LIFELINES: The Resilient Infrastructure Opportunity

FROM A ROCKY ROAD TO SMOOTH SAILING

Building Transport Resilience to Natural Disasters

Julie Rozenberg
Xavier Espinet Alegre
Paolo Avner
Charles Fox
Stéphane Hallegatte
Elco Koks
Jun Rentschler
Mersedeh Tariverdi

WORLD BANK GROUP

1818 H Street NW, Washington, DC 20433
Telephone: 202-473-1000; Internet: www.worldbank.org

1 2 3 4 19 18 17 16

Cover design by Brad Amburn.

Summary

Reliable transport infrastructure is one of the backbones of a prosperous economy, providing access to markets, jobs and social services. Sustainable Development Goal 9 (SDG9) calls for increased access to sustainable transport infrastructure in low- and middle-income countries. Collectively, these countries will need to spend between 0.5 percent and 3.3 percent of their GDP annually (US$157 billion to 1 trillion) in new transport infrastructure by 2030 – plus an additional 1 percent to 2 percent of GDP to maintain their network – depending on their ambition and their efficiency in service delivery (Rozenberg and Fay, 2019).

Because of the wide spatial distribution of transport infrastructure, many transport assets are exposed and vulnerable to natural hazards, increasing costs for national transport agencies and operators. During the 2015 floods in Tbilisi, Georgia, the repair of transport assets contributed approximately 60% of the total damage cost (GFDRR, 2015). In the 1995 earthquake in Kobe, Japan, accessibility as measured by the length of open networks directly after the shock dropped by 86% for highways and by 71% for railways (Kazama and Noda, 2012b). Such transport disruptions necessarily have direct impacts on the local economy. Employees face difficulties commuting, access to firms is disrupted for clients, interruptions in the supply chain inhibit production, and finished products cannot be easily shipped (Kajitani and Tatano, 2014).

This paper, prepared as background material for the *Lifelines* report on infrastructure resilience, summarizes the main findings on the risk faced by transport networks and users as a result of natural disasters and climate change, and the main recommendations for building more resilient transport networks. It starts by describing how transport disruptions affect firms and households either directly and through supply chains. It then proposes a range of approaches and solutions for building more resilient transport networks, showing that the additional cost of resilience is not high if resources are well spent. Finally, it provides a set of practical recommendations.

Contents

1. Natural disasters are expensive for transport networks and their users

Even in the absence of extreme natural shocks, weather can disrupt road, rail, water, and air transportation. In the United States, about 16 percent of flight delays are caused by relatively minor weather events and only about 4 percent by extreme weather (Bureau of Transportation Statistics 2018). And a survey of the empirical literature finds that precipitation increases the frequency of road accidents and increases congestion by reducing vehicle speeds (Koetse and Rietveld, 2009). In the United States, about 15 percent of road traffic congestion is attributed to bad weather (Cambridge Systematics Institute and Texas Transportation Institute, 2005). Such effects are not limited to road networks: in Finland, 60 percent of freight train delays between 2008 and 2010 were related to winter weather (Ludvigsen and Klæboe, 2014).

Meanwhile, warm summers with low precipitation can affect inland waterway transportation: in northwestern Europe, the dry summer of 2013 resulted in low water levels and losses of €480 million stemming from the inoperability of some large vessels and a shift to other forms of transport (Jonkeren et al. 2014).

Transport disruptions are costly. In the European Union, the total costs of the influence of extreme weather events on the transport system are an estimated €2.5 billion a year. Of these costs, about 72 percent are attributed to roads, 14 percent to air, and 12 percent to the rail sector. The remaining 2 percent are related, in descending order of magnitude, to maritime transport, inland waterways, and intermodal freight transport (Enei et al. 2011). Looking at the next four decades in the European Union and using the same methodology, Doll, Klug, and Enei (2014) expect the road transport costs arising from extreme weather events to increase by 7 percent. Higher flood risks and less predictable winters could increase rail traffic costs by up to 80 percent.

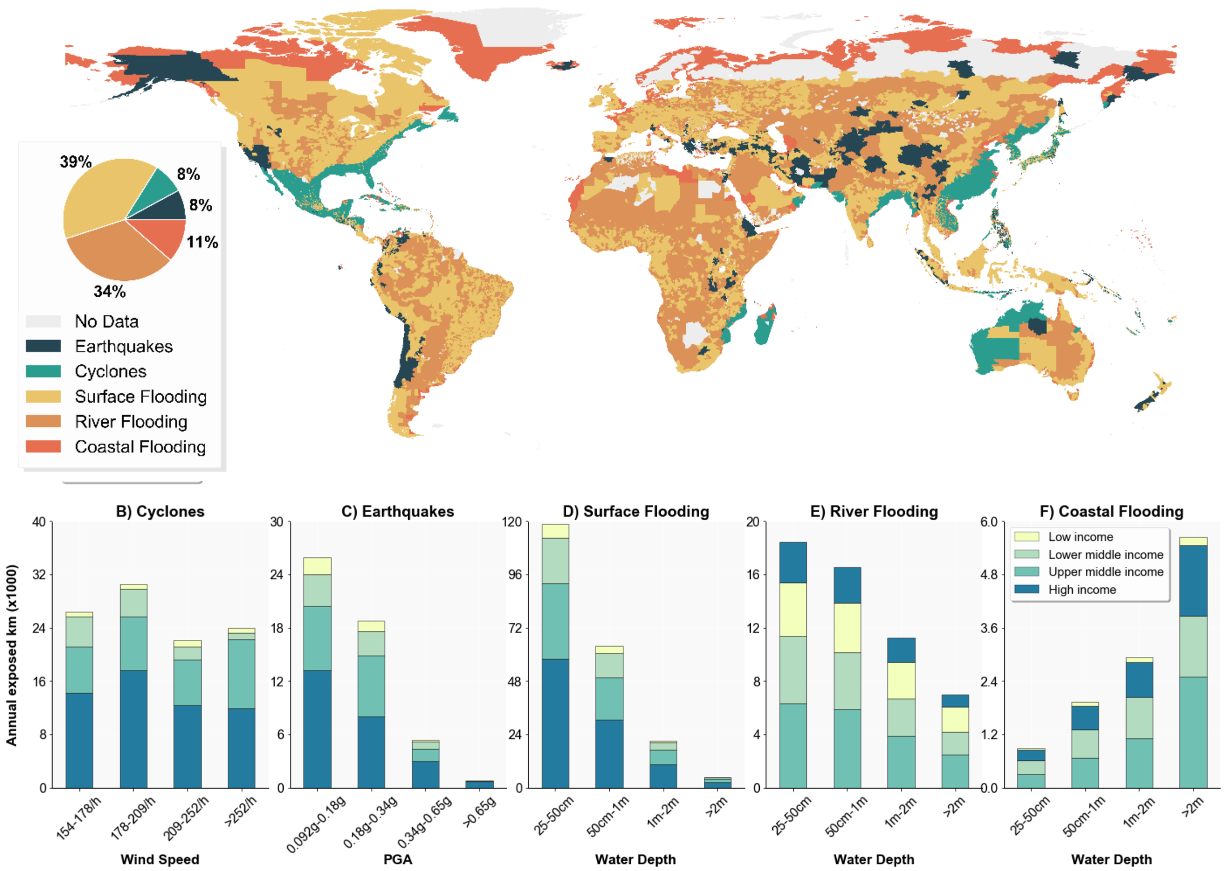
The next section explores the direct damages that extreme events cause to transport infrastructure.

1.1. Global estimates of multi-hazard exposure and risk to road and rail infrastructure

A study by Koks et al., (2019) combines road and rail network asset data with information on natural hazards, at a resolution that is unprecedented at the global scale. This global study assesses damaged networked infrastructure at the asset level, such as individual road segments or bridge structures. The road and railway data in this analysis are based on open access data from OpenStreetMap which, through a global set of voluntary contributors, provides a comprehensive dataset (Barrington-Leigh and Millard-Ball, 2017; Meijer et al., 2018). The exposure and risk of these assets is assessed for the most frequently recorded and costliest disasters: tropical cyclones, earthquakes, surface flooding, river flooding, and coastal flooding. Crucially, assets are only considered to be exposed when the probability of occurrence of the hazard exceeds the assumed design protection standards of the assets. This way, countries' different resilience standards are incorporated into the analysis.

This analysis finds that about 27% of all global road and railway assets are exposed to at least one hazard, and that about 7.5% of assets are exposed to a 1/100 years flood event. Road and rail networks are exposed most to surface flooding, followed by tropical cyclones, river flooding, and earthquakes (Figure 1). As exposure is driven by both the occurrence of hazards and the existence of assets, high-income countries with more transportation infrastructure can be expected to be more exposed. Indeed, for earthquakes and surface flooding, richer countries with more assets are proportionally more exposed. For river and coastal flooding, however, high-income countries have fewer exposed kilometers, because of the higher flood protection standards in these countries. For tropical cyclones and earthquakes, the relatively large share of exposed infrastructure in upper-middle- and high-income countries is caused predominantly by the geographic occurrence of the hazards.

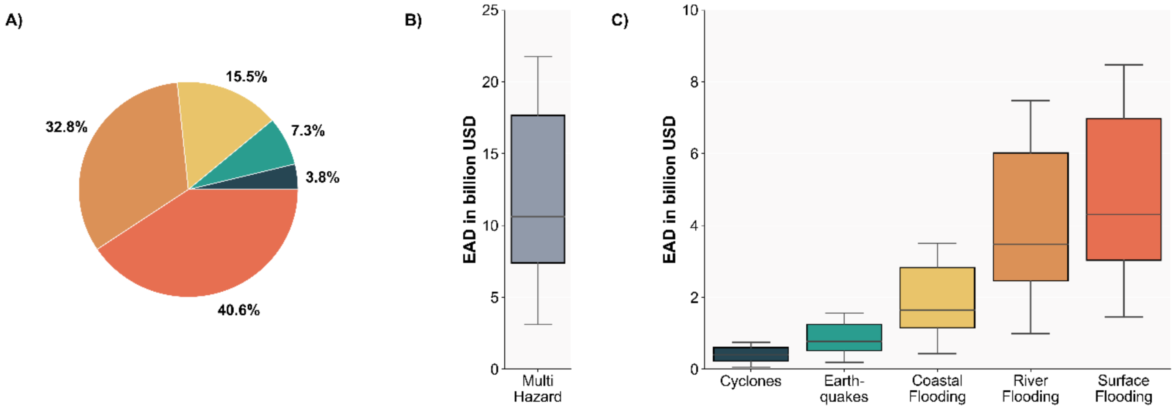
Figure 1: Global multi-hazard transport infrastructure exposure. Panel A presents the hazard causing the highest transport infrastructure exposure in each region. The pie chart shows the relative percentage of land area where that specific hazard causes the highest exposure. Panels B to F present the exposure for the four income groups per hazard and per hazard intensity.



Source: Koks et al. (2019)

The global Expected Annual Damages (EAD) to transport infrastructure assets are presented in Figure 2. The total global EAD for all hazards combined ranges from $3.1 to 22 billion (Figure 2b), depending on the assumptions made on the vulnerability of roads, and construction and repair costs. These values represent between 0.2 and 1.5% of annual global maintenance needs, using the assumptions described in the cost-benefit methods section to assess maintenance needs. The mean EAD for transport infrastructure assets is $14.6 billion (1% of annual global maintenance needs), and about $8 billion in low- and middle-income countries. Approximately 73% of the global EAD is caused by surface and river flooding (Figure 2a), followed by coastal floods (15.5%), earthquakes (7.3%), and tropical cyclones (3.8%).

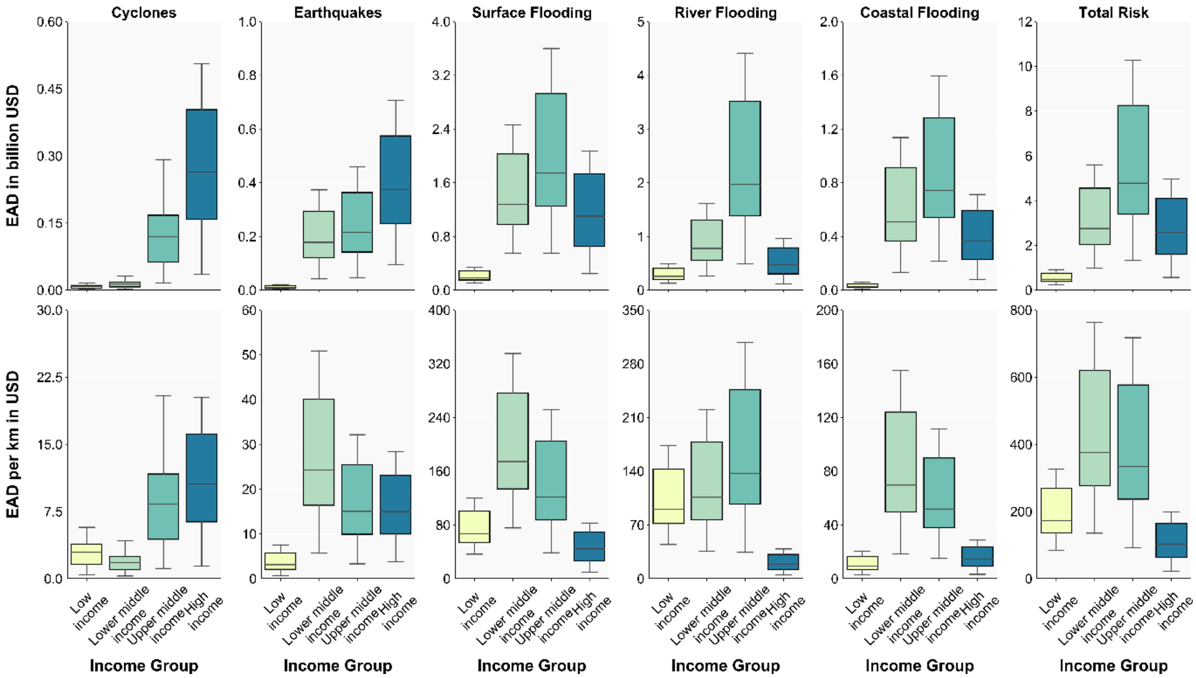
Figure 2 Total EAD per hazard. Panel A shows the relative distribution of the total EAD to infrastructure assets among the different hazards. Panel B shows the calculated range of total multi-hazard global EAD. Panel C shows the calculated range of the EAD per hazard. The lower and upper whiskers in Panel B and C represent, respectively, the lowest 25% of the calculated EAD's and the highest 25% of the calculated EAD's.



Source: Koks et al. (2019)

As countries' wealth increases, their transportation infrastructure damages first rise, and then fall again. This bell-shaped relationship between income and EAD is shown in Figure 3. It is caused by two key – and countervailing - dynamics: at first, states accumulate infrastructure as GDP increases. This comes at the expense of higher disaster exposure and greater damages. But after they reach a given level of income (in the middle-income category), they have enough resources to prioritize higher resilience. Thus, they reduce the exposure and vulnerability of their infrastructure assets through investments in more rigorous design standards for transport assets and increased flood protection.

