

ROAD INFRASTRUCTURE AND CLIMATE CHANGE IN VIETNAM

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Abstract

Climate change is a potential threat to Vietnam's development as current and future infrastructure will be vulnerable to climate change impacts. This paper focuses on the physical asset of road infrastructure in Vietnam by evaluating the potential impact of changes from stressors, including: sea level rise, precipitation, temperature, and flooding. Across 56 climate scenarios, the mean additional cost of maintaining the same road network through 2050 amount to 10.5 billion USD. The potential scale of these impacts establishes climate change adaptation as an important component of planning and policy in the current and near future.

1. Introduction

Vietnam recognizes the long-term benefits and short-term need to enhance the country's overall infrastructure, including ports, roads and energy. To this end, the government is implementing a national infrastructure improvement and expansion plan using a combination of public and private funding. Unlike traditional approaches to infrastructure planning, Vietnam is considering both conventional concerns over construction costs, as well as the potential effects of climate change on infrastructure. While the costs of climate change are a concern for most countries, they are of particular concern for developing countries, where the financial resources needed to address climate change are especially limited. The challenge is therefore to identify the impacts of climate change on infrastructure; develop adaptation approaches and incorporate these into medium to long-term development plans; and secure the resources needed to finance any additional costs for adaptation.

Previous studies have quantified the impact of climate change on physical assets (see, for example, World Bank 2009). Our study extends earlier work by evaluating the implications of climate change for road infrastructure within developing countries – in this case, Vietnam – across a fuller range of climate change projections. We focus on paved, gravel and unpaved roads because of their socioeconomic importance for Vietnam. We examine the extent to which climate change, as reflected in global and country-specific climate projections, diverts resources away from extending Vietnam's road infrastructure towards maintaining and adapting existing

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infrastructure. Our analysis incorporates two kinds of impacts: (i) “climate stressors” (i.e., precipitation and temperature changes) and (ii) projected sea level rise (SLR) of one meter. Both impacts are important given the significance of Vietnam’s coastal zones.

This study expands upon the methodology presented in Chinowsky et al. (2011b), which introduced an engineering-based stressor-response methodology to quantify the impact of climate change on physical assets. The analysis is conducted at multiple scales (e.g., national and provincial) and for the period until 2050. Importantly, the concept of “opportunity cost” is used to identify the benefits of adapting to projected climatic changes. In other words, given the need to extend existing road networks, should Vietnam postpone costly adaptation measures on critical infrastructure? By addressing this question, our study provides context for policy-makers to understand climate change’s implications for long-run economic development in Vietnam.

This paper is one of four papers in this issue of *Global Environmental Change* that estimate climate change’s biophysical and economic impacts on Vietnam using an integrated or multi-sector modeling framework. Additional impact channels include water and agriculture (Strzepek et al.) and cyclones and storm surge (Neumann et al.). These sectoral impact channels are combined to provide an economywide assessment of climate change for Vietnam (Arndt et al.). Our paper on road infrastructure introduces this assessment by; 1) introducing an overall methodology for calculating climate change impacts, 2) presenting the overall results for the study at a national level, and finally 3) addressing the impacts on a regional level to highlight the differences in the country. A discussion and conclusion provides thoughts on how these results need to be considered by infrastructure planners.

2. Climate Change and Road Infrastructure

The literature related to climate change adaptation in the infrastructure sector is primarily qualitative in nature and provides broad recommendations and warnings, primarily based on general weather studies or qualitative climate change predictions. Research completed by the Transportation Research Board in the United States, the Scottish Executives, and Austroads in Australia are notable efforts in this regard (TRB 2008; Galbraith et al 2005; AUSTRROADS 2004). These studies compare weather-related disasters and their perceived severity with predicted climate change impacts.

Another strand of the literature are studies that determine specific climate impacts on road infrastructure, such as temperature, rain, snow and ice, wind, fog, and coastal flooding (see, for example, CCSP 2006). Such studies are often undertaken in areas where specific climate change concerns threaten infrastructure that is unique to that locale. For example, Industrial Economics (2010) find that ice and winter roads in Canada are particularly vulnerable to rising

temperatures. Similarly, Jackson and Puccinelli (2006) find that northern climates may experience increased infrastructure degradation due to increased freeze-thaw cycles (2006).

The above studies are mainly motivated by the need to raise awareness and inform public officials about climate change's implications for infrastructure. A comprehensive study in this regard is Mills and Andrey (2002), who present a framework for considering climate impacts on transportation. The authors enumerate baseline weather conditions and episodic weather-influenced hazards that comprise the environment in which infrastructure is built, maintained and used. They note that weather patterns will be altered by climate change, affecting the frequency, duration and severity of hazards. These hazards may affect transportation infrastructure itself, its operation, and demand for transportation. The latter can arise from a variety of sources, such as climate's effect on the location of agricultural production and, therefore, the need and mode for shipping agricultural products.

Specific concerns are raised about rising sea levels and their potentially dramatic effect on economies and populations. Industries operating in low-lying coastal areas, such as tourism, shipping and agriculture, may face significant pressures if sea levels rise (Neumann et al. 2007). Road infrastructure may also be vulnerable to SLR. For low-lying coastal areas, making forward-looking decisions about infrastructure is a key to mitigating potentially costly impacts.

