains at least the following information for each type of natural hazard: a) spatial extent; b) magnitude of severity; and c) probability. Unfortunately, only the fluvial flood maps provided for this study contained all three of the above attributes. The typhoon-induced flood maps contained only the spatial extent and magnitudes (flood depths) of flooding, and no probabilities. In the flashflood and landslide susceptibility maps, likelihood banded-scores (representing high or very high susceptibility) over areas were used as proxies for serve flashflood and landslide events respectively, while there was no probabilistic information.

Some of the natural hazards further maps were also provided with future climate change model outputs based on the Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios (Meinshausen et al 2011). RCP4.5 scenarios assume that global emissions peak around 2040 and then decline, while RCP8.5 scenarios assume no decline in global emissions through the 21st century. Flashflood and landslide susceptibility maps for eight northern provinces generated for RCP4.5 and RCP8.5 scenarios in 2025 and 2050 were available for the study. Fluvial flood maps for the whole country were also provided for current flooding and future flooding under RCP4.5 and RCP8.5 scenarios in 2030, from the GLOFRIS (Winsemius et al 2013) model. In addition, the study looked at a baseline model presenting current flooding conditions, called EUWATCH. Also, the study considered flooding outcomes under different climate change scenarios, using bias-corrected future meteorological data for an ensemble of five Global Climate Models (GCMs) in the CMIP5 project – GFDL-ESM2M,[1] HadGEM2-ES,[2] IPSL-CM5A-LR,[3] MIROC-ESM-CHEM,[4] and NorESM1-M.[5] All the current and future flood maps were derived by downscaling global distributed hydrological models with a resolution of 0.5° × 0.5° (approximately 50 m × 50 km at the equator) to 1/120° × 1/120° (900 m × 900 m around the equator) to give country scale maps. Using these models, the future flood maps showed average maximum flood depths from 2010 to 2049, which in this study are assumed to represent flood scenarios for the year 2030. For each model output, nine different flood intensity maps were produced to represent fluvial floods that could occur every: 2, 5, 10, 25, 50, 100, 250, 500, and 1,000 years.

Table B.2. Natural Hazard Datasets Assembled for the Study Notes

Hazard type	Model name	Year	Climate scenarios	Probabilities	Banded values	Flood depth (meter)	Spatial resolution	Spatial coverage	Source
Landslide susceptibility	MoNRE	2016	—	—	3-high, 4-very high	—	30m×30m	8 Central provinces[a]	VIGMR-MONRE 2014[b]
		2016			4-high, 5-very high			Thanh Hoa[c]	
	IMHEN	2016						15 Northern provinces[d]	MARD 2017[e]
		2025	RCP4.5, RCP8.5						
		2050							
Flash flood susceptibility		2016	—						
		2025	RCP4.5, RCP8.5						
		2050							
Typhoon flooding	MARD Level 13 – 16[f]	2016	—		—	>= 1m	100m×100m	28 Coastal provinces[g]	MARD 2016
Fluvial flooding	MARD	2016	—	0.01, 0.05, 0.1, 0.2			30m×30m	Thanh Hoa	MARD 2012[h]
	WATCH	2016	—	0.001, 0.002, 0.004, 0.01, 0.02, 0.04, 0.1, 0.2, 0.5			900m×900m	Whole country	GLOFRIS[i]
	MIROC-ESM-CHEM	2030	RCP4.5, RCP8.5						
	GFDL-ESM2M								
	NorESM1-M								
	IPSL-CM5A-LR								
	HadGEM2-ES								

Notes:
a. Provinces of Phu Yen, Binh Dinh, Qunag Nam, Da Nang, Thua Thien Hue, Quang Tri, and Quang Binh.
b. Landslide investigation, assessment and zonation for mountainous areas in Vietnam for disaster mitigation conducted in 2014 by the Vietnam Institute of Geosciences and Mineral Resources, Ministry of Natural Resources and Environment.
c. The original dataset contained color-coded bands, which were translated to integer values, based on following rules: (1) Red = Band 5; and (2) Orange = Band 4.
d. Provinces of Lao Cai, Lai Chau, Dien Bien, Yen Bai, Son La, Hoa Binh, Phu Tho, Tuyen Quang, Ha Giano, Cao Bang, Bac Kan, Tha Nyugen, Bac Giang, and Lang Son.
e. Promoting Climate Resilient Rural Infrastructure in Northern Viet Nam project funded by UNDP and ADB and completed in 2017 by the Ministry of Agriculture and Rural Development, Vietnam.
f. Typhoon levels are determined by wind speeds based on the Beaufort classification, with following winds speeds for different levels: (1) 13: 134–149 km per hour; (2) 14: 150–166 km per hour; (3) 15: 167–183 km per hour; and (4) 16: 184–201 km per hour.
g. All provinces from Ninh Thuan to Quang Ninh touching the Eastern coastline of the country.
h. Integrated Disaster Risk Management Project funded by the World Bank and completed in 2012 by the Central Project Office, Ministry of Agriculture and Rural Development, Vietnam.
i. Winsemius et al 2013