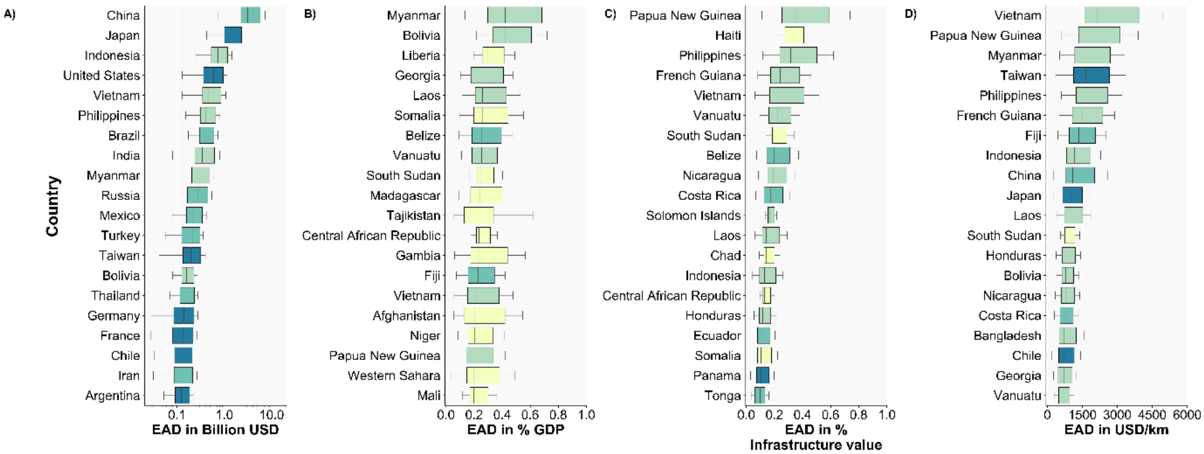
Figure 3: Expected Annual Damages (EAD) per hazard by income group. The upper row of boxplots presents the absolute EAD for each individual hazard and, in the rightmost boxplot, the total multi-hazard EAD. The lower row of boxplots presents the EAD per kilometer of infrastructure for each individual hazard and, in the right-most boxplot, the total multi-hazard EAD per kilometer.



Source: Koks et al. (2019)

At the country level, total damages are highest for countries with large asset totals. But considering EAD in relation to GDP, infrastructure value, or infrastructure length, low and middle-income countries are often more severely affected (Figure 4). In Small Island Developing States, for example, annual damages relative to total infrastructure value are more than double the global average.

Figure 4: Multi-hazard risk per country. Panel A presents the twenty countries that have the highest multi-hazard Expected Annual Damages (EAD) in absolute terms. Panel B presents the twenty countries that have the highest multi-hazard EAD relative to the country's GDP. Panel C presents the twenty countries that have the highest multi-hazard EAD relative to the country's infrastructure value. Panel D presents the twenty countries that have the highest multi-hazard EAD per kilometer of infrastructure in that country.



Source: Koks et al. (2019)

At the global level, expected annual damages are small relative to the budget required for maintaining reliable transport networks (0.2 to 1.5%). However, these results reveal geographical disparities in exposure and risk, with the particular vulnerability of transport infrastructure in Small Island Developing States as an example of this. Countries like Fiji already spend 30% of their government budget every year in maintaining their transport network (The World Bank, 2017); the bill becomes prohibitive when damages from natural hazards are added to this. In other words, for several countries and regions, investing in transport asset resilience should be a priority.

In addition, climate change will intensify the impacts of natural hazards on transport infrastructure. Cervigni et al. (2016) explore the impacts of climate change on transport infrastructure in Sub-Saharan Africa. They find that climate change could increase rehabilitation costs due to river flooding up to 17 times compared to historical values. Additionally, the latent increase of temperatures and precipitation due to climate change could shorten the life-cycle of paved roads and increase by up to 10 times the cost of maintenance and rehabilitation. This same report finds that bridges are the most critical piece of infrastructure in the transport network, and that the additional risk imposed to bridges due to climate change could increase up to 3 times compared to historical values. These results are consistent with other country-level studies, for example in Mozambique, where Kwiatkowski et al. (2019) found that the risk of river flooding to bridges under current conditions amounted to $200 million a year, or 1.5% of Mozambique's GDP. This could increase to up to $400 million by 2050 in the worst-case climate change scenario.

This global analysis cannot capture flood risks at the city level, which are driven by inadequate drainage systems. Urban flooding is covered in detail in the next section.

Urban flooding

Urban flooding is a major cause of transport disruptions in cities across the world, and these disruptions extend well beyond the flood-zone. From Buenos Aires to Dar es Salaam, Amman, Dhaka, and Jakarta – around the world, urban flooding is a frequent and devastating occurrence, especially in developing countries. Yin et al (Cambridge Systematics Institute and Texas Transportation Institute, 2005) integrate numerical pluvial flood modelling, GIS-based road failure analysis and a risk assessment model in the center of Shanghai, China. Their findings indicate drastic impacts, with 37% of road networks being at risk of disruption from a flood event with a 5-year return period. In a 100-year shock, almost half of all roads would be closed due to flooding. Aside from these direct effects, Hilly et al (Ludvigsen and Klæboe, 2014) demonstrate in a case study of the Sukhumvit area in Bangkok, Thailand, how an extreme flood can also cause further disruptions such as the loss of critical services, damages to assets and goods, loss of business and income, and further disturbances to residents.

Inadequate drainage systems are a key driver of floods in many cities across the developing world. The built environment in cities, including roads and buildings, drastically reduces the capacity of the soil to absorb water. Thus, to facilitate the effective outflow of rainfall and prevent pluvial flooding, cities rely on drainage systems. However, in many cities these drainage systems are poorly designed and maintained – and often simply absent.

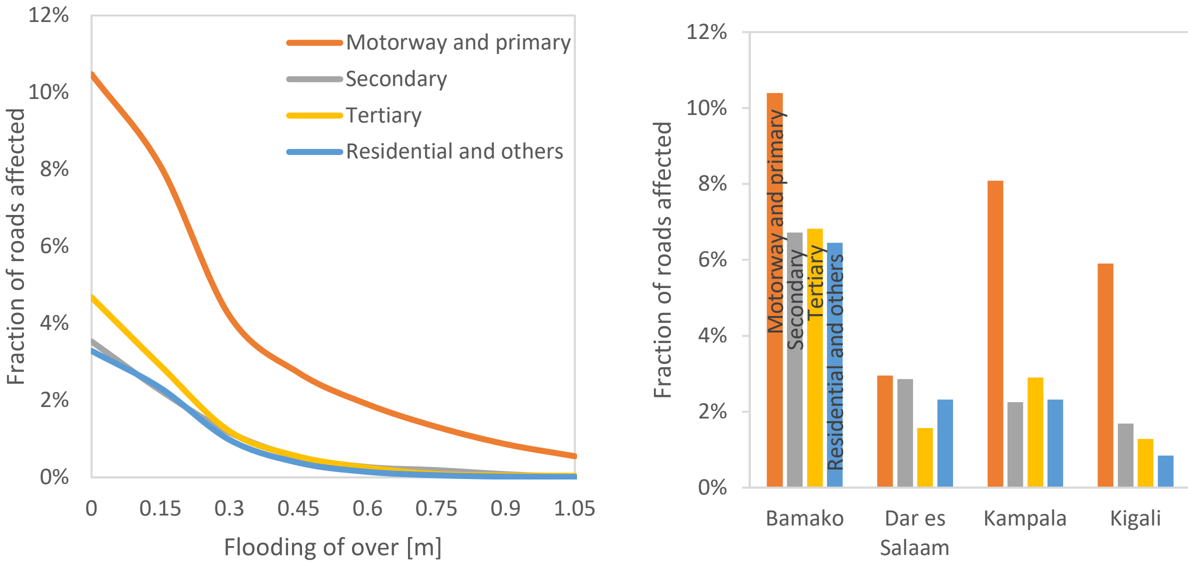
In Inner Kampala, Rentschler et al. (2019a) estimate, about 4% of all roads are affected by a flood with a return period of 50 years (Figure 5). Small residential streets and highways have very different traffic intensities and thus play very different roles in enabling urban connectivity. When distinguishing different road types in Kampala, primary roads (e.g. motorways) can be seen to be disproportionally located in flood zones. In a 50-year flood, about 10% (or 11km) of all primary roads in Inner Kampala are estimated to become flooded. 8% of all primary roads are estimated to be flooded with a depth of greater than 15cm, thus blocking them off for most conventional cars. On the other hand, only 3% (or 45km) of residential roads are directly affected.

The consulting firm ICF (2019) finds that in Dar es Salaam the bus rapid transit (BRT) lanes, the bus depot, and the port access road are highly exposed to flooding by rainfall events with intensities as low as 4– 6 millimeters per hour over a 24-hour period, which currently occur every 2–10 years. Climate change will likely increase the frequency and intensity of rainfall events and thus lead to more frequent flooding. By 2050, all phases of Dar es Salaam's BRT system will be exposed to routine flooding by events on the order of 4–6 millimeters an hour

Considering four African cities, Rentschler et al. (2019a) compare the fraction of different road types flooded by more than 15cm for a 50-year return period (Figure 5, right). As in Kampala, main roads are disproportionally affected by flooding in Bamako and Kigali. The high exposure of main roads suggests that urban floods cause significant indirect effects to the wider urban economy, as they affect the linkages even between non-flooded areas. Indeed, the authors demonstrate that infrastructure disruptions are by no means limited to certain low-income neighborhoods:

infrastructure systems are networks that transmit the disruptions from urban flooding across wide areas.

Figure 5: Left: Fraction of roads affected by flooding in Kampala by road type and flood depth. Right: Fraction of roads in Bamako, Dar es Salaam, Kampala, and Kigali affected by flood depth of over 15cm in an event with 50-year return period.



Source: Rentschler et al. (2019a)

1.2. Indirect costs to households and firms

The economic and social costs of transport disruptions go well beyond direct infrastructure damage. Studies that estimate the economic impact of disasters through transport-economic models that account for the impact of transport interruption on the ability of supply chains to maintain production, conclude that indirect losses as a result of infrastructure failure represent a large share of the total cost of disasters (Cho et al., 2001; Espinet Alegre et al., 2018; Rose and Wei, 2014; Tsuchiya et al., 2007). The next section considers the wider costs of transport disruptions on firms and households.

Unreliable transport infrastructure services have negative impacts on households

As has been shown, transport systems are networks that transmit disruptions across wide areas, affecting the operations of firms, the delivery of services, and the accessibility of jobs. Transport disruptions are costly for households, due to increased travel times, fuel waste, and missed work opportunities. Drivers spent on average 36 hours in gridlock in 2013 in French, British, German and American metropolitan areas (Cebr, 2014). The time lost to congestion increases threefold to 111 hours when additional planning time is included.[1] According to these estimates, congestion

[1] Planning time is the time lost due to uncertainty in travel speed, because drivers have to leave earlier to make sure they arrive on time (here, at least 95 percent of the time).

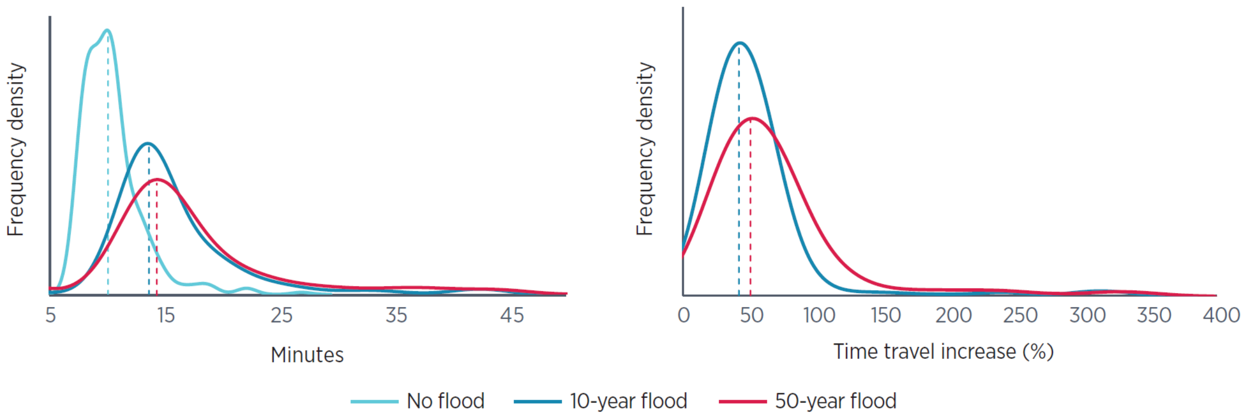
across the UK, Germany and US cost almost $450 billion in 2016, or $971 per capita (INRIX Research, 2018).

In Kampala, urban flooding causes transport disruptions that severely affect people's ability to quickly reach hospitals and health facilities. Based on a network analysis, Rentschler et al. (2019a) estimate that health service providers can be reached from most locations in Inner Kampala within 15 minutes by car. However, in the case of a 10-year flood, disruptions to the road network mean that travel times increase significantly (Figure 6). A common rule of thumb in emergency response states that the survival rate for life-threatening health issues drops significantly after the "golden hour", i.e. 60 minutes after the incident. Road disruptions due to a 10-year flood would mean that about a third of locations in Inner Kampala would no longer be within reach of a health facility within the golden hour: assuming that ambulances are based at hospitals, a one-way travel time of at least 30 minutes would mean that a round trip exceeds the 60-minute threshold.

Figure 6 Floods in Kampala, Uganda, cause transport disruption and congestion

a. Distribution of average travel times from locations across Inner Kampala to health care facilities for different flood scenarios

b. Travel times between 400 firms surveyed in Kampala, by road network disruptions due to urban flooding



Source: (Rentschler et al., 2019a)
Note: Panel a: The vertical line denotes the "golden hour" (the window of time that maximizes survival of a major health event such as a heart attack), assuming that ambulances complete a return trip starting at a hospital. As shown in the graphs, "the return period" (10 years, 50 years) is the estimated average time between events such as earthquakes, floods, or landslides.

When road networks are vulnerable to natural shocks it can have longer term impacts on income and food security. Poverty increased by 18% in Guatemala in the aftermath of tropical storm Agatha, which struck in 2010, mainly because of higher food prices (Baez et al., 2017). The inflation was likely caused by increased friction along the entire food supply chain, including transportation links. Income per capita decreased by 10 percent, driven mostly by a drop in income for urban salaried jobs. The income shock constrained the ability of households to smooth consumption. As a result, affected households cut back on food expenditure by 10 per cent, equivalent to a reduction of over 100 calories per day per household member. Households also reduced expenditure on basic durables, such as stoves or refrigerators. Similarly, in rural areas, transport network failure can have long term impacts on income. As a consequence of the 1998 "flood of the century" in Bangladesh, nonfarm labor suffered long-term wage losses. Households in areas further from centers of economic activity were particularly vulnerable because the flood cut their access to the labor market by disrupting road networks (Mueller and Quisumbing, 2009).