Existing impact studies on infrastructure are limited in that they either focus on a narrow potential impact of climate change, or they do not provide specific estimates of costs or damages that may result under different climate change scenarios. In contrast, Chinowsky et al (2011a) estimate the potential cost impacts of climate change on road infrastructure in ten countries that are geographically and economically diverse. The authors illustrate the real costs that countries may incur due to climate change, and the opportunity costs of diverting infrastructure resources to climate change adaptation. Recent studies have extended this stressor-response methodology to determine climate change impacts on bridges (Stratus 2010) and roads in northern climates (Industrial Economics 2010).

3. Stressor-Response Methodology

Our stressor-response methodology is based on the concept that exogenous factors (stressors) have a direct effect on and subsequent response by focal elements. In the context of climate change and infrastructure, the exogenous factors are the individual results of climate change, including changes in sea levels, precipitation, temperature, storm frequency and wind speeds. The focal elements are the different infrastructure types, such as roads, railroads, water and power distribution facilities, and public buildings. Therefore, a stressor-response value is the quantitative impact that a specific stressor has on an infrastructure element. At the core of our

analysis is a two-step procedure that first determines the appropriate climate effects on the given infrastructure inventory in selected locations, and then determines the cost impacts on this infrastructure based on a set of stressor-response functions.³

The stressors considered in this study include SLR, precipitation, temperature and flooding, while the infrastructure response elements are paved, gravel and dirt roads. For example, we will estimate how an increase in precipitation affects the lifespan of unpaved roads depending on the magnitude of the increase in precipitation. In this manner, our study diverges from qualitative summaries and emphasizes quantitative damage estimates. Flooding, precipitation and temperature are analyzed on a time-series basis with cost adjustments calculated each year through 2050. Elevation and spatial infrastructure data for Vietnam is limited and so our analysis of sea levels is restricted to a uniform one-meter SLR, and projections assume that all road stocks in an inundated area are completely destroyed. Therefore, costing for the impacts of SLR are equal to the replacement cost for inundated road stocks. The data required for our analysis includes future climate projection scenarios from General Circulation Models (GCMs), stressor-response parameters, spatial data on elevation and infrastructure locations, SLR estimates, and country-specific infrastructure cost estimates.

3.1 Parameters of analysis

Several parameters are chosen in order to create an approach that is consistent and comparable when looking at different assets and time periods. First, a consistent and uniform road stock inventory is used for analysis in all time periods. The existing road stock is allocated and utilized for all future analysis (see below). This eliminates uncertainty surrounding planned and actual future construction of new inventory. Second, all cost estimates are shown without discounting and in constant 2010 US dollars. Third, “Adaptation” options are presented in tandem with “No Adaptation” options, and refer to policy choices surrounding climate change and infrastructure investments. The Adaptation option assumes that the future climate is accurately known and that all new roads being resurfaced are adequately upgraded to the changes in climate projected over these roads’ entire lifespan. The upgraded roads are then considered “climate proof” against the incremental degradation caused by variation in precipitation and temperature resulting from climate change. Normal maintenance schedules are assumed and not counted in the costing since they would have been performed even in the absence of climate change.

In addition to these base parameters, a consistent set of adaptations are used for each road type. For paved roads, the adaptation upgrades include a new binder, which is more resilient to increased pavement temperatures. For gravel roads, adaptation upgrades focus on protection from precipitation and flooding – an upgraded road is resurfaced with crushed gravel mix and a deeper road base is laid. Increased culvert size and capacity is also included in the costing.

³ See Chinowsky et al. (2011b) for a recent application of stressor-response functions for precipitation, temperature and flooding on road infrastructure in Africa.

Finally, for unpaved roads, the adaptation option is to upgrade unpaved (dirt) roads to an “adapted” gravel road. The upgrading of an unpaved road to a gravel road reduces maintenance costs since the annual maintenance assumed for unpaved roads is no longer needed. Additional benefits to reducing transport time are not included in our costing analysis.

3.2 Road inventory and climate data

Variation in climate change outcomes means that the allocation of the national road inventory across sub-national regions is an important determinant of the costs of climate change. Provincial road inventories were estimated based on population densities (i.e., the relative population and land area of each province as a percentage of the national total):

$$R_A = R_N \cdot 12 \cdot \frac{P_A}{P_N} + \frac{A_A}{A_N} \cdot R_N$$

where N is national (country) and A is administrative region (province)

P_A and P_N are national and regional populations (people)

A_A and A_N are total national and regional land areas (km²)

R_A and R_N are total national and regional road stocks (km²)

This allocation is done for each of the nine road types analyzed, i.e., paved, gravel and unpaved and by primary, secondary and tertiary. Due to a lack of spatial data on the exact location of roads within provinces, as well as the course resolution of climate projection data, we assume that road stocks are uniformly distributed within administrative regions. This process may result in some over-estimates as impact-prone areas will be avoided over time by infrastructure planners. However, this provides a reasonable baseline from which to undertake this study.