Notes

1. From NOAA in US: https://www.gfdl.noaa.gov/earth-system-model/.

2. From UK Met Office: https://portal.enes.org/models/earthsystem-models/metoffice-hadley-centre/hadgem2-es.

3. From IPSL in France: http://icmc.ipsl.fr/index.php/icmc-projects/icmc-international-projects/international-project-cmip5.

4. From Japan: Watanabe, Mashahiro, Tatsuo Suzuki, Ryouta O'ishi, Yoshiki Komuro, Shingo Watanabe, Seita Emori, Toshihiko Takemura, Minoru Chikira, Tomoo Ogura, Miho Sekiguchi, Kumiko Takata, Dai Yamazaki, Tokuta Yokohata, Toru Nozawa, Hiroyasu Hasumi, Hiroaki Tatebe, and Masahide Kimoto. 2010. "Improved Climate Simulation by MIROC5: Mean States, Variability, and Climate Sensitivity." *Journal of Climate* 23: 6312–35. doi: 10.1175/2010JCLI3679.1.

5. From Norway: Bentsen, M., I. Bethke, J. B. Debernard, T. Iversen, A. Kirkevåg, Ø. Seland, H. Drange, C. Roelandt, I. A. Seierstad, C. Hoose, and J. E. Kristjánsson. 2013. "The Norwegian Earth System Model, NorESM1-M—Part 1: Description and Basic Evaluation of the Physical Climate." *Geosci Model Dev* 6 (3): 687–720. doi: 10.5194/gmd-6-687-2013

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Appendix C: Vulnerability Results for Ports

For the air transport, inland waterway, and maritime sectors, the report presents results of the criticality and vulnerability assessment performed at the major ports scales, as these are the most important assets on these networks. Here, the following section presents the summary tables for each sector showing the name and location of a port, the minimum and maximum average annual daily freight (AADF) daily tonnage at the port that could potentially be vulnerable to disruptions, the type of hazard that could cause said disruption, the climate scenario for the hazard, and the minimum and maximum probabilities of hazard exposure of the port.

For each sector, the risks of hazard exposures due to climate change will increase. Every table shows that wherever the identified hazard has climate scenarios with probabilities, the maximum probabilities of exposure under the climate scenario is greater than the current probability of exposure. For example, in Table C.1 the maximum hazard probability of flooding in Ho Chi Minh port increases to 0.2 (1 in five-year flooding) under the RCP4.5 and RCP8.5 scenarios, in comparison to the 0.04 (1 in 25-year flooding) probability at present. This means that the Ho Chi Minh port is about 5 times more prone to frequent flooding in the future than at present. Similar trends are observed for all the major ports in every sector, including maritime (table C.2) and inland waterways (table C.3).

Table C.1. Airports with AADF Flows and Hazard Exposure Scenario Results

Name	Commune	District	Province	AADF (tons/day)		Hazard type	Climate scenario	Probability	
				Min	Max			Min	Max
Đà Nẵng	Hoa Thuan Tay	Hai Chau	Da Nang	26.0	28.3	Landslide	—	—	—
						Typhoon Flooding	—	—	—
Cát Bi	Thanh To	Hai An	Hai Phong	5.6	5.8	Typhoon Flooding	—	—	—
Phú Bài	Phu Bai	Huong Thuy	Thua Thien Hue	2.8	2.8	River Flooding	—	0.001	0.002
							RCP 4.5	0.001	0.01
							RCP 8.5	0.001	0.01
						Landslide	—	—	—
						Typhoon Flooding	—	—	—

Table C.2. Major Maritime Ports with AADF Flows and Hazard Exposure Scenario Results