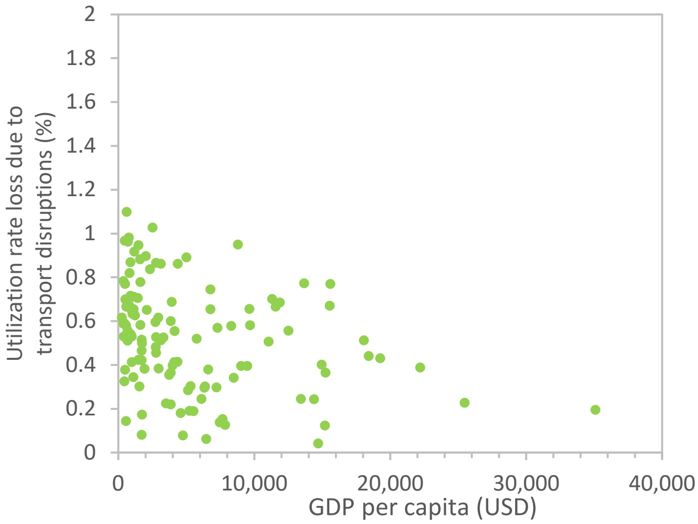
Transport disruptions have a serious impact on firms and supply chains

Frequent disruptions of transport infrastructure often mean that firms are unable to fully utilize their available production capacity. Capacity utilization is a common measure of the effectiveness with which a firm converts its resources into output; a firm that is frequently forced to halt production due to input shortages caused by transport disruptions will be operating below its full capacity, i.e. at relatively lower levels of capacity utilization.

The impacts of transport disruptions were estimated using a pooled dataset of firms from 118 mostly low- and middle-income countries that total about 25% of global GDP. The dataset is based on the World Bank's Enterprise Surveys, which provide harmonized firm-level data on the features of the operating environment experienced by businesses around the world. As part of the survey, firms report transport disruptions using a subjective ordinal scale. Crucially, firms disclose their utilization rates allowing for the isolation of the effect of infrastructure when controlling for a range of other factors.

The results show that most utilization losses are caused by disruptions in transport infrastructure, accounting for losses of $ 107 billion annually. These losses associated with transport amount to 0.42% of sample GDP. In addition, transportation disruptions have a significant impact in all countries (Figure 7). While poorer countries still tend to incur higher utilization losses, these remain significant even for middle-income countries.

Figure 7: Utilization rate losses due to transport disruptions at the country-level. Transport disruptions cause significant utilization losses even in middle income countries.



Source: Rentschler et al. (2019c)

Rentschler et al. (2019a) estimate that a 10-year flood in Kampala, Uganda, increases average travel times between firms by 54%. Many firms are even more severely affected: more than a quarter of firms would face an increase in average travel time of 100 to 350 percent. However, the results also indicate that it does not take an extreme event to significantly disrupt supply chains. While no flood maps exist for more frequent events, these results suggest that even the impacts of high-frequency events could be significant.

In Tanzania, transport disruptions and power outages are among the leading causes of supply chain delays. A survey of over 800 businesses in Tanzania showed that more than 90% of the surveyed firms had experienced delays delivering to their clients in the last 12 months (Rentschler et al., 2019c). More than half of the firms had experienced delays both from suppliers and to their clients. Asked about the most common reason for supply delays, firms reported that that their supplier's own suppliers were delayed –suggesting the second-order pass-on of disruptions along supply chains. The second most common reason for supply delays was transport disruptions. When asked about their own firm's delays in delivering to their clients, the effect of infrastructure disruptions (i.e. combining both power and transport disruptions) caused more delays than any other reason, including disruptions passed on indirectly through the supply chain.

The examples from Kampala and Dar es Salaam suggest that impacts of transport disruptions are particularly significant and long-lasting. These insights also confirm previous assessments of the impact of the Northridge earthquake in 1994 in Los Angeles.[2] Tierney (2002) surveyed small businesses for the reasons they had to close after the earthquake. The most common reason, invoked by 65% of the respondents (several answers were possible), was the need for clean-up. The next most common reasons, with percentages ranging from 59% to 40%, were loss of

[2] See (Hallegatte, 2014; Henriet et al., 2012; Rose and Krausmann, 2013) and (Rinaldi et al., 2001)

electricity, the inability of employees to get to work, and the loss of telephone connections, Similarly, Kadri et al. (2014) asked businesses to assess the earthquake loss due to transportation perturbations, and found that this loss amounted to 39% of total losses. Overall, these results show that the loss of utility services and transport played a key role in driving disaster impacts.

Barker and Santos, (2010) and Ouyang (2014) find comparable results for the Loma Prieta earthquake in San Francisco in 1989: the major problems for small businesses were customer access, employee access, and shipping delays, not structural damages. Utilities (electricity, communication, etc.) caused problems, but only over the short term, since these services were restored rapidly; only transportation issues led to long-lasting consequences. Wender et al (2017) investigate the impact of a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas, and find that even in the absence of other losses, regional gross output could decline by as much as $13 billion at the port region level.

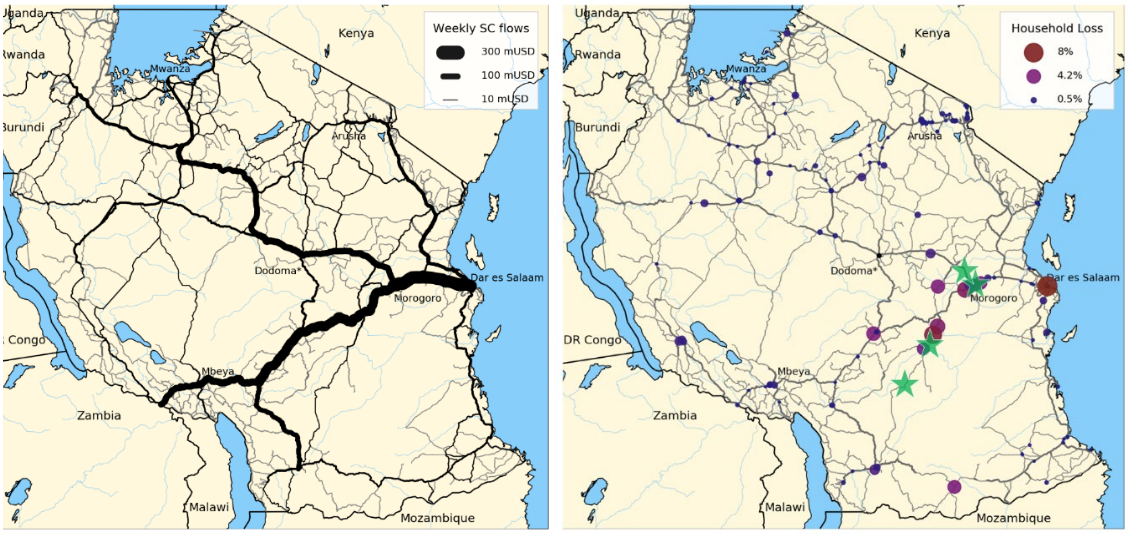
Transportation and logistics, the key enablers of supply chains, are particularly vulnerable. Disasters that disrupt transport infrastructure can destabilize supply chains even without destroying any assets. In 2010, the eruption of the Eyjafjallajökull volcano disrupted air transportation, leading to global supply disruption of low- volume high-value goods, such as electronic components, and of perishable goods such as food or flowers (BBC, 2010). Rose and Wei (2013) investigated the impact of a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas, and found that – even in the absence of other losses – regional gross output could decline by as much as $13 billion. In Tanzania, 22% of firms in a large survey report that transport disruptions are the primary reason for delayed deliveries to their clients (Rentschler et al., 2019c). Transport disruptions are also reported to be the primary cause (for 37% of surveyed firms) of post-disaster sales losses.

Understanding the interactions between supply chains and transport disruptions is key to assessing the resilience of an economy. In a new supply chain model developed for this report, Colon et al. (2019) calibrate an agent-based model for Tanzania that evaluates the impacts of transport disruptions on supply chains and household consumption. The model dynamically maps the domestic and international supply chains of Tanzania onto its transportation network, using subnational and trade data. In addition, firm-level data was collected using a dedicated survey that explores the response and coping measures by firms, including the level of reserve inventories or the number of suppliers.

The data indicates that supply chains connect firms not only across sectors, but also across the country and across borders. Physically, these connections take the form of freight flows on the road network between the main cities (Figure 8 (a)). Flows are particularly significant around Dar es Salaam and its port, which acts as a trade hub for shipments to and from neighboring landlocked countries, including the Democratic Republic of Congo, Zambia, Burundi, Rwanda, and Uganda. In monetary terms, these freight flows account for about 20% of the total volume. Exports and imports by Tanzanian firms also primarily transit through the Dar es Salaam port, accounting for another 20%.

Figure 8 Mapping Tanzania's supply chains onto its transport network (panel a) reveals the impact of transport disruptions on Tanzanian households (panel b)

a. Weekly supply chain flows **b. Impacts of transport disruptions on households**

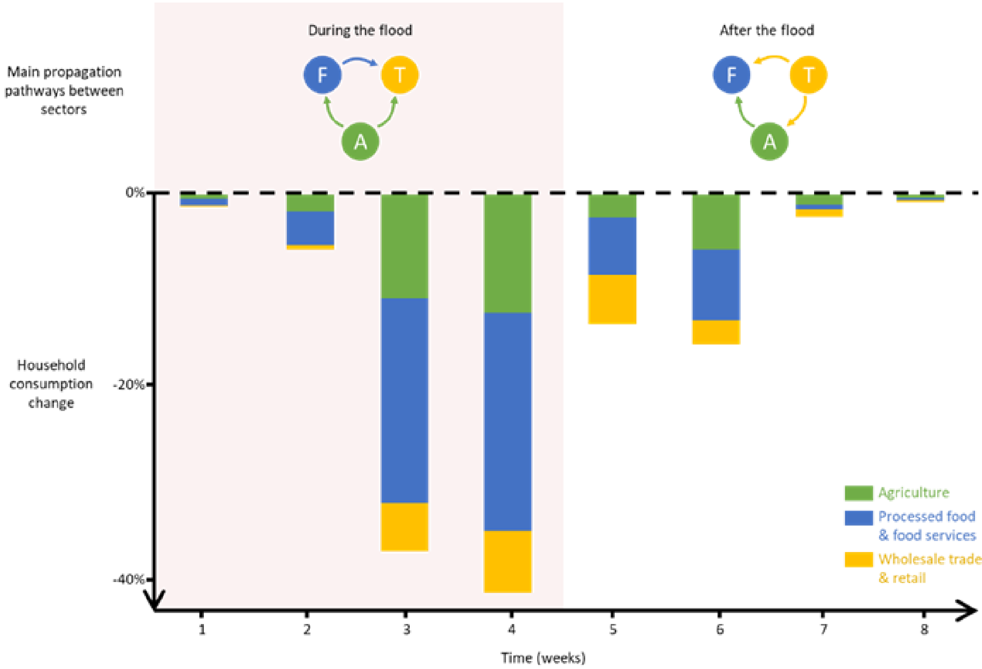


Source: Colon et al. (2019).

Note: Panel a: Weekly supply chain flows are mapped onto the road network. The width of the black lines is proportional to the monetary value of the flow. The widest lines are in the Dar es Salaam region, and amount to $260 million a week. Panel b: Simulation of the indirect impact of the 2016 Morogoro flood. The location of the disrupted roads is indicated by green stars. The size and color of the bubbles represent household losses, shown as a percentage of weekly household consumption.

Floods are frequent in Tanzania, and often render roads impassable, thus triggering disruptions of freight flows and supply chains. One recent event was the flood in Spring 2016 in the Morogoro region, about 200km West of Dar es Salaam. As a result, the road network was severely disrupted in four main areas (Figure 8 (b)). Shipments were rerouted, delayed or blocked, resulting in price increases. Disruptions were long enough – about a month – to induce shortages in several local supply chains. In addition to the direct damages caused by the disaster, households also suffered as local businesses fell short of supplies (see circles in Figure 8 (b)). Due to cascading shortages and costlier transportation, even households in Dar es Salaam, where the flood did not hit, felt the effects of the disaster.

Figure 9. Long-duration floods trigger disruptions in Tanzania, with cascading impacts on supply chains and households



Source: Colon et al. 2019.

Note: The 2016 Morogoro flood triggered disruptions with cascading impacts on supply chains and households. The bar chart shows the time series of household impacts, measured in percentage of weekly consumption that is lost due to shortages. Each bar shows the share of products from Tanzania's three main sectors: agriculture (A), food (F), and wholesale and retail (T). Over the 0% line, the two 3-node graphs show the three main propagation pathways between the three sectors during and after the flood

Overall, the estimated indirect costs on households amount to about 0.5% of annual consumption, mostly due to shortages in three of the largest sectors in Tanzania: agriculture, food (i.e., processed food and food-related services), and the wholesale and retail trade. Figure 9 shows how these impacts evolve through time and ripple across these sectors. First, consumption losses pile up during the flood. Blocked shipments of agricultural products trigger production delays in the food sector, and induce a lack of product availability for wholesalers and retailers. After the flood, losses remain significant for another two weeks. In the flooded area, production recovery in the agricultural and food sectors are slowed down by missing inputs from wholesalers and retailers.

Applying this model allows disasters of different magnitudes and locations to be simulated, revealing useful insights. For example, simulating similar transport disruptions that vary in duration shows that the macroeconomic impact increases in a nonlinear fashion with the duration of the disruptions. A four-week disruption is on average 23 times costlier for households than a two-week disruption. This result highlights the major benefits of a rapid response to disaster and the ability to build back faster. These depend on the systems in place for road network maintenance and the availability of financial resources after a disaster.

Sectors also differ in their vulnerability to transport disruption. For example, because agricultural products are primary products, they are less dependent on suppliers, which reduces their vulnerability. Impacts on food products and manufacturing are, by contrast, magnified by supply chain issues. By applying this model, the most vulnerable firms and municipalities can be assessed, depending not only on their location but also on their economic structure. It is then possible to target interventions to strengthen the resilience of firms and supply chains where it matters the most - which can be far from where disruptions are the most likely to occur.

Such analyses enable assessment of the relative importance of individual segments of infrastructure networks in enabling supply chains, and identification of the most vulnerable users of infrastructure services. By identifying bottlenecks and vulnerability hotspots, they help prioritize investments and develop resilience strategies—the topic of the next section.