Climate change data was drawn from two sources. For the climate stressor analysis, a selection of GCMs and emissions scenarios was taken from the Intergovernmental Panel on Climate Change’s (IPCC) Fourth Assessment Report (IPCC 2007). The GCMs provide climatological data for future climate change scenarios through 2100. The data used in this analysis include the available A2, A1B and B1 emissions scenarios, which reflect different assumptions about future socioeconomic development. To provide a comprehensive analysis of climate change projections, those GCM datasets approved by the IPCC containing complete data projections for climate and flood data for Vietnam were used (i.e., 25 climate change projections combining GCMs and emissions scenarios). Each GCM produces annual predicted precipitation and maximum temperatures. To obtain a broad assessment of the potential effects of climate change, the range and likelihood of the low-impact, medium-impact, and higher-impact scenarios were developed in relation to the other climate scenarios. This is designed to give policy makers

and planners a broader understanding of the risk and options presented by different climate change projections.

To analyze the impact of SLR, data was used from the Center for Remote Sensing of Ice Sheets at the University of Kansas. This provided information for a one meter or greater projected SLR, which was used to estimate the share of each Vietnamese grid cell that would be inundated, i.e., land completely covered by more than 1 meter of SLR. Where inundation was projected, it was assumed that all nine types of road stock located in an inundated area would be destroyed. The impact function methodology is described in Section 4 below.

To ensure consistent application of the data, both the SLR and provincial mapping of Vietnam were translated into a standard grid system. Climate Research Unit (CRU) grid cells of 0.5 degree latitude by 0.5 degree longitudinal (approximately 250km²) provided the basis of this data overlay translation (Climate Research Unit Time Series Version 2.1). Provinces were allocated across grid cells based on the share of their geographic area lying within a CRU grid cell. For example, an administrative area might be allocated across grid cells A and B at 30 and 70 percent, respectively. In this case, the province is recorded as having proportional area allocations in each grid location. In regions where detailed road locations are unknown, the road stock is uniformly distributed between grid cells at the same ratio of 30 and 70 percent, respectively. The result of this process is that the kilometers of roads in each province are allocated proportionally on a grid cell level.

4. Impact Functions

4.1 Climate impact analysis

Utilizing the GCM climate projections described above and a baseline “no climate change” scenario, it is possible to determine costs and impacts on individual infrastructure elements using the stress-response methodology. As mentioned earlier, the three climate stressors considered for Vietnam include precipitation, temperature and flooding.

The stressor-response factors are divided into two general categories: (i) impacts on new construction costs, and (ii) impacts on maintenance costs. New construction cost factors focus on the additional resources required to adapt the design and construction of roads when rehabilitating an asset to changes in climate expected to occur over the asset’s lifespan. Maintenance effects are changes in costs that are anticipated to incur due to climate change. In both categories, the underlying objective is to retain the design lifespan for road infrastructure. This premise is motivated by a preference for maintaining infrastructure rather than rebuilding on a frequent basis.

4.2 Sea level analysis

Climate and SLR impacts are analyzed separately and on different time scales. The climate stressor impacts (i.e., from precipitation and temperature) are estimated on a daily basis and results are aggregated to decadal totals in order to give an overall assessment of climate change over the medium-term. A lack of time-scaled data on SLR projections means that the SLR analysis is done at a single instant in time utilizing one impact scenario, i.e., a uniform one meter SLR.

There are a number of limitations to the robustness of this approach. First, projections on the amount of SLR that will occur in a specific region are uncertain and vary widely. Some recent studies predict a future SLR greater than one meter by 2100 (see Nichols and Cazenave 2010), while the IPCC's Fourth Assessment Report predicts an average 0.6 meters by 2100 (IPCC 2007). Our analysis of SLR should therefore be viewed as one possible climate change outcome that is likely by 2100 but is unlikely to occur before 2050.

Secondly, our SLR impact methodology makes several assumptions: (i) a uniform distribution of road stock throughout each administrative region; (ii) a uniform one meter SLR estimate applied to land at or below one meter elevation; and (iii) land inundation requires a permanent relocation of road stocks. Costing is applied to the inundated road stock at the amount required to rebuild the existing road stock (see Table 1). For example, we assume that half of a grid cell's road stock is destroyed if half of that grid cell is projected to be inundated by SLR. If the grid cell contains road stock from more than one provincial level, then half of that road stock is destroyed in each of the affected provinces. The specific kilometers of road affected correspond to the initial road stock allocation at the national, provincial, and grid cell levels. A detailed example of this calculation procedure is provided in the appendix.

[Insert Table 1]

After determining the kilometers of roads inundated for each grid cell, the costs of replacing these roads are estimated at the grid cell level and for each road type. In the case of SLR, current costing analysis is done using the cost to build a new kilometer of road of each type. Other adaptation options, such as abandoning damaged roads, are not explored in this analysis.

5. Metrics of Measuring Impacts

Climate change impacts on road infrastructure can be measured in several ways. While *Total Cost* is an important metric for policy makers, an additional concern is the relative effect of reallocating funds towards climate change that might have otherwise been used to fund

development in other critical areas, including expanding the existing road inventory. To provide a set of metrics for understanding the broader impact of climate change, we use the following three metrics:

Total Cost: The overall estimated costs of climate change impacts on road infrastructure (at 2010 prices and without discounting).

Opportunity Cost: The amount of paved road inventory that could have been built with the funding that is diverted to climate change costs. Opportunity cost is calculated by first estimating the amount of money required to respond to climate change divided by the cost of a kilometer of paved secondary road. This amount is then divided by the existing paved road inventory to give the share of the paved road inventory that could have been extended if funds had not been allocated to responding to climate change.