Name	Commune	District	Province	AADF (tons/day)		Hazard type	Climate scenario	Probability	
				Min	Max			Min	Max
TP. Hồ Chí Minh	Cat Lai	Quan 2	Ho Chi Minh	84,050.0	106,425.6	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.2
Hải Phòng	May To	Ngo Quyen	Hai Phong	80,688.2	101,739.6	Typhoon Flooding	—	—	—
Cần Thơ	Binh Thuy	Binh Thuy	Can Tho	68,863.8	86,686.3	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.1
Đồng Nai	Long Binh Tan	Bien Hoa	Dong Nai	27,534.1	29,102.7	River Flooding	—	0.001	0.001
							RCP 4.5	0.1	0.1
Nghi Sơn	Nghi Son	Tinh Gia	Thanh Hoa	18,140.3	18,822.4	Typhoon Flooding	—	—	—
Quy Nhơn	Hai Cang	Quy Nhon	Binh Dinh	4,917.8	5,376.7	Landslide	—	—	—
Thuận An	Thuan An	Phu Vang	Thua Thien Hue	1,105.6	2,893.8	Landslide	—	—	—
						Typhoon Flooding	—	—	—
Cửa Lò	Nghi Thuy	Cua Lo	Nghe An	1,428.6	2,021.0	Typhoon Flooding	—	—	—
Bến Thủy	Nghi Hoa	Cua Lo	Nghe An	1,131.2	1,655.5	Typhoon Flooding	—	—	—
Cái Mép	Phuoc Hoa	Tan Thanh	Ba Ria — Vung Tau	416.8	416.8	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.1
							RCP 8.5	0.001	0.1

Table C.3. Major Inland Waterway Ports with AADF Flows and Hazard Exposure Scenario Results

Name	Commune	District	Province	AADF (tons per day)		Hazard type	Climate scenario	Probability	
				Min	Max			Min	Max
Cảng Bình Long	Binh Long	Chau Phu	An Giang	24,681.4	55,018.2	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.1
Cảng Thủy nội địa Hà Hùng Anh	Gia Duc	Thuy Nguyen	Hai Phong	32,265.7	40,662.7	Typhoon Flooding	—	—	—
Cảng Nhiệt Điện Thái Bình 2	My Loc	Thai Thuy	Thai Binh	36,441.7	37,206.7	Typhoon Flooding	—	—	—
Cảng TNĐ Liên hiệp Khoa học Công nghệ Tài nguyên khoáng sản, môi trường và năng lượng	Dien Cong	Uong Bi	Quang Ninh	33,948.1	34,822.8	Typhoon Flooding	—	—	—
CẢNG LONG BÌNH	Long Binh	Quan 9	Ho Chi Minh	25,214.8	31,927.5	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.2
Cảng Khuyến Lương	Yen So	Hoang Mai	Ha Noi	18,291.7	18,552.1	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
Cảng Bốc xếp hàng hóa An Giang	Vinh Thanh Trung	Chau Phu	An Giang	6,174.6	14,637.2	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.1
Cảng Thủy nội địa Long Đức	Long Duc	Tra Vinh	Tra Vinh	3,257.6	14,515.1	River Flooding	—	0.001	0.004
							RCP 4.5	0.001	0.04
							RCP 8.5	0.001	0.04
An Hòa	An Hong	An Duong	Hai Phong	8,064.4	10,160.4	Typhoon Flooding	—	—	—
CẢNG TNĐ KHO VẬN MIỀN NAM	Truong Tho	Thu Duc	Ho Chi Minh	7,553.0	9,560.9	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.2
	Phuong 5	Vinh Long	Vinh Long	8,051.3	9,080.0	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.04
							RCP 8.5	0.001	0.04
CẢNG TNĐ TÍN NGHĨA	Long Tan	Nhon Trach	Dong Nai	8,320.2	9,022.3	River Flooding	—	0.001	0.02
							RCP 4.5	0.001	0.04
							RCP 8.5	0.001	0.1