2. Solutions for increasing transport network resilience

This second section investigates the reduction of disruption costs through engineering and planning solutions that can help strengthen transport infrastructure. In practice, for these solutions to be effective, resilience must be integral to decision making at different levels:

1. *Resilience of infrastructure assets***.** In the narrowest sense, resilient infrastructure refers to assets such as roads, bridges, and power lines that can withstand external shocks, especially natural hazards. Here, the primary benefit of more resilient infrastructure is a reduction in the lifecycle cost of assets.
2. *Resilience of infrastructure services.* Infrastructure systems are interconnected networks, and the resilience of individual assets is a poor proxy for the resilience of the services provided at the network level. For infrastructure, a systemic approach to resilience is preferable. At this level, the benefit of more resilient infrastructure is the higher reliability of the services it provides.
3. *Resilience of infrastructure users.* Ultimately, the resilience of users is what really matters. Infrastructure disruptions can be catastophic or more benign, depending on whether users—including people and supply chains—can cope with them. At this level, the major benefit of more resilient infrastructure is a reduction in the total impact of natural hazards on people and economies.

Resilience is one of the many determinants of high-quality infrastructure. Integrating resilience in the design and implemenation of infrastructure investments not only helps manage natural shocks but also complements the cost-effectiveness, efficiency, and quality of infrastructure services more generally.

2.1. More resilient transport infrastructure assets tend to be more expensive, but often not by much

The additional cost of making assets stronger in the face of natural hazards depends on the hazard and the type of assets. Increasing the flood resilience of a railway by elevating it, for example, costs fifty percent of its value (Miyamoto, 2019). For new roads, it is estimated that upgrading the drainage system or providing barriers -- to increase the design standard or approximately halve the expected damages -- costs about 2% more in capital expenditures (Miyamoto, 2019). However, for some existing paved roads, increasing standards would mean re-building road sections almost entirely to replace culverts and drains. It would thus not usually make sense to upgrade the standard until the road requires major rehabilitation. For rural roads, on the other hand, cheaper adjustments can be made to existing roads by digging trenches on the side, also for about 2% of the road cost. For bridges, foundations can be protected against erosion and scour caused by floods for 1% of the bridge capital value (Miyamoto, 2019). Modern design practice can ensure resistance to wind damage in all but the severest of cyclones.

Some resilience-building interventions can even lower the cost of the assets. Advances in construction technology mean some low-cost technologies perform better than traditional approaches, with advanced materials and methods making for infrastructure that is both less expensive and more climate-resilient. One example is the use of modular bridge solutions that encase the deck structure of the bridge in stainless steel. This approach results in a significantly longer design life of up to 100 years with associated lower maintenance costs, a performance well beyond that which can be achieved at a reasonable cost with traditional in-situ reinforced concrete. Construction costs are also lower because standardized formwork (including reinforcing) can be delivered to the site in a container, with deck casting done in a single pour, as opposed to the longer times and complex formwork needed for traditional in-situ structures (Cordeiro et al. 2017).

Quality control is a crucial component of the incremental cost of resilience. The improved quality control necessary to ensure that the asset is actually built up to standard – and maintained to standard – is required to make infrastructure assets able to cope with increased intensity of natural hazards. Miyamoto (2019) estimates that this quality control costs from one to five percent of the asset value for most assets and hazards but can cost up to fifteen percent to highway systems can cope with flooding.

The total cost of more resilient assets depends on the ability to spatially target strengthening

How much would it cost to ensure future transport systems are more resilient to natural hazards? Rozenberg and Fay (2019) estimate how much low- and middle-income countries need to spend on infrastructure to achieve their development goals, and find that estimates vary widely depending on country's objectives (in terms of service provision) and their spending efficiency. This section explores how much these estimates would change if infrastructure systems were designed and built in a more resilient manner.

Given the sometimes high incremental costs of increasing their resilience, it is important to target strengthening of assets where exposure to natural disasters is significant. Ideally, infrastructure standards and codes should be asset- and localization-specific. Designing a road for a given return period requires historical hydrological and hydraulic data on the location of the road, and it also requires looking at the range of impacts that climate change can have on the probability of flood events in the future.

We explore two extreme possibilities in terms of knowledge on the spatial distribution of the hazards, and the ability to target strengthening in the places that are exposed. In one case, it is assumed that the hazard is perfectly known, now and in the future, and different standards can be applied in different locations, depending on the level of risk. In the other extreme, it is assumed that the hazard is unknown or too uncertain to be acted upon, and that a uniform standard has to be applied to the full network. In both scenarios, we assume that future infrastructure assets are exposed similarly as existing infrastructure on average in each region, so that the only option is to strengthen the exposed assets.

In the transport sector, estimated baseline investment needs – with current resilience standards – range from $157 billion to $1.1 trillion every year between now and 2030. The exact value depends on mode choice (e.g., individual cars vs. public transit in cities) and on the policies in place to incentivize a mode switch towards rail and public transportation. In addition, $550 billion to $700 billion will be needed every year for maintaining existing and new transport infrastructure in low- and middle-income countries by 2030, bringing the total spending needs to between $700 billion to $1.8 trillion (Rozenberg and Fay, 2019). How would those costs need to increase to make transport systems more resilient?

- If all new transport assets were to be made more resilient to floods and landslides regardless of their exposure, the incremental cost would range from $8 billion to $350 billion per year depending on mobility demand and mode choices (flood proofing rail is much more expensive than it is for roads). This is a 5.5 percent increase in cost on average across scenarios, but potentially a 17 percent increase in the most expensive scenario, with many rail investments. Considering only the cost of repairs after disaster as benefits of upgrades, Koks et al (2019) estimate that the benefit-cost ratio of strengthening all transport infrastructure is below one, suggesting that in the absence of hazard data, it is not cost-effective to strengthen transport systems.
- In comparison, the incremental cost of making new transport assets more resilient to floods and landslides only if they are exposed to high intensity events is only between $860 million and $35 billion, again depending on mode choice. These investments would reduce damage risk by two for new infrastructure. This is a 0.6 percent increase in cost on average across scenarios, and potentially a 5 percent increase in the most expensive scenario.

There is thus high value in knowing the spatial distribution of natural hazards, including those caused by climate change. The savings from the ability of governments and institutions to target the most-exposed infrastructure assets for strengthening appear to be orders of magnitude larger than the cost of the data collection and modeling that would be required to improve knowledge of current and future hazards. Indeed, a global platform like ThinkHazard!, which compiled most of the hazard data that was used for the risk assessments presented earlier, costs a few million dollars to create and maintain. At most, creating high-resolution digital elevation models and hazard maps for all cities in low- and middle-income countries would cost a few hundred million dollars (Croneborg et al. 2015).

However, the benefits of risk data and models will be realized only if the data is available and affordable; this requires a push to make data and models more open and accessible, with due attention to issues related to privacy and security. Remote sensing using satellites and drones, and advances in computing, have made it easier and cheaper to monitor and model environmental conditions and hazards, and to map the exposure and vulnerability of infrastructure and other assets. But these new tools cannot fully replace the networks of well-maintained weather stations and data processing that are still missing in many low-income countries (Rogers and Tsirkunov, 2013).

In the use of these data and model results, it is critical to take into account the deep uncertainty that surrounds current and future risks and makes it impossible to design "optimal" systems or assets. An alternative is to look for a robust decision -- one that performs well across a wide range of futures, preferences, and worldviews, though it may not be optimal in any particular one. Robust strategies can be identified through systematic stress-testing of possible options to ensure that the residual vulnerabilities of an infrastructure system are acceptable and can be managed (see Espinet Alegre et al., (2018); and Rozenberg et al. (2017) for examples).

In conclusion, the cost of building the resilience of transport infrastructure assets in low- and middle-income countries is small compared to total infrastructure needs, provided that the right data and approaches are available. Increasing the resilience of only the assets exposed to hazards would increase investment needs in transport between $860 million and $35 billion. While not negligible, this is less than 0.05 percent of the GDP of most low- and middle-income countries. Therefore, making transport infrastructure more resilient does not affect the current affordability challenges for new infrastructure, and it would decrease damage risk for new infrastructure by a factor of between two and three.

Increasing the resilience of transport assets is cost-effective

Despite the difficulties, it is interesting to get a sense of the potential benefit-cost ratio of upgrading existing roads to reduce the risk of flood damage. To do so, a cost-benefit analysis (CBA) is performed on each road segment. The CBA estimates the benefit-cost ratio (BCR) of upgrading the road by spending 2% of the road's value on barriers and better drainage. For roads that are not exposed to any hazard, such an investment does not have any benefit and thus has negative returns. For roads that are exposed to floods, it is assumed that this 2% cost increase allows a doubling of the standard of the roads, expressed in return period (i.e. the road can withstand a flood with a 1/100 return period instead of a flood with 1/50 return period).

It is found such an improvement only has a BCR higher than 1 for 4.5% of all kilometers of roads. This is not surprising, given that only 7.5% of all roads are exposed to at least one flood event with a 1/100 year return period.

However, results show a BCR higher than 1 for around 60% of all kilometers of exposed roads (to at least one flood event with a 1/100 year return period). Improving design standards of exposed primary and secondary roads in upper middle-income countries to better cope with surface flooding is beneficial for 85% of these roads, with an average BCR of 6. These results highlight the value of keeping hazard information for the upgrading of roads, which makes it possible to target improvements on exposed roads only. In the absence of any hazard information, upgrading all roads by spending 2% of their value would be very cost inefficient.

These results are consistent with local analyses. In a study in rural Mozambique, Espinet Alegre et al. (2018) assess the cost and benefits of multiple road interventions in a region with high flood risk, and find that strengthening culverts and bridges can yield benefits in avoided flood damages six times higher than the more traditional benefits of these investments (decreased maintenance costs and reduced road user cost). When roads are exposed to flooding, strengthening them is cost-efficient even without considering the full consequences of disruptions on users.

It is important to emphasize that in this study, the focus is on only the direct asset damages. When network disruptions and the wider economic impacts are included, total avoided losses are expected to increase, making investments in adaptation potentially more beneficial in more places. When users are taken into account, the benefits of resilience investments quickly balloon. In a study in Ethiopia on rural roads, it was estimated that an additional expense of 5 percent of the road value would generate a return of four times the cost as early as the first year, as the investment was designed to support water management strategies and increase the productivity of local farmers (Van Steenbergen et al., 2019).

Even if more resilient transport assets pay for themselves in many cases, public and private decision-makers often do not have incentives to implement the most cost-effective options.

Governments have to build a consistent system of regulations to set a minimum standard for resilience, and the financial incentives to make infrastructure service providers go "beyond the code" when it is cost-effective and possible. The most widely-applied solution is for the government to enforce a minimum level of resilience that is expected from public or private infrastructure providers, and to apply it either through its procurement rules, its market regulations, or through a contractual engagement in Public-Private Partnerships. And with climate change, it is critical that standards are revised regularly and designed for the local context taking local construction practices and climate into account.

Good maintenance of assets is fundamental to reliable and resilient transport systems

Generally, improved maintenance of assets is a good resilience investment. Cordeiro et al. (2017) find that improved road maintenance could reduce asset losses by 12 percent in Belize and 18 percent in Tonga. Better maintenance is also a way of reducing the overall lifecycle cost of infrastructure, with $1 in maintenance leading to $1.5 savings in new investment needs (Kornejew et al., 2019). Rozenberg and Fay (2019) also find that without good maintenance, infrastructure capital costs could increase fifty percent in the transport sector by 2030.

To provide the maintenance necessary for a reliable transport network, transport asset management systems are an important starting point. They include all strategic, financial, and technical aspects related to the management of infrastructure assets across their lifecycle. The objective of these systems is to move towards an evidence-based and preventive maintenance schedule, and to move away from a reactive approach to maintenance. Most asset management systems, however, do not include a resilience component. Thus, they would need to be upgraded to include information on hazard exposure and vulnerability, and it would need to be ensured that this information is updated over time, taking the effects of climate change into consideration. A good example of this can be found in Dominica, where a sustainable risk-based asset management system (AMS) was developed in a project for the Dominica Ministry of Public Works and Ports (MoPWP)'s roadway infrastructure. The AMS identifies optimal investment strategies to reduce the roadway's risk and vulnerability to hazards, and to maintain its functionality performance at an acceptable level (Cordeiro et al., 2017).

Financing of maintenance is also critical, and needs to be ensured through appropriate budgets for infrastructure agencies and dedicated instruments. For example, Performance-Based Contracts (PBCs) can be used to improve the management and maintenance of infrastructure assets. PBCs are widely used to contract the maintenance of transport infrastructure, especially roads (Iimi and Gericke, 2017; Lancelot, 2010). They explicitly link payment to the performance of assets, providing a powerful incentive for the contractor maintaining or operating an asset to ensure that its resilience is taken into account in all decisions. However, incorporating natural disaster and climate change considerations into performance-based contracting (PBC) efforts is challenging (Henning, Hughes, and Faiz 2018). If too much risk is shifted to the contractor, costs may increase, and the performance may be compromised, which places the PBC at risk of failure; if too much risk remains with the owner, the PBC will not result in the expected savings or improved efficiencies.

2.2. From more resilient assets to more resilient networks and services

The resilience of infrastructure assets is only a small part of the challenge related to resilient infrastructure. Since the cost of disruptions exceeds the repair costs by a substantial margin, a better approach is to look at infrastructure *services*. For networked infrastructure, looking at services means taking a systemic-view -- considering the resilience of the full system.

Criticality analysis: investing where it matters

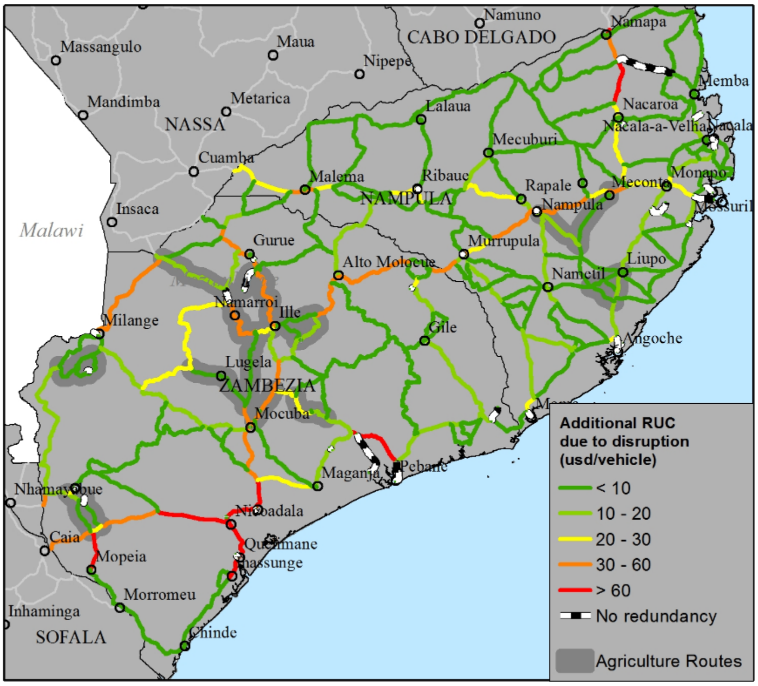
Not all assets need to be made resilient to all hazards. Countries can increase the resilience of their networks and users at very limited cost by prioritizing incremental costs on the assets that are *critical* to users or the functioning on their economic system. For example, the U.S. government defines critical infrastructure as "the assets, systems, and networks, whether physical or virtual, so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, public health or safety, or any combination thereof." The OECD (2019) defines critical infrastructure as "systems, assets, facilities and networks that provide essential services for the functioning of the economy and the well-being of the population." Criticality analysis can identify the most important transport infrastructure assets and their vulnerability, but also the possible failure cascades from systemic effects, or even across-system interdependencies.