Adaptive Advantage: The benefit of adapting to climate change measured as the percentage cost savings between the “Adapt” and “No Adapt” policy options (discussed below).

Using these three metrics, our results are presented for both a proactive “Adapt” approach and a reactive “No Adapt” approach. For the adaptation approach, we introduce the concept of “maintenance savings”, which indicates the amount of standard maintenance that will be saved if an adaptation approach is adopted. These categories are detailed as follows:

Adapt: The “Adapt” policy approach assumes perfect foresight with respect to climate change impacts and a policy that applies these forward-looking climate projections to upgrade new roads as they are re-built and maintained. The Adapt scenario incurs up-front costs to adapt a road to mitigate future damages that are projected from increases in precipitation or temperature. For unpaved road infrastructure, roads are upgraded to an adapted gravel road and therefore are less susceptible to increased precipitation impacts.

No Adapt: The “No Adapt” policy approach assumes no adaptation options are enacted and roads are rebuilt according to baseline design standards. The costs incurred are from the increased maintenance needed to retain the design life of the original road (i.e., to overcome the degradation in road infrastructure from climate change stressors).

Maintenance Savings: Maintenance savings is reported in order to emphasize the costs and benefits associated with adaptation in Vietnam. Maintenance costs are applied to unpaved (dirt) roads. Many of the costs of an unpaved road network arise from precipitation damage or traffic levels.⁴ Upgrading dirt roads to gravel surfaces reduces annual maintenance requirements because gravel is more resistant to both precipitation

⁴ Traffic levels are approximated by information on population density.

and traffic. Therefore, maintenance savings represent both the savings in traditional maintenance that would have been required for the dirt surfaces, as well as the additional maintenance that would be required due to increased precipitation from climate change.

6. Study Results

6.1 National climate change damages with and without adaptation policy

The estimates presented in this section are for the total cost of new construction, maintenance and repairs for the existing road inventory. The “mean GCM” is the GCM whose total damage cost *without adaptation* is closest to the average total damage cost of all “No Adapt” scenarios among the 25 GCMs. However, as discussed below, the GCMs are unevenly distributed across the range of damage cost estimates and so, depending on the concern of policy maker, the extremes or quartile numbers may be of more interest to policy makers than the mean. We therefore present the results “minimum” and “maximum” damage cost scenarios.

Figure 1 reports the distribution of total damage costs across the 25 GCM projections, both with and without adaptation policy. Combined costs include impacts from flooding, temperature and precipitation. We first consider scenarios that allow for adaptation policies that optimally maintain road stocks. The figure shows that the combined damage cost estimates for a majority of climate projections (88 percent) lie between US\$3.6 billion and US\$7.2 billion. Only two extreme GCMs lead to total damage costs greater than US\$14 billion. However, even the lower projection that generates US\$3.6 billion in damages has an opportunity cost of 32 percent, implying that more than 24,000 kilometers of secondary paved road could be built with the money that will need to be diverted to adaptation spending.

[Insert Figure 1]

As illustrated in Figure 1, the damage estimates can be decomposed into climate stressor (i.e., precipitation and temperature) and flooding components. The total damage costs for the scenarios at the lower end of the distribution are almost entirely a result of climate stressors, with very modest (often zero) flooding damages to road stocks. The uneven distribution of the combined damage costs in Figure 1 is due to the uneven distribution of flooding impacts.

We now consider scenarios without adaptation. Figure 1 shows that damage cost estimates are significantly higher without adaptation for the same set of GCMs. Again, the damage costs for 22 out of 25 GCMs (88 percent) fall within the lower end of the distribution, with only a few GCMs projecting more extreme climate impacts. The minimum damage cost without adaptation is US\$567 million higher than the scenario with adaptation. Both the mean

and maximum damage estimates are substantially higher without adaptation; an incremental cost of US\$4.7 and US\$39 billion, respectively. This “adaptive advantage” suggests that policymakers should consider a proactive approach to adapting to climate change. For instance, in the maximum damage scenario without adaptation has an opportunity cost of 482 percent. This means that an equivalent of 367,000 kilometers of new secondary paved road could be built with the funds diverted to mitigating climate change damages. Even in the mean damage scenario, the opportunity cost is 92 percent and equivalent to about 70,000 kilometers of new secondary paved road stock. This is significantly higher than the opportunity costs when adaptation of road infrastructure is undertaken, i.e., 341 and 41 percent for the maximum and mean damage scenarios, respectively.

“Maintenance savings” measures the savings derived when adaptations are adopted for road infrastructure. This measure is required because the cost incurred in upgrading dirt and gravel roads can be offset by savings in the annual maintenance required by lower-quality road infrastructure. Tables 2 and 3 report the maintenance savings, damage costs and adaptive advantages for the minimum, mean and maximum damage scenarios (i.e., 3 of the 25 GCMs shown in Figure 1) for both the combined impacts and the impacts without flooding.