Table C.3 *continued*

Name	Commune	District	Province	AADF (tons per day)		Hazard type	Climate scenario	Probability	
				Min	Max			Min	Max
XÓA TÊN KHỞI DS (CẢNG TNĐ VẬN TẢI SONADEZI)	An Binh	Bien Hoa	Dong Nai	8,261.4	8,747.6	River Flooding	—	0.001	0.001
							RCP 4.5	0.1	0.1
Cảng Phượng Hoàng	Cam Thuong	Hai Duong	Hai Duong	6,186.8	6,226.3	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
CẢNG HÙNG TÀI	Thien Tan	Vinh Cuu	Dong Nai	5,526.7	5,949.2	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.2
CẢNG TNĐ XĂNG DẦU LONG BÌNH TÂN	Long Binh Tan	Bien Hoa	Dong Nai	5,516.1	5,879.8	River Flooding	—	0.001	0.001
							RCP 4.5	0.1	0.1
Cảng Hồng Vân	Hong Van	Thuong Tin	Ha Noi	4,585.8	4,690.7	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
CẢNG TNĐ AJINOMOTO	An Binh	Bien Hoa	Dong Nai	4,402.2	4,651.0	River Flooding	—	0.001	0.001
							RCP 4.5	0.1	0.1
Cảng thủy nội địa Vissai Gia Tân	Gia Tan	Gia Vien	Ninh Binh	3,392.6	3,762.9	River Flooding	NONE	0.001	0.001
							RCP 4.5	0.001	0.002
							RCP 8.5	0.001	0.004
Cảng thủy nội địa CuBi	Kim Xuyen	Kim Thanh	Hai Duong	3,705.2	3,715.1	River Flooding	—	0.001	0.001
							RCP 8.5	0.001	0.001
CẢNG TNĐ HOÀNG LONG	Thien Tan	Vinh Cuu	Dong Nai	3,301.7	3,488.7	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.2
CẢNG TNĐ BÊ TÔNG LY TÂM LA PHƯƠNG NAM	Luong Binh	Ben Luc	Long An	2,237.7	2,673.5	River Flooding	—	0.001	0.02
							RCP 4.5	0.001	0.1
							RCP 8.5	0.001	0.1
Cảng Binh Đoàn 11	Thanh Tri	Hoang Mai	Ha Noi	2,282.2	2,310.8	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
Cảng thủy nội địa xi măng Xuân Thành	Thanh Nghi	Thanh Liem	Ha Nam	1,905.3	1,910.0	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
Cảng Thủy Nội Địa Cống Câu	Ngoc Son	Tu Ky	Hai Duong	1,855.1	1,870.9	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02

Table C.3 *continued*

Name	Commune	District	Province	AADF (tons per day)		Hazard type	Climate scenario	Probability	
				Min	Max			Min	Max
Cảng thủy nội địa Vissai Hà Nam	Thanh Thuy	Thanh Liem	Ha Nam	1,435.2	1,456.7	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
Cảng xi măng Vicem Bút Sơn	Chau Son	Phu Ly	Ha Nam	1,429.5	1,435.6	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
CẢNG TNĐ VIỆT HÓA NÔNG	Phuoc Dong	Can Duoc	Long An	978.3	1,214.8	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.1
							RCP 8.5	0.001	0.1
Cảng hàng hóa Thành Hưng	My Khanh	Phong Dien	Can Tho	801.1	1,088.8	River Flooding	—	0.001	0.02
							RCP 4.5	0.001	0.04
							RCP 8.5	0.001	0.04
Cảng Trường Nguyên	Gia Minh	Thuy Nguyen	Hai Phong	797.0	1,000.3	Typhoon Flooding	—	—	—
Cảng thủy nội địa Nhà máy xi măng Thành Thắng	Thanh Nghi	Thanh Liem	Ha Nam	859.0	866.0	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
Cảng thủy nội địa xi măng Hoàng Long	Thanh Nghi	Thanh Liem	Ha Nam	856.4	856.6	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
CẢNG TNĐ XI MĂNG SÀI GÒN	Long Binh	Quan 9	Ho Chi Minh	660.9	833.0	River Flooding	—	0.001	0.04
							RCP 4.5	0.001	0.2
							RCP 8.5	0.001	0.2
Cảng xuất sét xi măng Vicem Hải Phòng	Song Khoai	Quang Yen	Quang Ninh	682.0	719.4	Typhoon Flooding	—	—	—
Cảng Hoàng Gia	Kim Luong	Kim Thanh	Hai Duong	614.2	617.5	Typhoon Flooding	—	—	—
Cảng Hải Nam	Luu Ky	Thuy Nguyen	Hai Phong	416.0	552.3	Typhoon Flooding	—	—	—
Minh Đức	Dong Hai 1	Hai An	Hai Phong	388.8	513.4	Typhoon Flooding	—	—	—