Once critical assets are identified, governments need to define a shared vision of the levels of risk that are considered acceptable or intolerable. For example, major transport infrastructure – such as large bridges or tunnels – cannot fail and collapse when affected by storms or moderate earthquakes, because the human and economic impact would be unacceptable. Major highways cannot close several times a year due to local flooding, because the frequency of the disruptions would have a significant economic impact.

A simple approach is to assign a level of criticality to assets based on the quantity of service they provide (i.e. their capacity). For example, construction standards are often higher for primary roads like highways and freeways than for tertiary roads that have much lower traffic volumes. While this may be a useful first scan for criticality, it is limited in that it does not include information on the type of service that the asset provides (i.e. a freeway that provides access to a leisure area is less critical than one that leads to the main port or hospital), or the role that the asset plays in the overall network functionality.

Criticality can also be assessed by systematically simulating disruptions in a network, and estimating the resulting functionality loss (see Briceño-Garmendia et al., (2015) for a literature review on criticality and resilience in transport networks, and Box 1 for a discussion of networks). Links and nodes can be removed one by one or several at a time, and the network functionality (e.g. for transport, travel time and cost) is recalculated in the absence of these elements. This approach allows identification of the most critical links as the ones that lead to the highest loss of functionality when they are removed (Figure 10).

Figure 10. Criticality of links measured as the additional road user cost resulting from the disruption of the link, in Zambezia province, Mozambique.



Source: Espinet Alegre et al. (2018)

Box 1. Networks, resilience and criticality

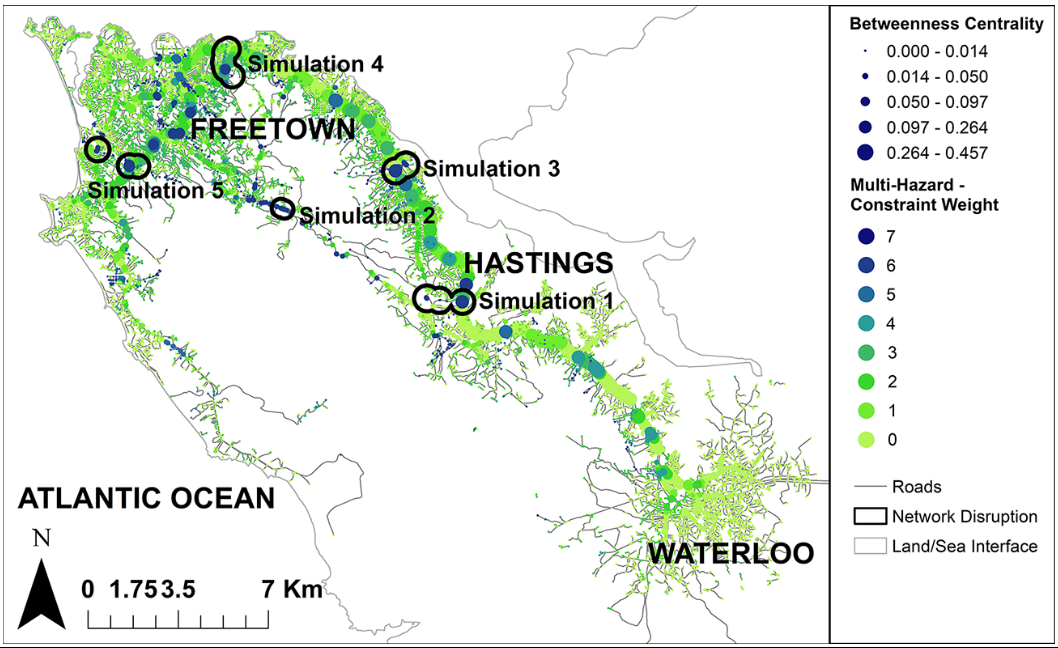
Infrastructure systems can be represented by an abstract network of nodes and connecting links. A network establishes and maintains connectivity between a set of interacting nodes to facilitate a flow between them. A flow is the movement of people, goods, material, energy, and services across the system. The vulnerability of the system, thus, can be linked to the network connectivity that guarantees an available and functional path between intended origin-destination (O-D) pairs. Here, vulnerability describes the system loss of functionality from the original, or pre-event, conditions. A loss of functionality can be a partial or complete loss of access to and from parts of the network.

The shape of a network determines its coping capacity. Since an infrastructure system network shape is static in practice (e.g., a new road cannot be built in an instant), the network topological attributes are viable indications of its coping capacity against disruptive events. Overall, networks with a higher number of interconnection paths between O-D pairs have a greater redundancy, which generally translates into higher accessibility and lower probability of node isolation. Therefore, connectivity and accessibility measures from graph theory can be directly employed to gage the system's coping capacity. See (Briceño-Garmendia et al., 2015) for a full discussion on the links between accessibility, redundancy and resilience.

Typical network topology measures can be grouped in connectivity and accessibility. Connectivity measures describe basic network characteristics such as the ratio of links to nodes, or the maximum possible number of links. Accessibility measures describe the best possible flow conditions. One such measure, for example, is network diameter, defined as the maximum distance between all shortest distances between all O-D pairs in the network. Accessibility measures can also be used to identify potential critical nodes (or links) in the network. For example, we can expect that a node crossed by many of the shortest paths in the network (the node with largest betweenness centrality[3]) would have higher impact in maintaining the flow. Accessibility measures are usually defined for each node, or link, and information on distribution of the measure (or summary statistics, like maximum or median of all nodes) can be used to characterize the network. These measures are focused primarily on what networks are capable of inherently, and are not necessarily representative of real flow. Transport network users, for example, might not always choose the shortest or the cheapest path.

A combination of these connectivity and accessibility metrics can describe the overall network capability to cope with disruptions by providing rough estimate of network functionality loss. Nelson et al. (2019) used this approach to identify the criticality and resilience of Freetown's urban road network to natural hazards, including sea-level rise, floods, and landslides, and estimated the network functionally loss as the change in betweenness centrality. The analysis supported the government of Sierra Leone to identify and prioritize climate resilient interventions in the city road network.

Figure 11: Road disruption simulations based on high risk node eliminations – Western Area, Sierra Leone

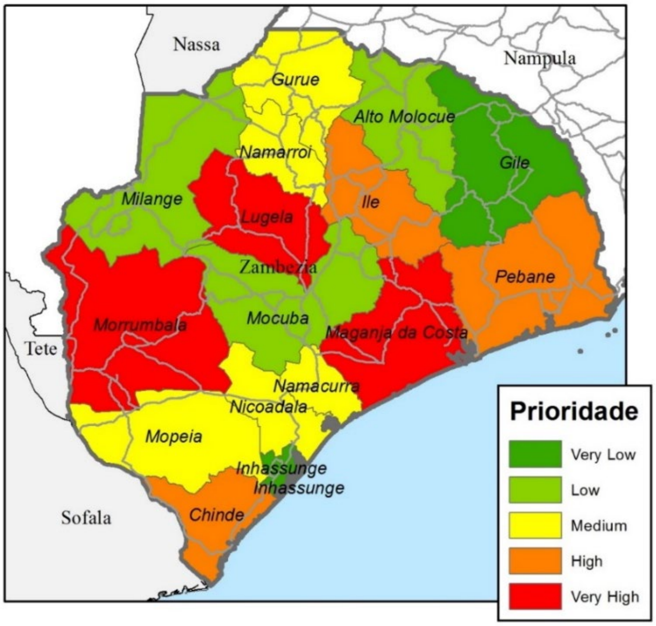


Espinet Alegre et al. (2018) prioritize interventions in the rural road network in Mozambique based on a combination of criticality and risk to the infrastructure (i.e. expected annual damages

[3] Betweenness centrality is an indicator of a node's centrality in a network. It is equal to the number of shortest paths from all OD pairs that pass through that node.

based on hazards and vulnerability) (Figure 12). In this case, criticality is defined as a combination of variables: (i) poverty in the province served by the road; (ii) agriculture potential in the province served by the road; and (iii) loss of functionality if the road is removed.

Figure 12. Priority for infrastructure asset strengthening depends on risk level and criticality.



		Risk to the infrastructure				
		1	2	3	4	5
Criticality	1	1	1	1	1	2
	2	1	2	2	2	3
	3	2	2	3	3	4
	4	3	3	4	4	5
	5	3	4	4	5	5

Source: Espinet Alegre et al., 2018

Networks should also be stress-tested against realistic shocks that include multiple simultaneous disruptions (n-p), not only against shocks to a single component. For instance, Kwakkel et al. (2019) test the vulnerability of the Bangladeshi transport network to past flood events, to maintain the spatial correlation of disruptions, and find that the impact of disruptions on freight demand – and the best solutions for increasing the resilience of the network – depend mostly on the event that is used for simulating the disruptions. If data on the full distribution of possible events are not available, it might be more effective to invest in improvements that will improve the resilience of the network to a wide range of random events.

Figure 13 Belgium and Madagascar road networks illustrate the variety of network configurations.

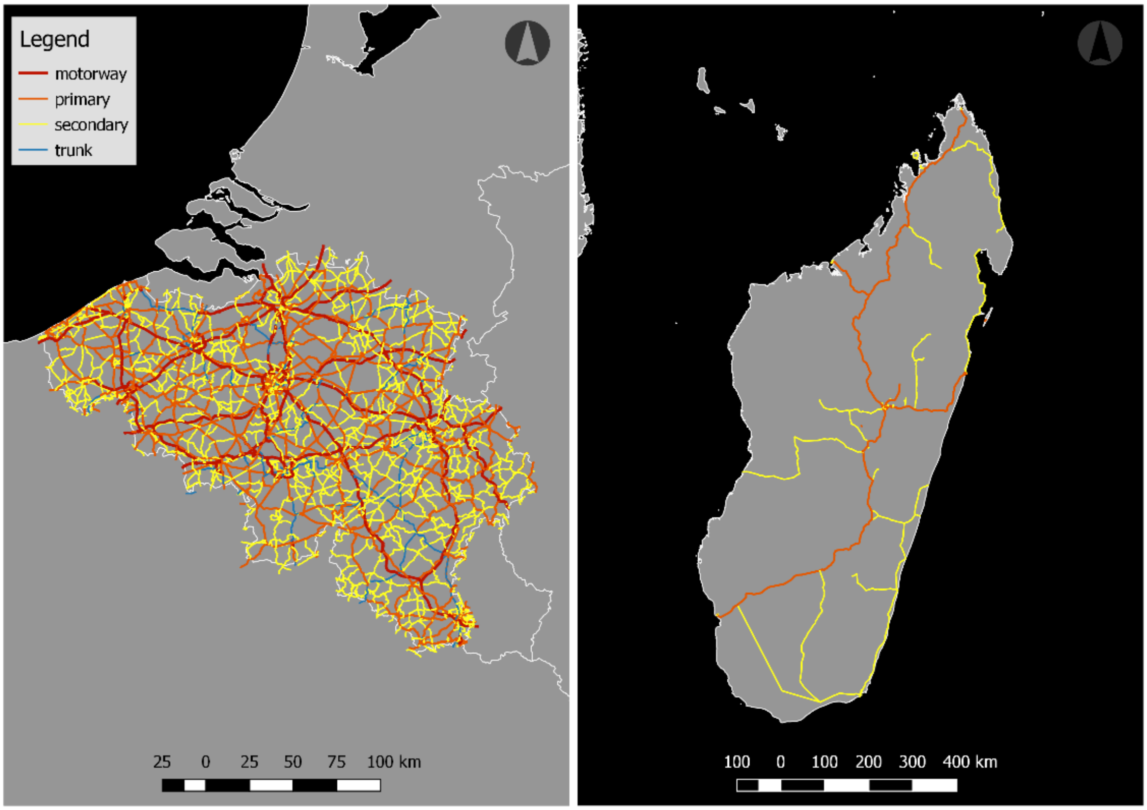
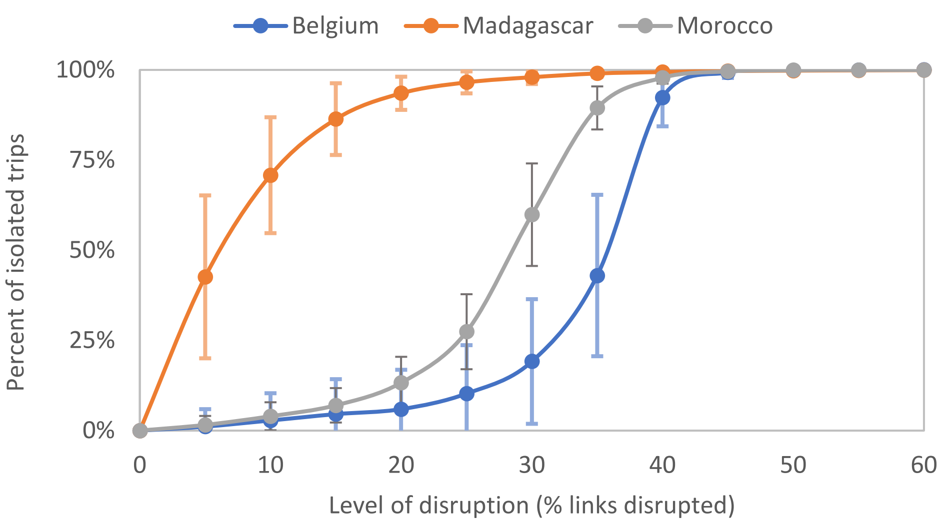


Figure 14 Examples of functionality loss (isolated trips) as a function of the percentage of links disrupted in the Belgium, Morocco and Madagascar transport networks



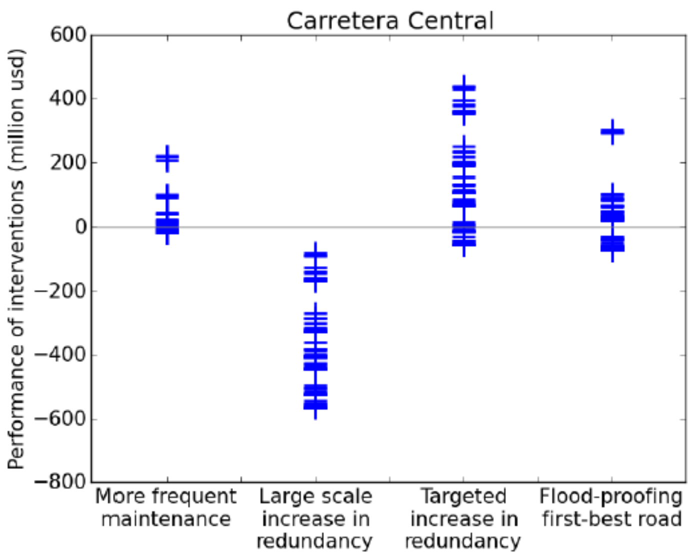
These approaches make it possible to measure *the resilience of a network*, defined as the ratio of the loss of functionality to the loss of asset. A high resilience transport network can lose many assets (e.g., road segments) without losing much functionality. Figure 14 represents the functionality loss (expressed as isolated trips, that can no longer reach their destination) resulting from the disruption of random transport links, as a function of the percentage of links disrupted. Because of its redundancy, the Belgium transport network (left) displays much more resilience than the Madagascar network (right). For low levels of disruption (below 20% of links), functionality losses are negligible in most cases in Belgium, while in Madagascar they quickly rise up to 80%. This is because the Madagascar network has much less redundancy, and a disruption of critical roads can paralyze the whole network. This type of analysis provides much more information than static network metrics, as they allow identification of the extreme cases in which even a small number of disrupted links can lead to high functionality loss.