[Insert Tables 2 and 3]

Table 2 highlights the advantage of an adaptation strategy when the combined impacts are considered. As illustrated, the mean damage scenario has an adaptive advantage of US\$4.8 billion, i.e., the difference between the total costs with and without adaptation. When maintenance savings of US\$4.5 billion are included, the overall benefit of adaptation almost doubles to US\$9.3 billion. This highlights the benefits of proactive adaptation policy that includes long-term investments in improved road infrastructure. Even in the minimum damage scenario there are clear benefits to adaptation in the form of maintenance savings, i.e., US\$1.7 billion. Maintenance savings lower adaptation costs and raise the adaptive advantage under all GCM scenarios. However, it should be considered that a few GCM scenarios result in little or no difference between the damage costs with and without adaptation. This is because the climate stressor impacts for these scenarios derive from single events where repair costs are equal to or less than the costs of proactive adaptation. For example, for the GCM “MIROC3_2(medres)_A2”, the cost of adaptation equals the cost of reactive maintenance (see Table A1 in the appendix).

Table 3 illustrates a different perspective when the flooding impacts are removed. As illustrated, the variation in the potential impact is reduced when the potential impact of flooding is removed. The Adapt maximum impact scenario has a cost of USD\$7.5 billion with an opportunity cost of 66%. The No Adapt maximum impact scenario is only slightly higher at USD\$8.7 billion. Similarly, the Mean results for these scenarios are USD\$5.8 and \$6.4 billion respectively. This lack of variation in both the range of impacts and the adaptation advantage is

reflective of; 1) the similarity in projections of the GCMs in terms of precipitation and temperature trends, and 2) the variation in projections for individual precipitation events resulting in flooding occurrences.

6.3 Damages from rising sea levels

We evaluate the impact of a one meter rise in sea levels on land inundation and roads damages. Based on the existing road inventories and provincial allocations, one meter SLR would inundate, and hence destroy, 19,000 kilometers of roads in Vietnam, which is equivalent to 12 percent of existing road stocks. As reported in Table 4, rebuilding these damaged roads would cost approximately US\$2.1 billion.

[Insert Table 4]

Road damages from SLR are unevenly distributed within the country, with most road losses occurring in the southern coastal regions of the country. There is complete inundation in several provinces, resulting in a total loss of road infrastructure (i.e., in Bac Lieu, Hau Giang, Soc Trang, Tra Vinh and Ca Mau). As a region, the Mekong River Delta is most vulnerable, with ten of the most affected provinces located within the region and where an average of 77 percent of road infrastructure is destroyed (i.e., nearly 15,200 kilometers). Figure 2 shows the share of road stocks in each province that would be destroyed by SLR (left-hand-side) and the total cost of rebuilding these roads (right-hand-side).

[Insert Figure 2]

6.4 Regional level results

Vietnam has a diverse geography, ranging from coastal lowlands to higher plains and mountainous terrain in the north. Climate change will affect these areas differently, especially the impacts of SLR, and so sub-national analysis is essential. We select two GCMs that represent the 75th and 25th percentiles of climate impact in the Adapt scenario for consistency in comparing regional impacts. We discuss the results for each region below. A summary of results is presented in Table 5.

INSERT TABLE 5 HERE

Central highlands: This region is the least affected by SLR since none of its provinces have coastal boundaries. Therefore, all damage costs are from climate and flooding stressors. Adaptation policy saves nearly US\$100 million in the Maximum Hot scenario, which is the cost difference from expanding existing infrastructure by nearly 50 percent as opposed to a 10 percent opportunity cost for adaptation.

Mekong river delta: This region incurs the largest total and opportunity costs of all regions under the combined climate change scenarios. This can largely be attributed to SLR, given that most of this southernmost region in Vietnam is at an elevation of less than three meters. In the region's thirteen provinces, coastal inundation destroys between 14 and 99.5 percent of provincial road infrastructure. More than three quarters of the national cost of SLR is borne by this region (i.e., US\$1.6 billion).

Northern central and central coast area: Climate change impacts in the selected GCMs show that impacts in this region are quite modest relative to other regions in Vietnam. However, total costs reach as much as US\$115.9 million under the maximum-hot scenario, with an opportunity cost of 57 percent. Adaptation policy reduces this opportunity cost to 16 percent, which is a savings of US\$83.7 million. Even though the median-hot scenario has a lower projected impact (25 and 34 percent with and without adaptation, respectively), there is still a significant benefit to adaptation of road infrastructure. Approximately one percent of the region's road stock is affected by SLR and this exposure is fairly evenly distributed across provinces (ranging from 0.03 to 1.3 percent). The largest damages occur in Da Nang and Phu Yen provinces, with costs of US\$1.6 and US\$2.4 million, respectively, and with road losses of 44 and 29 kilometers, respectively.

Northern midlands and mountain areas: With adaptation policy this region incurs the lowest total and opportunity costs from climate change. This is partly because of the region's location away from the coast: the largest SLR impact is in Bac Giang where less than one percent of roads are destroyed (i.e., three kilometers of roads at a replacement cost of US\$162,000). The climate impacts from temperature, precipitation and flooding could cost as much as US\$100 million, but with adaptation this is reduced to US\$11 million. Adaptation policy is therefore highly effective in this region.