Table C.3 *continued*

Name	Commune	District	Province	AADF (tons per day)		Hazard type	Climate scenario	Probability	
				Min	Max			Min	Max
Cảng thủy nội địa Châu Sơn	Chau Son	Phu Ly	Ha Nam	303.9	353.6	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
NGỪNG HOẠT ĐỘNG (CẢNG NHÀ MÁY KHÍ ĐIỆN NHƠN TRẠCH 2)	Phuoc Khanh	Nhon Trach	Dong Nai	62.3	141.3	River Flooding	—	0.001	0.02
							RCP 4.5	0.001	0.1
							RCP 8.5	0.001	0.1
Cảng Bến Kiền	An Hong	An Duong	Hai Phong	10.9	38.6	Typhoon Flooding	—	—	—
Cảng Kho trung chuyển xăng dầu Thái Bình	Hoa Binh	Vu Thu	Thai Binh	10.2	30.8	River Flooding	—	0.001	0.01
							RCP 4.5	0.001	0.02
							RCP 8.5	0.001	0.02
						Typhoon Flooding	—	—	—

Appendix D. Communes and Districts by Exposure of Road Networks to Natural Hazards

Table D.1. Twenty Communes Most Exposed to Flooding in Lao Cai Province

Commune	District	Total km	Flashflood susceptibility			River flooding			Landslide susceptibility		
			Current (2016)	RCP 4.5 (2025)	RCP 8.5 (2025)	Current (2016)	RCP 4.5 (2030)	RCP 8.5 (2030)	Current (2016)	RCP 4.5 (2025)	RCP 8.5 (2025)
Tong Sanh	Bat Xat	9.2	46.0	46.0	20.4	41.6	41.6	41.6	7.8	7.8	19.7
Trung Leng Ho	Bat Xat	3.7	30.7	30.7	0.0	0.0	0.0	0.0	1.8	1.8	1.8
Nam Sai	Sa Pa	6.6	21.2	21.2	21.2	0.0	0.0	0.0	9.3	9.3	16.3
Muong Vi	Bat Xat	13.8	19.0	19.0	19.0	19.5	19.5	19.5	1.6	1.6	9.2
Nam Khanh	Bac Ha	15.5	17.6	17.6	17.6	0.0	0.0	0.0	0.6	0.6	0.6
Coc San	Bat Xat	16.2	17.0	17.0	2.4	10.2	10.2	10.2	7.2	7.2	16.2
Sa Pa	Sa Pa	32.3	15.2	15.2	15.2	0.0	0.0	0.0	11.2	11.2	11.2
Ban Cai	Bac Ha	23.5	14.2	14.2	14.2	0.0	0.0	0.0	3.2	3.2	3.2
Nam Xe	Van Ban	21.8	14.0	14.0	14.0	0.0	0.0	0.0	14.9	14.9	14.9
Den Sang	Bat Xat	20.8	12.4	12.4	12.4	0.0	0.0	0.0	4.2	4.2	3.3
Ban Lien	Bac Ha	49.3	10.9	10.9	10.9	0.0	0.0	0.0	1.8	1.8	1.8
Tham Duong	Van Ban	18.9	10.4	10.4	10.4	0.0	0.0	0.0	4.7	4.6	6.1
Y Ty	Bat Xat	23.4	9.6	9.6	11.2	0.0	0.0	0.0	3.4	3.4	3.4
Nam Rang	Van Ban	15.2	9.2	9.2	9.2	0.0	0.0	0.0	10.0	10.0	10.0
Duong Quy	Van Ban	30.8	9.1	9.1	9.1	0.0	0.0	0.0	2.1	2.1	2.1
Ta Phoi	Lao Cai	35.7	8.4	8.4	7.0	16.5	16.5	16.5	11.1	8.6	8.7
Nam Cang	Sa Pa	6.2	8.3	8.3	8.3	0.0	0.0	0.0	1.8	1.8	4.2
Lao Chai	Sa Pa	11.6	8.3	8.3	8.3	0.0	0.0	0.0	20.8	20.8	20.8
Lang Giang	Van Ban	18.9	7.7	8.0	8.0	0.0	0.0	0.0	5.0	5.3	5.3
Ta Phin	Sa Pa	20.2	7.2	7.2	7.2	0.0	0.0	0.0	14.3	14.3	14.3