The resilience of the transport network and the criticality of individual assets provide useful information for prioritizing interventions. While industrialized countries may focus on their current infrastructure stock and its vulnerability, developing countries can use similar methods to identify *critical gaps* in their infrastructure systems. For example, Kwakkel et al. (2019) used a criticality analysis and simulation model to identify which new bridges can increase redundancy, and do the most to increase the resilience, of the transport network in Bangladesh.

In Fiji, a criticality analysis of roads and bridges was carried out as part of the Fiji Climate Vulnerability Assessment (Government of Fiji and World Bank, 2017). The analysis identified about twenty structures (including bridges, crossings and culverts) that need to be strengthened, and that together could reduce future transport service loss 22 percent, with a rate of return of 25 percent (Cordeiro et al., 2017).

Accounting for user losses associated with disruptions through network effects can justify redundant investments that would otherwise offer smaller direct benefits. Espinet Alegre et al. (2018) used a transport network model to assess the benefits of transport investments in rural Mozambique. They found that in provinces with high flood risk and low redundancy, the direct benefits of investments in new culverts and stronger bridges were relatively small given the low traffic volumes on these roads; however, the indirect benefits expressed in reduced expected annual road user costs due to flood disruptions were four times higher and largely justified the investments under most scenarios considered. Similar results were found in Peru, where Rozenberg et al. (2017) showed that targeted investments to increase the redundancy of the road network around the Carretera Central, a strategic export route for agricultural products, could be justified on the sole basis of avoiding expected annual user losses due to flood and landslide disruptions (Figure 15).

Figure 15 Economic performance of different interventions over 30 years, for different scenarios. The economic performance does not include traditional benefits of interventions in terms of reduced road user cost all year long.



Source: Rozenberg et al. (2017)

Redundancy can also be achieved through multi-modal transport planning. Urban planning, for example, can include non-motorized modes such as walking and cycling, and mass transit. If transport planning is accompanied by policies that incentivize higher urban density, this mode diversification can reduce traffic density and the need to build an increasingly large number of roads, thereby reducing obstacles to flood flow, and mitigating floods. In addition, by reducing the need to build more roads, urban planning can reduce the scale of the exposure and vulnerability of the transport sector to disasters. These alternative modes can also provide resilient forms of transport during an emergency (World Bank 2015).

Work with nature and across systems

Working with nature can help lower costs for the transport system. Roads are particularly vulnerable to landslides, and different forest management practices can have large implications for landslide susceptibility. For example, according to Dhakal and Sidle (2003), partial cutting produces fewer landslides, and reduced landslide volume by a factor of 1.5 compared to clearcutting.

Roads have a major impact on hydrology, by blocking and guiding water, concentrating runoff, interfering with subsurface flows, and changing flooding patterns. However, there is a beneficial connection between road planning and building, and water management. Water is considered the prime enemy of road infrastructure, and the single greatest factor in road damage. Therefore, there is a strong case for road-asset management to better manage water around roads, and to see roads as an integral part of the watershed and landscape in which they are situated. Such an integrated approach will preserve road infrastructure and reduce the maintenance burden, contributing to greater infrastructure productivity, while helping improve water supply and provide flood protection. Van Steenbergen et al (2019) describe how the negative impact of roads on the surrounding landscape can be turned around, and how roads can become instruments of beneficial water management. For example, in arid areas, the water intercepted by road bodies can be guided to recharge areas or surface storages or applied directly on the land. In floodplains and coastal areas, roads play a role in flood protection, doubling as embankments and providing evacuation routes and flood shelters. In low-lying wetland areas and floodplains, roads and bridges affect the shallow groundwater tables, and have enormous consequences for land productivity. The way in which a road is built, and the height of bridge sills and culverts, for example, will have considerable influence on the quality of the wetland on either side of the road (Van Steenbergen et al., 2019).

Fail gracefully and recover fast

No infrastructure asset or system can be designed to cope with all possible hazards, and there is a large area of uncertainty around the probability and intensity of the most extreme events.

As a result, transport systems need to be stress-tested against events that go beyond the likely. The goal of such stress-tests is to understand the consequences of an unexpected failure to prepare for the required response, both in terms of the management of infrastructure systems (e.g., how to recover from a major failure?) and in terms of support to the users (e.g., how to minimize impacts on hospitals?). Running scenarios of failures is the first and most critical step in the definition of contingency plans, which also include traffic management, coordination with other actors (in particular health centers, power, water and communication utilities). For a discussion on contingency plans in the transport sector, see Benavidez and Mortlock (2018).

Criticality analysis can also be used to identify which transport links need to be restored first during emergencies, either because they serve hospitals or because they maintain a connection to the rest of world. This is particularly important for countries dependent on energy imports, and for small countries that cannot afford all the equipment and specialized staff that are needed after a major disaster. A telling example is that of the 2011 earthquake in Haiti , which was completely isolated after the damage to all the major components of the transportation infrastructure – the seaport, Port-au-Prince airport, and the road connecting Port-au-Prince to the Dominican Republic (Holguín-Veras et al., 2012). Rapid interventions to reopen these infrastructures were required to allow the aid to enter the country.

Figure 16 A new low level bridge in Port Vila, Efate, Vanuatu was judged preferable by users than the previous, higher bridge.

Source: AFD

Finally, it is sometimes better to plan for regular but manageable failure than to suffer from unplanned catastrophic failure. In Vanuatu, the French development agency led a scenario exercise for the reconstruction of bridges on Efate Island after cyclone Dani. In a participatory process, users decided they would prefer it if bridges were replaced by low-level bridges or fording, instead of being rebuilt as before (Figure 16). The rationale was that it was better for them to be predictably disconnected for a few days every year than to be disconnected for several weeks or months if the bridge was to be destroyed by a major, unlikely event like a cyclone. This is particularly true for farmers who risk losing the totality of their production if the connection is disrupted for more than a few days. This example demonstrates the importance of bringing in users when planning for infrastructure resilience.

2.3. From more resilient infrastructure services to more resilient users

This paper has shown how transport networks could be made more resilient by employing a combination of interventions in assets (strengthening) and in networks (redundancy, working across systems). These strategies offer the benefit of a reduction in the lifecycle cost of assets and more reliable services. Ultimately, though, what matters is not the resilience of the infrastructure service supply, but that of the end users. After all, transport disruptions can be catastrophic or more benign, depending on whether users—including people and supply chains—can cope with them. At this level, the benefit of more resilient infrastructure is a reduction in the total impact of natural hazards on people and economies.

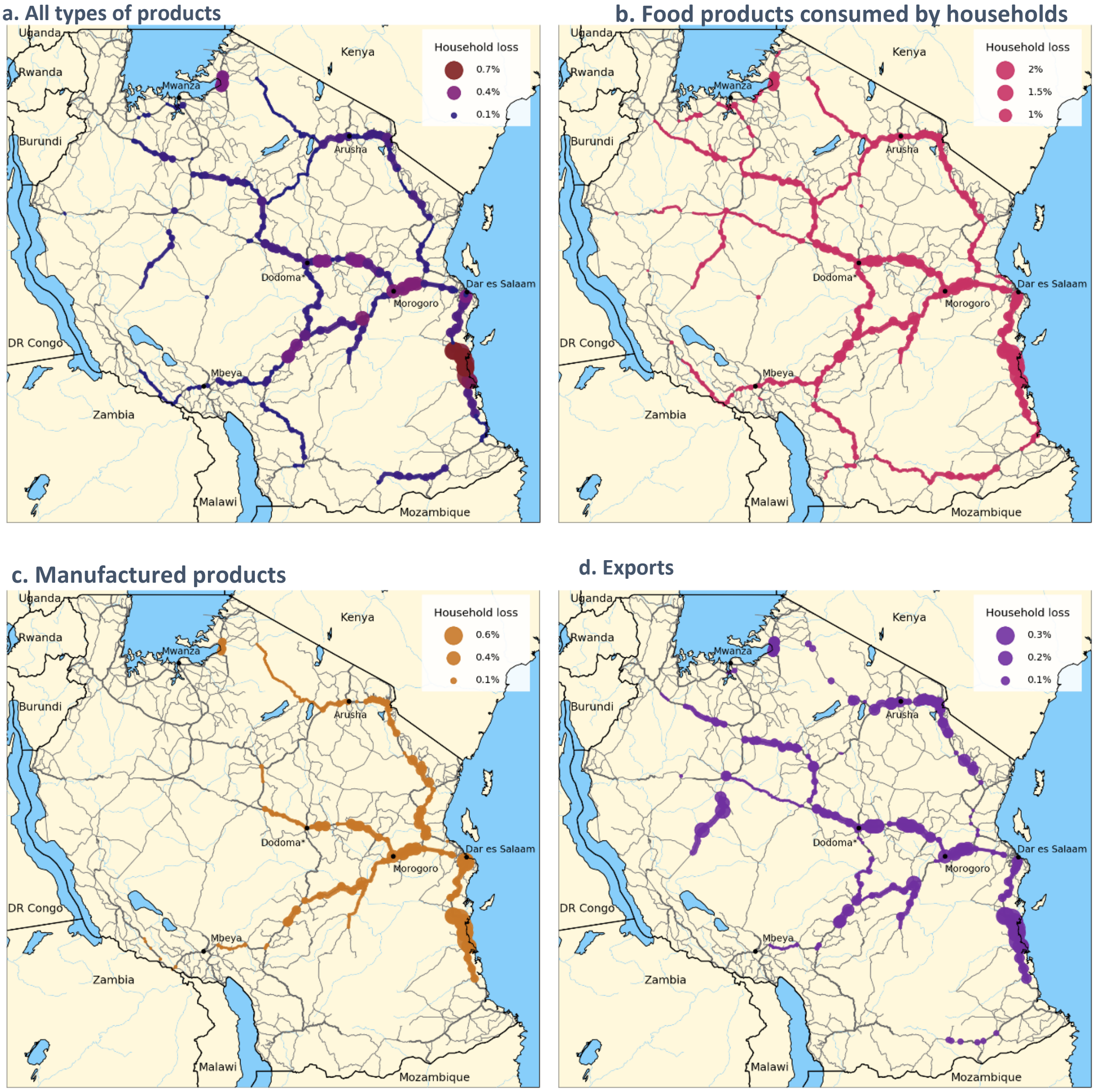
Criticality depends on the end-user: some assets are critical for food security; others for competitiveness

To better target where to invest and what part of the network to strengthen, criticality analysis needs to take into account how infrastructure assets are used, considering the resilience of users and supply chains. The criticality of the transport infrastructure system offers only a partial view of the importance of each infrastructure asset. To better measure the importance of a bridge, one has to consider who is using it. A road or a bridge that is used by an on-demand supply chain with no inventory (e.g. for fresh food) cannot tolerate short disruptions, while industries with large inventories only care about long disruptions.

To investigate how criticality depends on user and supply chains, Colon et al. (2019) combined a transport and a supply chain model to investigate the criticality of the transport network in Tanzania. As expected, the most critical road segments are defined by the types of products that are considered. Figure 17 shows how the most critical assets of the Tanzanian transport network using four different measures, considering four different users or supply chains. Figure 17a shows the critical segments for the economy as a whole. Figure 17b shows the same thing, but for food supply chains only. These are of high interest for food security issues, and highlight different priorities for strengthening the network. Figure 17c looks at impacts on the manufacturing sector, and Figure 17d at the impact on exports, which is important for trade competitiveness and the profitability of the port.

Comparing these maps shows that investment priorities depend on policy objectives. For example, segments of the T7 costal trunk road located about 200 km south of Dar-es-Salaam are critical for food security but rather irrelevant for international trade. For the latter purpose, improving the T3 road east of Morogoro is a priority. This segment carries very large freight flows between the Dar es Salaam port and landlocked countries such as the Democratic Republic of Congo and Zambia.

Figure 17. The criticality of a road depends on how it is used by various users and supply chains. Example with Tanzania.



Source: Colon, Hallegatte, and Rozenberg (2019)
Note: In all four panels, the width of the line overlaying a given road is proportional to the impacts that a one-week disruption of the road would trigger. Impacts are measured in percentage of daily consumption. They represent exceptional expenditures due to costlier transportation and missed consumption due to shortages. Panels a., b., and c. depict the products used by Tanzanian households. In panel d., the impacts are the exceptional expenditures and missed purchases from international buyers. They specifically relate to exports and transit flows.

End-users need to prepare for infrastructure disruptions and design more resilient supply chains

Natural disasters and related infrastructure disruptions can also affect supply chains. To be prepared to cope with natural disasters, firms cannot only focus on their own vulnerability and the vulnerability of their infrastructure services. A firm that is not affected directly or through infrastructure services can still be unable to produce because its suppliers cannot provide required inputs, or because its clients are not able to continue producing. A broader view of the full supply chain is needed to assess production risks.

Firms exposed to transport disruptions tend to rely on large inventories to mitigate the impact of these events: larger inventories protect firms against transport disruptions. In fact, firms in developing countries have already adapted to poor infrastructure and tend to hold larger inventories than in developed economies (Guasch and Kogan 2003). Simulations for Tanzania show that, when firms keep two weeks of inventories instead of one, the costs of disaster-related transport disruptions are reduced by 80% (Colon et al., 2019). In disaster-prone areas where transport disruptions are frequent but relatively short, inventories can be cost-effective coping solutions (Schmitt, 2011). With large inventories, firms still suffer from increased transport costs due to disruptions, but they have to interrupt their own production process only for long disruptions. However, excessive inventories are financial burdens which are costly to maintain and, in some cases, lead to significant losses (e.g., for perishable goods).