Red river delta: SLR destroys six percent of this region's roads, with losses as high as 21 percent in some provinces. Adaptation policy reduces total climate damage costs by nearly US\$150 million under the maximum-hot scenario. The opportunity cost savings from adaptation are similar across the two GCM scenarios in this region, but vary significantly without adaptation policies. This highlights the effectiveness of adaptation in reducing both the magnitude and variation of potential climate change damages. Avoiding a "worst case" scenario through adaptation policies that limit road infrastructure damages will be crucial in this region's densely populated urban areas, especially within the capital city, Hanoi.

Southeast: This small region contains key urban centers, including Ho Chi Minh City. Road losses from SLR vary across provinces from 0-21 percent, with Ho Chi Minh at the upper end of this distribution. With approximately 6800 kilometers of roads, this region incurs a total cost of US\$165 million in the maximum-hot scenario, and a potential road loss of 1360

kilometers. Adaptation generates savings of US\$122 million, which again underscores the need for proactive infrastructure adaptation policy.

7. Discussion and Conclusions

Vietnam's policy-makers recognize the crucial role that road infrastructure will play in supporting the country's economic development. However, as with most long-term investments, there is a trade-off between short- and long-run policy objectives. For road investment, the trade-off is most clearly seen in the choice between building a longer network of less expensive roads, or a shorter network of more climate-resilient (paved) roads. Climate change further complicates this trade-off by introducing greater climate uncertainty into the planning process, and by changing the potential returns to building paved roads (and the costs of maintaining them). It is essential then that policy-makers have information that reflects not only the complexities of road investments, but also, given the long life-span of roads, the potential implications of climate change.

In this paper, we have expanded on existing qualitative studies by estimating the damage costs from climate change and quantifying the long-run benefits of adaptation policies. We have used stressor-response functions to estimate how temperature, flooding and precipitation projections from climate change models will affect road conditions and maintenance costs. Our model accounts for differences in road surface types, and for specific engineering-based adaptations to make roads more resilient to adverse climate changes. By integrating these stressor-response functions with traditional costing methods, our analytical framework can estimate damage costs in detailed sub-national regions. Importantly, using existing expenditures, road inventories and estimated cost impacts, our framework provides an initial estimate of the opportunity costs of adaptation in the road. Unlike many previous studies, we used a number of GCMs and emission scenarios, and therefore provide a more comprehensive assessment of the range of potential climate change damages.

Our findings indicate that predicted changes in temperature, precipitation and flooding present a threat to Vietnam's road infrastructure. In the worst-case climate scenario, total damage costs at the national level are as high as US\$55 billion over the period 2010-2050 (undiscounted and in 2010 prices). However, this is an extreme outcome, with a majority of damage estimates falling between US\$4 billion and US\$9 billion. Most of this variation in damages across GCMs comes from the effects of flooding. Our analysis indicates high returns to adaptation policies that seal unpaved roads and make them more precipitation and flood-resistant. Moreover, the costs of adaptation are lower when "maintenance savings" are taken into account. These are the savings that arise from reducing the susceptibility of roads to deterioration from weather. These maintenance savings offset the higher construction costs of roads with improved surfaces.

We also estimated the potential road network damages from by rising sea levels, as well as the cost of replacing these roads. Sea levels are a major concern for Vietnam due to its 3400 kilometer coastline and the low elevation of the country's river deltas. This geography creates a scenario where extensive damage to road infrastructure could occur if sea levels rise by as much as one meter. It should be noted that the one meter rise is not predicted to happen before 2050 (depending on what analysis is chosen). As elevation data is only available at one meter steps, this level was chosen for the study. Our analysis suggests that based on this anticipated sea level rise, potential damages from inundation could amount to over US\$2 billion. This is in addition to the damages from changes in inland temperature, precipitation and flooding.

Our paper provides an initial assessment of climate change's impact on Vietnam's road infrastructure. There are, however, at least two key limitations where further work is needed. First, the parameter values of our stressor-response functions are drawn from the global engineering literature, and so, while our model uses recognized authorities and studies, our quantitative cost estimates depend on the accuracy of these studies and their transferability to the Vietnamese context. Issues such as specific pavement types, local conditions, and construction and maintenance techniques can influence cost assessments. Secondly, as emphasized, a lack of high resolution elevation data constrained our SLR assessment to a uniform, one meter analysis. More detailed databases, including on the location of coastal infrastructure, would strengthen our analysis. Nevertheless, our quantitative approach is an advance over existing studies and provides necessary information for evaluating adaptation options for road infrastructure, particularly for Vietnam and other developing countries.

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Table 1. Costs of rebuilding inundated roads after one meter sea level rise

	Costs of New Road (US\$ per kilometer)		
	Paved	Gravel	Unpaved
Primary	500,000	226,000	128,000
Secondary	150,000	135,000	75,000
Tertiary	70,000	75,150	41,750

Table 2. National damage costs from combined climate change impacts, 2010-2050

	GCM damage cost ranking		
	Maximum	Mean	Minimum
<u>With adaptation</u>			
Total cost (US\$ mil.)	16,105	5,779	3,613
Opportunity cost (%)	141	51	32
Maintenance savings (US\$ mil.)	0	4,540	1,730
<u>Without adaptation</u>			
Total cost (US\$ mil.)	55,149	10,560	4,180
Opportunity Cost (%)	482	92	37
<u>Adaptive advantage</u>			
Total cost (US\$ mil.)	39,044	4,781	567
Opportunity Cost (%)	341	42	5

Notes: Combined costs include damages from temperature, precipitation and flooding.