Table D.2. Twenty Communes Most Exposed to Flooding in Binh Dinh Province

Commune	District	Total km	River flooding			Landslide susceptibility	Typhoon flooding
			Current (2016)	RCP 4.5 (2030)	RCP 8.5 (2030)	Current (2016)	Current (2016)
Thi Nai	Quy Nhon	11.8	87.2	87.2	87.2	0.0	43.2
Nhon Hoa	An Nhon	89.4	76.4	80.4	80.4	8.0	15.2
Ly Thuong Kiet	Quy Nhon	15.7	78.9	78.9	78.9	0.0	0.0
Le Hong Phong	Quy Nhon	16.1	71.6	71.6	71.6	0.0	0.0
Tay Xuan	Tay Son	34.7	67.2	67.2	67.2	9.7	0.0
Phuoc Nghia	Tuy Phuoc	33.5	55.0	55.0	55.0	9.8	14.2
Tran Phu	Quy Nhon	6.5	60.4	60.4	60.4	0.0	0.0
Phuoc Hiep	Tuy Phuoc	92.3	45.1	45.1	45.1	5.6	14.3
Nhon Binh	Quy Nhon	68.6	41.2	41.2	41.2	0.0	20.9
An Tuong Dong	Hoai An	38.5	33.9	33.9	33.9	37.3	0.0
Phuoc Thanh	Tuy Phuoc	100.8	41.0	41.4	41.4	8.4	0.2
Tay Phu	Tay Son	32.4	37.0	37.0	37.0	13.9	0.0
Canh Lien	Van Canh	6.3	24.2	24.2	24.2	45.8	0.0
Nhon Tan	An Nhon	38.6	35.2	35.2	35.2	8.0	0.0
Nhon Tho	An Nhon	41.8	32.0	32.0	32.0	10.3	2.8
Phuoc An	Tuy Phuoc	108.5	27.9	29.3	29.3	16.1	0.1
Vinh An	Tay Son	5.0	25.8	25.8	25.8	18.5	0.0
Tran Hung Dao	Quy Nhon	6.4	27.6	27.6	27.6	0.0	3.3
Binh Nghi	Tay Son	89.6	24.3	24.3	24.3	12.7	0.0
An Dung	An Lao	8.6	0.0	0.0	0.0	81.8	0.0

Table D.3. Twenty Communes Most Exposed to Flooding in Thanh Hoa Province

Commune	District	Total km	River flooding			Landslide susceptibility	Typhoon flooding
			Current (2016)	RCP 4.5 (2030)	RCP 8.5 (2030)	Current (2016)	Current (2016)
Dong Son	Bim Son	47.7	96.9	96.9	96.9	1.7	0.0
Dong Xuan	Dong Son	8.3	96.1	96.1	96.1	0.0	0.0
Thinh Loc	Hau Loc	12.5	94.3	94.3	94.3	0.0	0.0
Hoang Long	Thanh Hoa	10.4	91.8	91.8	91.8	0.0	0.0
Nga Thach	Nga Son	37.5	87.0	87.0	87.0	0.0	3.1
Hoa Loc	Hau Loc	34.7	87.7	87.7	87.7	0.0	0.0
Dong Tien	Trieu Son	39.3	84.7	84.7	84.7	0.0	0.0
Rung Thong	Dong Son	5.7	82.5	82.5	82.5	0.0	0.0
Dinh Tang	Yen Dinh	51.5	81.3	81.3	81.3	0.3	0.0
Lam Son	Bim Son	22.3	79.7	79.7	79.7	2.2	0.0
Dong Loi	Trieu Son	37.4	78.7	78.7	78.7	2.8	0.0
Hau Loc	Hau Loc	16.2	79.6	79.6	79.6	0.0	0.0
Xuan Lam	Tho Xuan	22.7	76.9	76.9	76.9	0.5	0.0
Lien Loc	Hau Loc	28.4	76.5	76.5	76.5	0.0	0.0
Ha Vinh	Ha Trung	57.4	73.1	73.1	73.1	1.3	0.0
Hung Loc	Hau Loc	36.6	71.5	71.5	71.5	0.0	3.3
Loc Tan	Hau Loc	35.5	72.1	72.1	72.1	0.0	0.0
Nga Nhan	Nga Son	19.3	72.0	72.0	72.0	0.0	0.0
Xuan Vinh	Tho Xuan	42.2	72.0	72.0	72.0	0.0	0.0
Yen Ninh	Yen Dinh	17.1	70.8	70.8	70.8	0.0	0.0

With support from:

Australian Aid

8 Dao Tan Street, Ba Dinh
District, Hanoi, Vietnam
Telephone: +84 24 37740100
Facsimile: +84 24 37740111
Website: www.dfat.gov.au

WORLD BANK GROUP

8th Floor, 63 Ly Thai To Street, Hoan Kiem District, Hanoi, Vietnam
Telephone: +84 24 39346600
Facsimile: +84 24 39346597
Website: www.worldbank.org/en/country/vietnam