Maintaining a diversity of suppliers, from both local and distant locations, is another powerful safeguard, especially in the case of long disruptions. Many examples show that relying on a single supplier is a classical cause of supply chain disruptions. For example, in 2011 many carmakers used a paint pigment called Xirallic that was produced at only one factory in the world: the Onahama plant near the Fukushima-Daiichi nuclear power station in Japan.[4] When the factory was evacuated and closed after the earthquake, many automakers realized they had no alternative suppliers, and had to restrict sales of some colors of car. Maintaining a diversity of suppliers, if possible located in different areas and using different delivery routes that cannot be simultaneously hit by a shock, makes supply chains much more robust. The total benefits from more diversity in suppliers could be substantial; as an illustration, the modeling exercise suggests that, for Tanzania, sourcing critical inputs from two suppliers instead of one decreases the indirect costs of transport disruptions by about 70%. However, managing multiple suppliers creates significant transaction costs, which explains why recent supply chains have tended to reduce the numbers of suppliers (Bakos and Brynjolfsson, 1993; Berger et al., 2004; Goffin et al., 1997). There is therefore again a trade-off between the efficiency of supply chains in normal times, and their resilience to various shocks.

Local supply chains are more robust to transport disruption but more vulnerable to direct shocks. Sourcing from local partners decreases reliance on transportation, and significantly reduces the risks of incurring the indirect damages of a distant disruption. In Tanzania, simulations suggest that having suppliers twice as close reduces impacts by 20%. At the same time, local supply chains are more often entirely affected by a shock, which makes recovery more difficult. It has been

[4] https://www.reuters.com/article/us-japan-pigment/automakers-face-paint-shortage-after-japan-quake-idUSTRE72P04B20110326

shown that maintaining relationships with distant partners helps firms recover when their facilities and those of nearby partners are directly hit by a disaster (Todo, Nakajima, and Matous, 2015, Kashiwagi, Matous, and Todo, 2018). This is because affected firms can receive support and help from their non-affected clients and suppliers, and do not suffer a disaster-related drop in demand that makes recovery more challenging. One extreme example of support to and from suppliers is the case of Toyota, which in 2011 paid its employees to work at its suppliers so that they could restore production as fast as possible. Benefiting from this type of support makes a major difference, especially for small and medium enterprises which do not have the resources to prepare business continuity plans and have no specialist of post-disaster recovery.

A static supply chain cannot cope with large-scale disaster and disruptions; in such cases, adaptability is critical, and should be embedded within Business Continuity Plans. This is why the development of organizational capacities to handle unexpected disruptions across firms is a pillar of supply chain resilience(Blackhurst * et al., 2005; Christopher and Peck, 2004; Sheffi, 2005). Engaging in decentralized decision-making and increasing communication between services are particularly crucial for resilience (Sheffi, 2005). Specific actions include the development of internal business continuity plans, as well as rescue plans with suppliers and collocated companies. Following the 2011 Tohoku earthquake in Japan, several firms have come together to redesign their evacuation protocol and emergency communication procedures, and to develop new shared back-up solutions for critical utilities (World Bank, 2019).

Such plans can be also be calibrated by performing stress tests and exploring 'what if' scenarios to identify bottlenecks and particularly vulnerable points (Chopra and Sodhi, 2004). They should be continuously updated, integrating learnings from any new disruptions (Hamel and Valikangas, 2003). They also rely on sophisticated data management practices. Following the 2011 earthquake, during which it suffered from large production disruptions, Toyota created a new database, Rescue, with information on the inventories held by 650,000 different supplier sites across the globe.[5] This information is aimed at localizing more easily available resources and preventing bottlenecks in production processes.

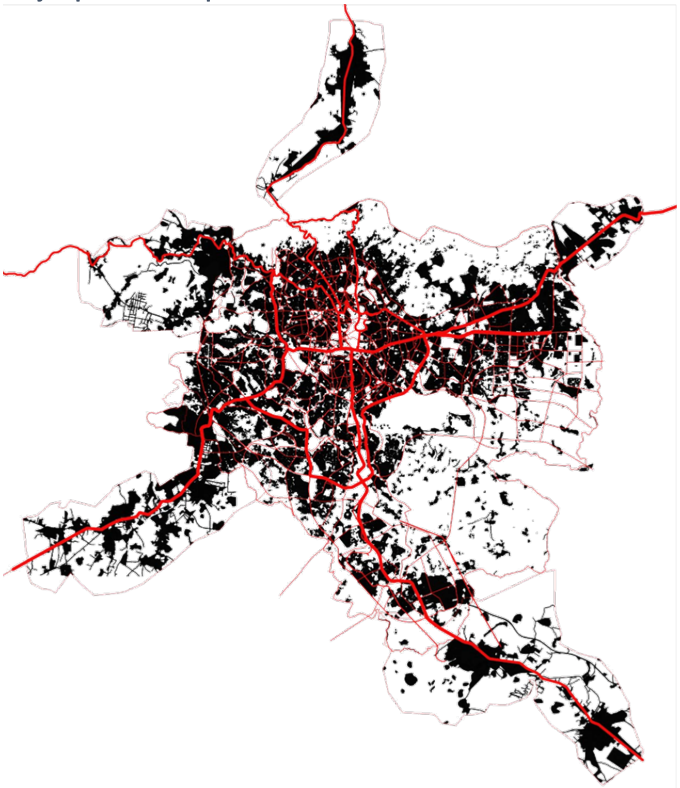
Transport infrastructure influences the exposure of its users to natural hazards

Infrastructure localization decisions drive urbanization patterns, and the exposure of populations and assets to risks, so they need to be coordinated with land-use and urban plans. Baum-Snow has provided both empirical (Baum-Snow, 2007a) and theoretical (Baum-Snow, 2007b) evidence that post-World War II suburbanization in the United States was largely driven by investments in highways that increased travel speeds relative to pre-existing surface streets. Transit infrastructure investments can also guide spatial development and influence land uses, land use intensity, land values and employment, and population densities. Typically, transit-oriented development investments have a unique ability to influence the resilience of communities because they inherently lead to concentrations of people and businesses around transit stops (Salat and Ollivier, 2017). However, if these investments are not made strategically, taking stock

[5] https://www.autonews.com/article/20160425/OEM/304259956/how-toyota-applied-the-lessons-of-2011-quake

of information about the exposure of areas to natural hazards, the outcome could be an increase in disaster vulnerability.

Figure 18: The pattern of urbanization in the urban area of Addis Ababa, Ethiopia closely follows the major public transport lines.



Infrastructure investments can be used to support the implementation of land-use and urbanization plans and to prevent unplanned developments. In cities in developing countries, a large share – if not the vast majority – of households flock to informal settlements, often on the periphery of urban areas, because they are priced out of the narrow formal housing market. Often, these informal neighborhoods are located in disaster-prone areas, because that is where land tends to be available. The large informal settlements on the outskirts of Dakar, Senegal, which became populated as droughts in the 1970's caused mass migration from rural areas, are a case in point. These areas proved to be highly exposed to floods (a fact only apparent once droughts had ended), with between 100,000 and 300,000 people impacted by floods during the rainy seasons annually, and particularly during unusually destructive episodes in 2009 (World Bank, 2016). In Conakry, Guinea's narrow peninsula capital, land is so scarce that many urban dwellers locate themselves in the most low-lying areas, increasing their exposure to storm surges and floods, or directly in the mangroves, increasing the exposure of the city to floods in the process (World Bank, n.d.). Once these neighborhoods have reached a critical mass, the relocation of households is very difficult. Similarly, retrofitting these neighborhoods to equip them with basic infrastructure and to adapt them to the risk of natural hazards is both expensive, time-consuming, and politically sensitive.

A possible solution lies in the early provision of low-risk areas with basic infrastructure before people arrive. Such investments guide populations toward areas that are relatively safe from natural hazards – as the basic servicing of areas acts as a signal for migrants that more infrastructure is likely to come, and that the current area is at least tolerated by authorities, limiting the risk of eviction. Only the most basic infrastructure is needed in the early days, to guide development while preserving the possibility of upscaling in the future. Essentially what is needed is to secure the rights of way for roads (and sewage systems). This is exactly the approach that was followed in the Comás squatter community in Lima, Peru. Its basic structure was laid out by volunteer engineering students in the 1960s before it was occupied. These students laid out the roads in such a way that it created small accessible blocks that would later be filled by residential structures. Today, a 160 m^2 house in this neighborhood (a slum not so long ago ago) costs $180,000 (Angel, 2017). Similar conclusions are reached for sites and services projects in India (Owens et al., 2018) and in Tanzania (Michaels et al., 2017) where the provision of basic infrastructure and land plots' servicing is included.

Figure 19. Aerial view of the Comás neighborhood in Lima, Peru. In this informal neighborhood basic infrastructure preceded populations.

Source: Aerial photo from Google Earth, reproduced from (Angel 2017)

The selection of the areas that are to be prioritized for infrastructure development can be identified by simple GIS approaches. "Good" land can be identified based on the mapping of various hazards – today and in the future, accounting for climate change – and existing infrastructure and activities. The goal is to identify land that is safe, close to opportunities and jobs, and close to existing network infrastructure.

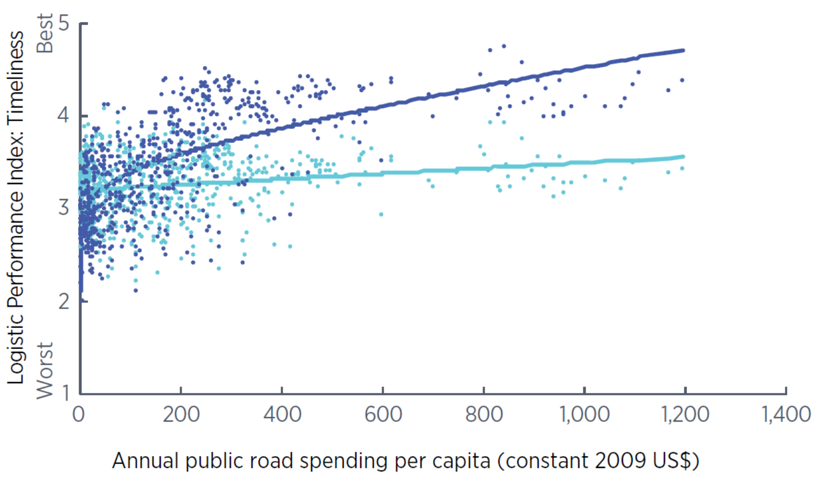
2.4. Quality infrastructure: It's about spending better, not necessarily more

A government's ability to implement resilience-building options depends on whether it has effective systems in place to implement, finance, manage, and maintain infrastructure assets. Strong institutions, the clear assignment of responsibilities, and transparent and reliable financing mechanisms are all crucial in ensuring the effective provision of public services.

Kornejew et al. (2019) explore the relationship between a measure of the reliability of the transport infrastructure (using the Timeliness sub-indicator of the Logistics Performance Index) and spending on transport infrastructure.

Increased investments in roads can improve transport reliability, but only if governance standards are strengthened at the same time. Without controlling for governance, higher spending appears to improve transport reliability (Figure 20). Doubling spending is estimated to significantly increase transport infrastructure performance as measured by the LPI:Timeliness by roughly 0.27 index points. For example, this corresponds to improving the transport service reliability of Mozambique to the standard of that of Cambodia. However, controlling for governance quality (as measured by the World Bank's World Governance Indicators) reduces the effect of spending by a factor of 6, such that governance quality now explains the bulk of statistical variation. Still, the positive impact of spending on transport reliability remains significantly larger than zero. Figure 20 illustrates the strength of this interaction, i.e. how the marginal effect of public road spending per capita melts away once governance quality is taken into account.

Figure 20. Spending more improves the reliability of the transport system, especially if governance improves too.

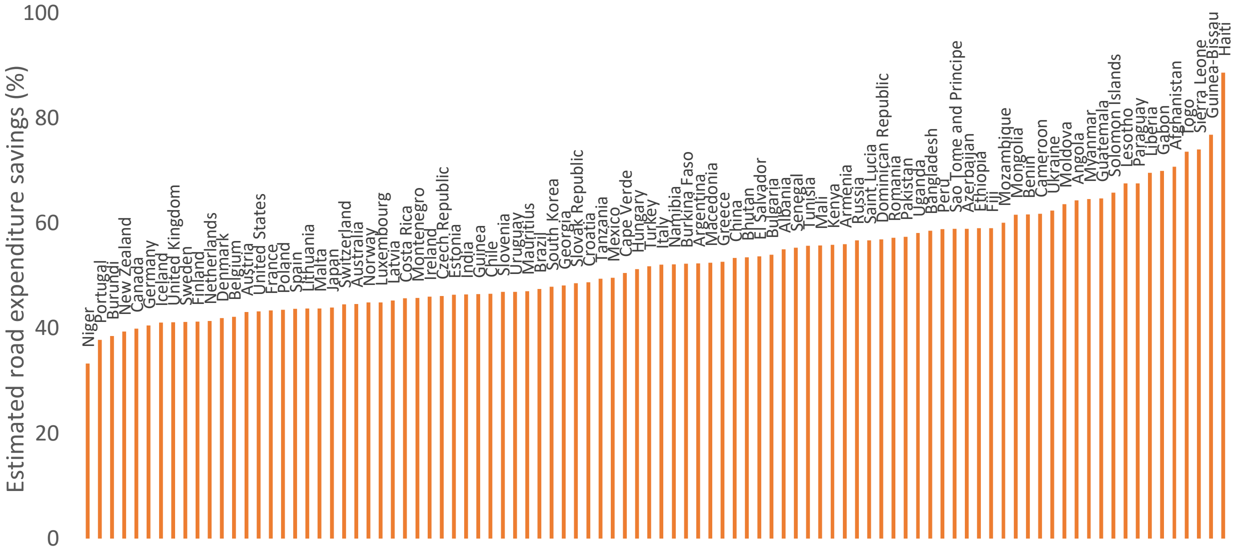


Source: Kornejew et al. (2019)

To illustrate the effectiveness (or indeed, ineffectiveness) of pouring money into transport infrastructure without also improving governance, Kornejew et al. (2019) conduct a simple cost-benefit analysis. The results suggest that a 10% increase in road spending yields an increase of

0.018 percentage points in the average capacity utilization rate of firms, by improving transport reliability. By taking public spending and GDP data from 94 countries into account (in constant 2010 USD), the study finds that in the vast majority of countries GDP gains are *smaller* than the initial 10 percent increase in public road expenditures. Especially in large economies, the costs of road spending significantly exceed the benefits. Brazil and Portugal are the only countries in which the benefits of road spending yields benefits over $1 million.

Figure 21: Potential road spending savings from governance reforms



Source: Kornejew et al. (2019)

What are the benefits of improving infrastructure spending? Building on the previous estimates, an assessment can be made of how improved governance could help reduce public spending on roads, while maintaining transport reliability unchanged.