Table 3. National damage costs from climate impacts only, 2010-2050

	GCM damage cost ranking		
	Maximum	Mean	Minimum
<u>With adaptation</u>			
Total cost (US\$ mil.)	7,543	5,778	3,613
Opportunity cost (%)	66	51	32
Maintenance savings (US\$ mil.)	0	4,540	1,730
<u>Without adaptation</u>			
Total cost (US\$ mil.)	8,668	6,394	4,180
Opportunity Cost (%)	76	56	37
<u>Adaptive advantage</u>			
Total cost (US\$ mil.)	1,125	616	567
Opportunity Cost (%)	10	5	5

Notes: Climate only costs include damages from temperature and precipitation (i.e., exclude flooding).

Table 4. National road damages from one meter sea level rise

	Road damages, 2010-2050	
	Kilometers	US\$ mil.
All road types	19,142	2,089
Paved primary	1,621	810
Paved secondary	3,775	566
Paved tertiary	3,719	260
Gravel tertiary	9,024	377
Unpaved tertiary	1,003	75

Table 5. Regional damages under the “75th and 25th Percentile” scenarios, 2010-2050

	Damage costs (US\$ mil.)		Opportunity costs (US\$ mil.)	
	With adaptation	Without adaptation	With adaptation	Without adaptation
<u>75th percentile</u>				
Central highlands	24.5	119.2	10	48
Mekong river delta	170.7	259.6	129	197
Northern central and central coastal areas	32.2	115.9	16	57
Northern midlands and mountain Areas	11.7	100.1	7	58
Red river delta	27.8	177.2	15	69
Southeast	55.6	177.5	17	63
<u>25th percentile</u>				
Central highlands	54.4	90.6	22	36
Mekong river delta	193.1	213.4	147	164
Northern central and central coastal areas	48.2	67.1	25	34
Northern midlands and mountain Areas	20.7	52.8	12	31
Red river delta	37.6	92.4	18	38
Southeast	97.7	152.5	33	54

Table A1. Decomposed damage cost estimates for individual GCMs), 2010-2050 (US\$ millions)

Damage ranking	GCM names	Flooding		Climate (temperature and precipitation)			Combined flooding/climate	
		With adaptation	Without adaptation	With adaptation	Without adaptation	Maintenance savings	With adaptation	Without adaptation
(Max)	1 IPSLCM4_A1b	8,561	47,606	7,544	7,544	0	16,105	55,150
	2 IPSLCM4_A2	7,381	40,835	6,184	7,021	0	13,565	47,856
(Mean)	3 CGCM3_1(T63)_B1	1,092	4,134	6,533	8,195	4,090	7,625	12,329
	4 GFDL2_1_A2	1,428	4,166	6,481	6,394	304	7,909	10,561
	5 MIROC3_2(medres)_A1b	1,095	3,941	5,621	5,274	2,237	6,715	9,215
	6 GISS_MODEL_ER_A1B	394	436	6,262	8,602	3,674	6,655	9,039
	7 GISS_MODEL_ER_A2	394	245	6,520	8,464	3,648	6,914	8,709
	8 CCCMACGCM3_1_A1b	0	0	6,503	8,668	4,257	6,503	8,668
	9 MIROC3_2(medres)_B1	1,128	4,367	4,812	4,188	2,304	5,940	8,555
	10 CCCMACGCM3_1_B1	0	15	6,382	8,049	4,161	6,382	8,064
	11 CCCMACGCM3_1_A2	100	44	6,179	8,003	3,427	6,279	8,047
	12 CNRMCM3_0_A1b	100	24	6,417	8,012	2,743	6,518	8,036
	13 CNRMCM3_0_B1	472	905	6,703	6,905	1,595	7,175	7,809
	14 INMCM3_0_A1b	1	121	5,779	7,006	4,541	5,779	7,127
	15 GFDL2_1_B1	1,154	1,797	4,400	5,248	1,602	5,554	7,044
	16 MIROC3_2(medres)_A2	534	1,144	5,114	5,114	0	5,648	6,258
	17 MPIECHOm5_A1b	0	20	5,277	6,182	3,133	5,277	6,202
	18 INMCM3_0_A2	0	85	5,201	5,935	2,691	5,201	6,020
	19 INMCM3_0_B1	2	405	5,721	5,565	3,632	5,723	5,970
	20 GISS_MODEL_ER_B1	394	556	4,400	5,248	3,310	4,794	5,803
	21 MPIECHOm5_A2	0	9	5,122	5,120	3,949	5,122	5,129
	22 MPIECHOm5_B1	0	17	5,096	4,808	4,615	5,096	4,826
	23 BCCRBCCM2_0_A1b	0	58	4,278	4,304	3,180	4,278	4,362
	24 MRICGCM3_2_3_A1b	20	39	4,218	4,218	0	4,238	4,257
	(Min)	25 BCCRBCCM2_0_A2	0	0	3,614	4,180	1,731	3,614

Notes: Tables in the paper report GCMs ranked (min, mean and max) according to total combined costs without adaptation (final column).