In the data, 10 percent of all the sample's country-year observations exhibit at least a +0.23 index points increase of the WGI "Government Effectiveness" over a three-year period (e.g. Ecuador 2010-13, Egypt 2006-09). Thus, +0.23 in this index might be regarded as an exceptional but feasible reform result. By hypothetically implementing similar reforms in each and every country at the current edge of the data, the model allows the calculation of how much public transport infrastructure spending could be reduced by, without harming transport service quality.[6]

According to the model, savings from improved governance – illustrated in Figure 21 – could be substantial. Improving governance as effectively as Ecuador did it between 2010 and 2013 allows cuts in expenditure of 30 % to 90 %. Relative savings are the highest for countries with poor

[6] Specifically, we extend the model of the previous section by interaction terms of log per capita road spending with "Government Effectiveness". This is necessary to generate meaningful variation across countries, which the model shown in the appendix cannot. Level coefficients are not found to be significantly positive and thus restricted to zero for this simulation.

governance quality but relatively high levels of per capita spending. Savings are very small in countries with good governance, or very small spending on roads, like Niger.

In conclusion, building more resilient transport infrastructure assets is usually costlier, but the additional cost of resilient infrastructure is small, provided that the right interventions can be implemented in the right places. Building the resilience of transport services and users at low cost is possible if investments are targeted using good hazard data and criticality analysis, and if decision-making processes help capture the users' point of view. The study also shows that resilience benefits from transport systems can go beyond reliable transport services: well-designed transport systems can reduce the exposure of populations and firms, and increase their overall resilience, without having to cost more.

The primary way to achieve more resilient transport infrastructure is by spending better, with improved governance and better asset management systems. In fact, the savings from higher spending efficiency could easily pay for resilience, in most countries in the world.

References

Angel, S. (2017). Urban Forms and Future Cities: A Commentary. Urban Planning *2*, 1.

Argyroudis, S., and Kaynia, A.M. (2014). Fragility Functions of Highway and Railway Infrastructure. In SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk: Buildings, Lifelines, Transportation Networks and Critical Facilities, K. Pitilakis, H. Crowley, and A.M. Kaynia, eds. (Dordrecht: Springer Netherlands), pp. 299–326.

Baez, J.E., Lucchetti, L., Genoni, M.E., and Salazar, M. (2017). Gone with the Storm: Rainfall Shocks and Household Wellbeing in Guatemala. Journal of Development Studies *53*, 1253–1271.

Bakos, J.Y., and Brynjolfsson, E. (1993). Information Technology, Incentives, and the Optimal Number of Suppliers. Journal of Management Information Systems *10*, 37–53.

Barker, K., and Santos, J.R. (2010). A risk-based approach for identifying key economic and infrastructure systems. Risk Analysis *30*, 962–974.

Barrington-Leigh, C., and Millard-Ball, A. (2017). The world's user-generated road map is more than 80% complete. PLOS ONE *12*, e0180698.

Baum-Snow, N. (2007a). Did highways cause suburbanization? The Quarterly Journal of Economics *122*, 775–805.

Baum-Snow, N. (2007b). Suburbanization and transportation in the monocentric model. Journal of Urban Economics *62*, 405–423.

BBC (2010). Iceland volcano: Nissan and BMW suspend some production.

Beck, M.W., Losada, I.J., Menéndez, P., Reguero, B.G., Díaz-Simal, P., and Fernández, F. (2018). The global flood protection savings provided by coral reefs. Nature Communications *9*, 2186.

Benavidez, M.J., and Mortlock, A.M. (2018). Transport Sector Recovery: Opportunities to Build Resilience.

Berger, P.D., Gerstenfeld, A., and Zeng, A.Z. (2004). How many suppliers are best? A decision-analysis approach. Omega *32*, 9–15.

Blackhurst *, J., Craighead, C.W., Elkins, D., and Handfield, R.B. (2005). An empirically derived agenda of critical research issues for managing supply-chain disruptions. International Journal of Production Research *43*, 4067–4081.

Briceño-Garmendia, C., Moroz, H., and Rozenberg, J. (2015). Road Networks, Accessibility, and Resilience: The Cases of Colombia, Ecuador, and Peru. World Bank, Washington, DC.

Bureau of Transportation Statistics (2018). Understanding the Reporting of Causes of Flight Delays and Cancellations.
Cambridge Systematics Institute, and Texas Transportation Institute (2005). Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation.
Cebr (2014). The future economic and environmental costs of gridlock in 2030.
Cervigni, R., Losos, A.M., Chinowsky, P., and Neumann, J.L. (2016). Enhancing the climate resilience of Africa's Infrastructure: the roads and bridges sector (The World Bank).
Chang, S.E., and Nojima, N. (2001). Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective. Transportation Research Part A: Policy and Practice *35*, 475–494.
Cho, S., Gordon, P., Moore II, J.E., Richardson, H.W., Shinozuka, M., and Chang, S. (2001). Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Urban Earthquake. Journal of Regional Science *41*, 39–65.
Chopra, S., and Sodhi, M.S. (2004). Managing risk to avoid supply-chain breakdown: by understanding the variety and interconnectedness of supply-chain risks, managers can tailor balanced, effective risk-reduction strategies for their companies. MIT Sloan Management Review *46*, 53–62.
Christopher, M., and Peck, H. (2004). Building the Resilient Supply Chain. The International Journal of Logistics Management *15*, 1–14.
Colon, C., Hallegatte, S., and Rozenberg, J. (2019). Transportation and Supply Chain Resilience in the United Republic of Tanzania (Washington DC: World Bank).
Cordeiro, D.A.R., Joao, M., Bennett, C.R.-000065273, Michaels, S.D., Pedroso, F.F.F., Forni, M.S., and Rozenberg, J. (2017). Climate and disaster resilient transport in small island developing states : a call for action (The World Bank).
Croneborg, L., Saito, K., Matera, M., McKeown, D., van Aardt, J. (2015). A Guidance Note on how Digital Elevation Models are created and used – includes key definitions, sample Terms of Reference and how best to plan a DEM-mission. Global Facility for Disaster Reduction and Recovery.
De Sitter, W.R. (1984). Costs of service life optimization" The Law of Fives". In CEB-RILEM Workshop on Durability of Concrete Structures (Copenhagen, Denmark, May 18-20, 1983), (Comité Euro-International du Béton), p.
Dhakal, A.S., and Sidle, R.C. (2003). Long-term modelling of landslides for different forest management practices. Earth Surface Processes and Landforms *28*, 853–868.
Doll, C., Klug, S., and Enei, R. (2014). Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years. Nat Hazards *72*, 211–239.
Enei, R., Doll, C., Klug, S., Partzsch, I., Sedlacek, N., Kiel, J., Nesterova, N., Rudzikaite, L., Papanikolaou, A., and Mitsakis, V. (2011). Vulnerability of transport systems - Main report (Karlsruhe).
Espinet Alegre, X., Rozenberg, J., Rao, K.S., and Ogita, S. (2018). Piloting the use of network analysis and decision-making under uncertainty in transport operations : preparation and appraisal of a rural roads project in Mozambique under changing flood risk and other deep uncertainties (The World Bank).
GFDRR (2015). Tbilisi Disaster Needs Assessment 2015.
Goffin, K., Szwejczewski, M., and New, C. (1997). Managing suppliers: when fewer can mean more. International Journal of Physical Distribution & Logistics Management *27*, 422–436.
Government of Fiji, and World Bank, T. (2017). Climate vulnerability assessment : making Fiji climate resilient. 1–172.
Guasch, J.L., and Kogan, J. (2003). Just-in-case inventories: A cross-country analysis (World Bank Publications).
Hallegatte, S. (2014). Modeling the role of inventories and heterogeneity in the assessment of the economic costs of natural disasters. Risk Analysis *34*, 152–167.
Hamel, G., and Valikangas, L. (2003). The Quest for Resilience. Harvard Business Review.

Henning, T.F.P., Hughes, J., and Faiz, A. (2018). Incorporating Criticality and Resilience into Performance Based Contracts (World Bank).

Henriet, F., Hallegatte, S., and Tabourier, L. (2012). Firm-network characteristics and economic robustness to natural disasters. Journal of Economic Dynamics and Control *36*, 150–167.

Holguín-Veras, J., Jaller, M., and Wachtendorf, T. (2012). Comparative performance of alternative humanitarian logistic structures after the Port-au-Prince earthquake: ACEs, PIEs, and CANs. Transportation Research Part A: Policy and Practice *46*, 1623–1640.

ICF (2019). Strategic assessment of the climate resilience of Dar es Salaam transport infrastructure.

Iimi, A., and Gericke, B. (2017). Output- and Performance-Based Road Contracts and Agricultural Production: Evidence from Zambia (The World Bank).

INRIX Research (2018). INRIX Global Traffic Scorecard. Inrix Global Traffic Scorecard 44.

Jonkeren, O., Rietveld, P., van Ommeren, J., and te Linde, A. (2014). Climate change and economic consequences for inland waterway transport in Europe. Regional Environmental Change *14*, 953–965.

Kadri, F., Birregah, B., and Châtelet, E. (2014). The Impact of Natural Disasters on Critical Infrastructures: A Domino Effect-based Study. Journal of Homeland Security and Emergency Management *11*, 217.

Kajitani, Y., and Tatano, H. (2014). Estimation of Production Capacity Loss Rate after the Great East Japan Earthquake and Tsunami in 2011. Economic Systems Research *26*, 13–38.

Kazama, M., and Noda, T. (2012). Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage). Soils and Foundations *52*, 780–792.

Koks, E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S.A., Hall, J., and Hallegatte, S. (2019). A global multi-hazard risk analysis of road and railway infrastructure assets. Nature Sustainability.

Kornejew, M., Rentschler, J., and Hallegatte, S. (2019). Well spent: How governance determines the effectiveness of infrastructure investments. World Bank Policy Research Working Paper.

Kwakkel, J., Jafino, B.A., Verbraeck, A., Eker, S., and Rozenberg, J. (2019). Resilience of the Transport Network in Bangladesh: A graph-theoretical and simulation-based approach (Washington DC: World Bank).

Kwiatkowski, K., Qiao, Y., Young, S., Bell, E., and Medina, R. (2019). Quantifying risk of flood-induced bridge failure in Mozambique considering climate variability (USA: University of New Hampshire).

Lancelot, E. (2010). Performance Based Contracts in the Road Sector : Towards Improved Efficiency in the Management of Maintenance and Rehabilitation - Brazil’s Experience.

Lopez-Cantu, T., and Samaras, C. (2018). Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States. Environmental Research Letters *13*, 074006.

Ludvigsen, J., and Klæboe, R. (2014). Extreme weather impacts on freight railways in Europe. Natural Hazards *70*, 767–787.

Meijer, J.R., Huijbregts, M.A.J., Schotten, K.C.G.J., and Schipper, A.M. (2018). Global patterns of current and future road infrastructure. Environmental Research Letters *13*, 064006.

Michaels, G., Nigmatulina, D., Rauch, F., Regan, T., Baruah, N., and Dahlstrand-Rudin, A. (2017). Planning Ahead for Better Neighborhoods: Long Run Evidence from Tanzania. CESifo Working Papers Series *6680*.

Miyamoto (2019). Overview of Engineering Options for Increasing Infrastructure Resilience (Washington DC: World Bank).

Mueller, V., and Quisumbing, A. (2009). Natural Disasters and their Labor Market Consequences : Evidence from the 1998 Flood in Bangladesh. Working Paper.

Nelson, A., Lindbergh, S., Stephenson, L., Halpern, J., Arroyo, F.A., Espinet, X., and González, M.C. (2019). Coupling Natural Hazard Estimates with Road Network Analysis to Assess Vulnerability and Risk: Case Study of Freetown, Building Disruption Simulations in Hydrometeorological Risk Areas in Data-Scarce Sierra Leone. Transportation Research Record 0361198118822272.

Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. Reliability Engineering & System Safety *121*, 43–60.
Owens, K.E., Gulyani, S., and Rizvi, A. (2018). Success when we deemed it failure? Revisiting sites and services projects in Mumbai and Chennai 20 years later. World Development *106*, 260–272.
Pardina, M.R., and Schiro, J. (2018). Taking Stock of Economic Regulation of Power Utilities in the Developing World: A Literature Review (The World Bank).
Rentschler, J., Braese, J., Jones, N., and Avner, P. (2019a). Three feet under: The impacts of flooding on urban jobs, connectivity, and infrastructure. (Washington DC: World Bank).
Rentschler, J., Kornejew, M., Hallegatte, S., Obolensky, M., and Braese, J. (2019c). Underutilized potential: The business costs of unreliable infrastructure in developing countries (Washington DC: World Bank).
Rinaldi, S.M., Peerenboom, J.P., and Kelly, T.K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Systems Magazine *21*, 11–25.
Rogers, D., and Tsirkunov, V. (2013). Weather and climate resilience: effective preparedness through National Meteorological and Hydrological Services. (World Bank Publications).
Rose, A., and Krausmann, E. (2013). An economic framework for the development of a resilience index for business recovery. International Journal of Disaster Risk Reduction *5*, 73–83.
Rose, A., and Wei, D. (2014). Estimating the Economic Consequences of a Port Shutdown: The Special Role of Resilience. Economic Systems Research.
Rozenberg, J., and Fay, M. (2019). Beyond the gap: How countries can afford the infrastructure they need while protecting the planet (Washington, D.C. : World Bank Group).
Rozenberg, J., Briceno-Garmendia, C., Lu, X., Bonzanigo, L., and Moroz, H. (2017). Improving the resilience of Peru's road network to climate events.
Salat, S., and Ollivier, G.P. (2017). Transforming the urban space through transit-oriented development : the 3V approach (The World Bank).
Schmitt, A.J. (2011). Strategies for customer service level protection under multi-echelon supply chain disruption risk. Transportation Research Part B: Methodological *45*, 1266–1283.
Sheffi, Y. (2005). The resilient enterprise : overcoming vulnerability for competitive advantage (MIT Press).
The World Bank (2017). Climate vulnerability assessment : making Fiji climate resilient (The World Bank).
Tierney, K.J. (2002). Business Impacts of the Northridge Earthquake. Journal of Contingencies and Crisis Management *5*, 87–97.
Tsuchiya, S., Tatano, H., and Okada, N. (2007). Economic Loss Assessment due to Railroad and Highway Disruptions. Economic Systems Research *19*, 147–162.
Van Steenbergen, F., Alemayehu, T., Woldearegay, K., and Agujetas Perez, M. (2019). Guidelines: Green Roads For Water. Road infrastructure in support of water managements and climate resilience (The Netherlands: Meta Meta Research).
Wender, B.A., Morgan, M.G., and Holmes, K.J. (2017). Enhancing the Resilience of Electricity Systems (National Academies Press).
World Bank Republic of Guinea. Planning, Connecting, Financing in Conakry (Washington, D.C: World Bank).
World Bank (2016). Perspectives Urbaines: Villes Émergentes pour un Sénégal Émergent (World Bank).
World Bank (2017). Sovereign Catastrophe Risk Pools (World Bank, Washington, DC).
World Bank (2019). Resilient Industries: Ensuring competitiveness in the face of natural disasters (The World Bank Group).