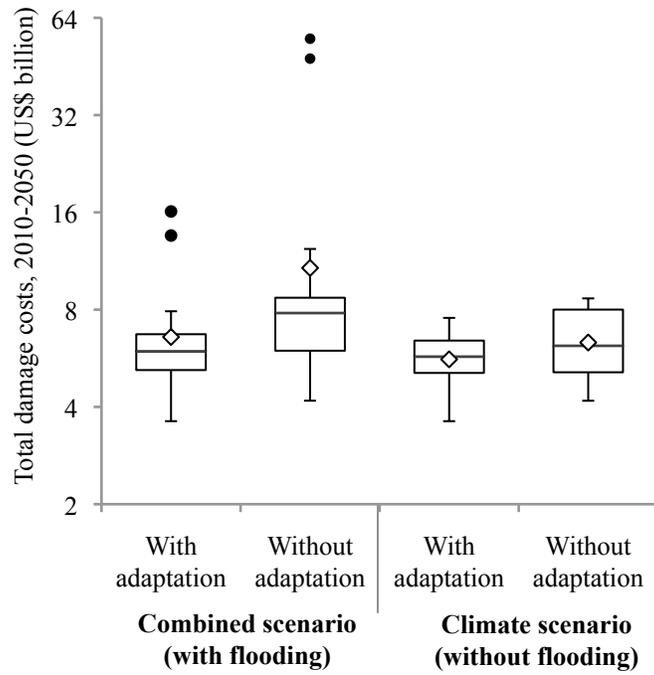


Fig. 1. Damage costs for road infrastructure, 2010-2050. Combined scenario includes damages from temperature, precipitation and flooding. Logarithmic scaled. Dots are outliers and diamonds are means.

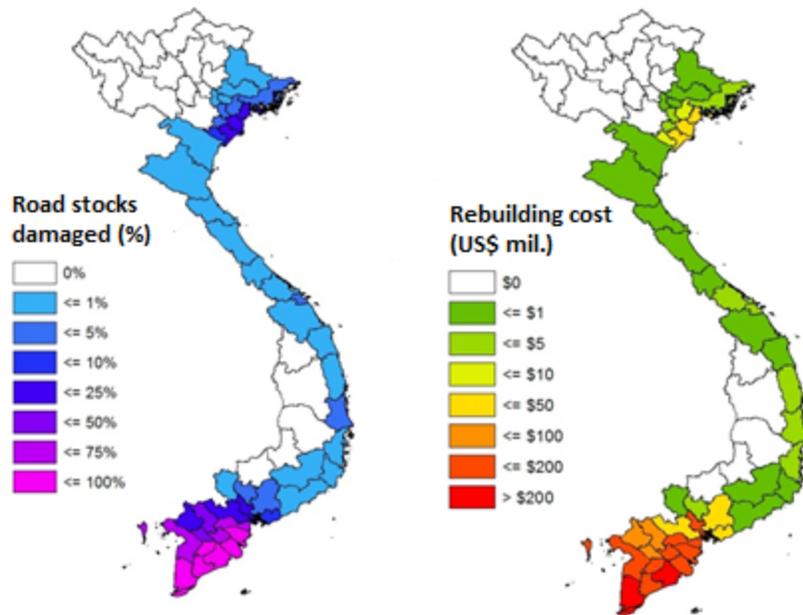


Fig. 2. Provincial road damages from one meter sea level rise. Share of roads destroyed (left-hand-side) and cost of rebuilding destroyed roads (right-hand-side)

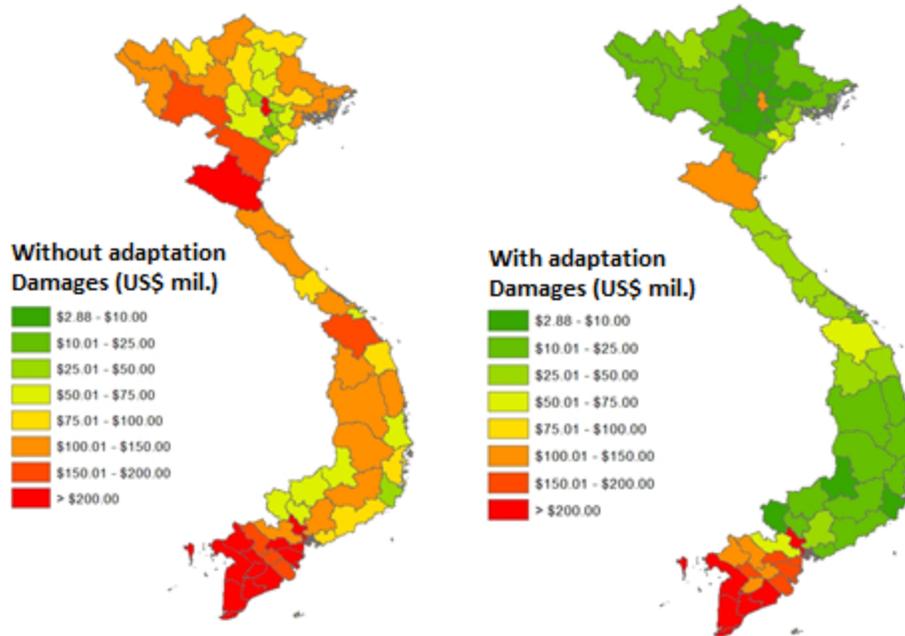


Fig. 3. Provincial total damages costs for the maximum-hot scenarios, 2010-2050.