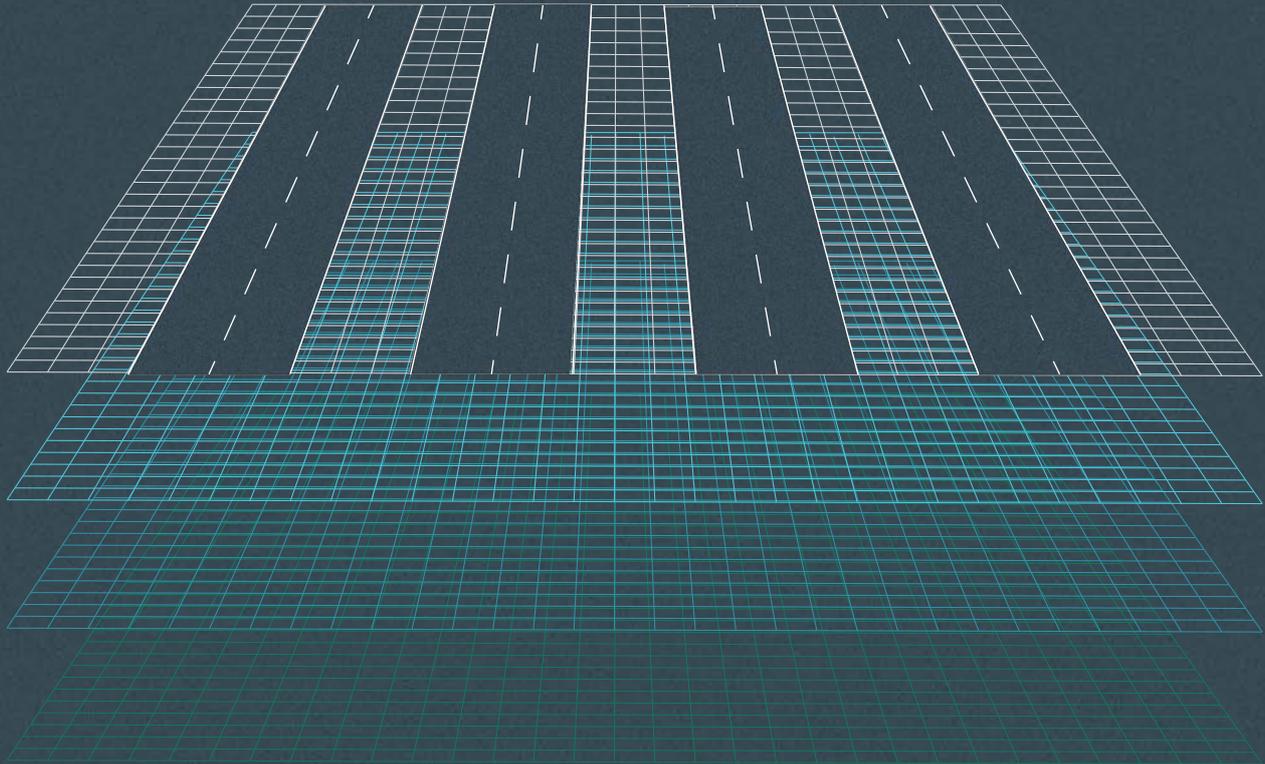
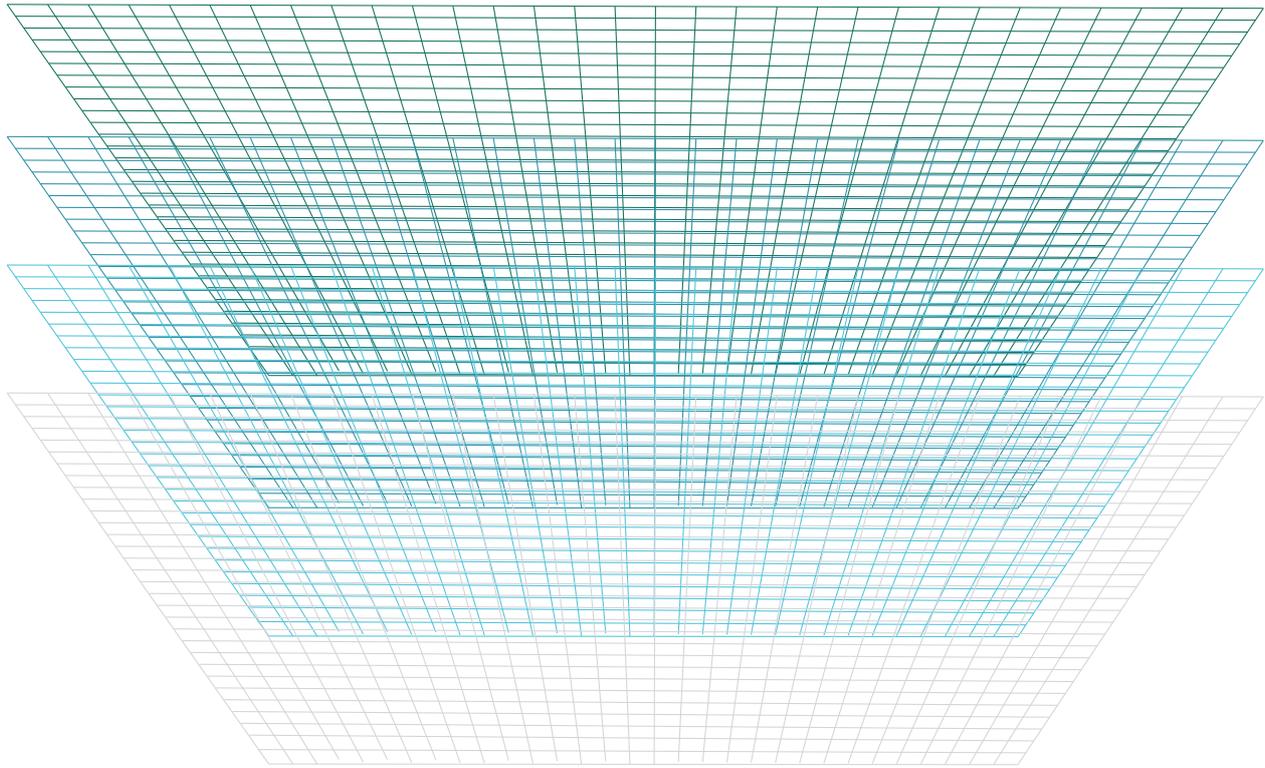


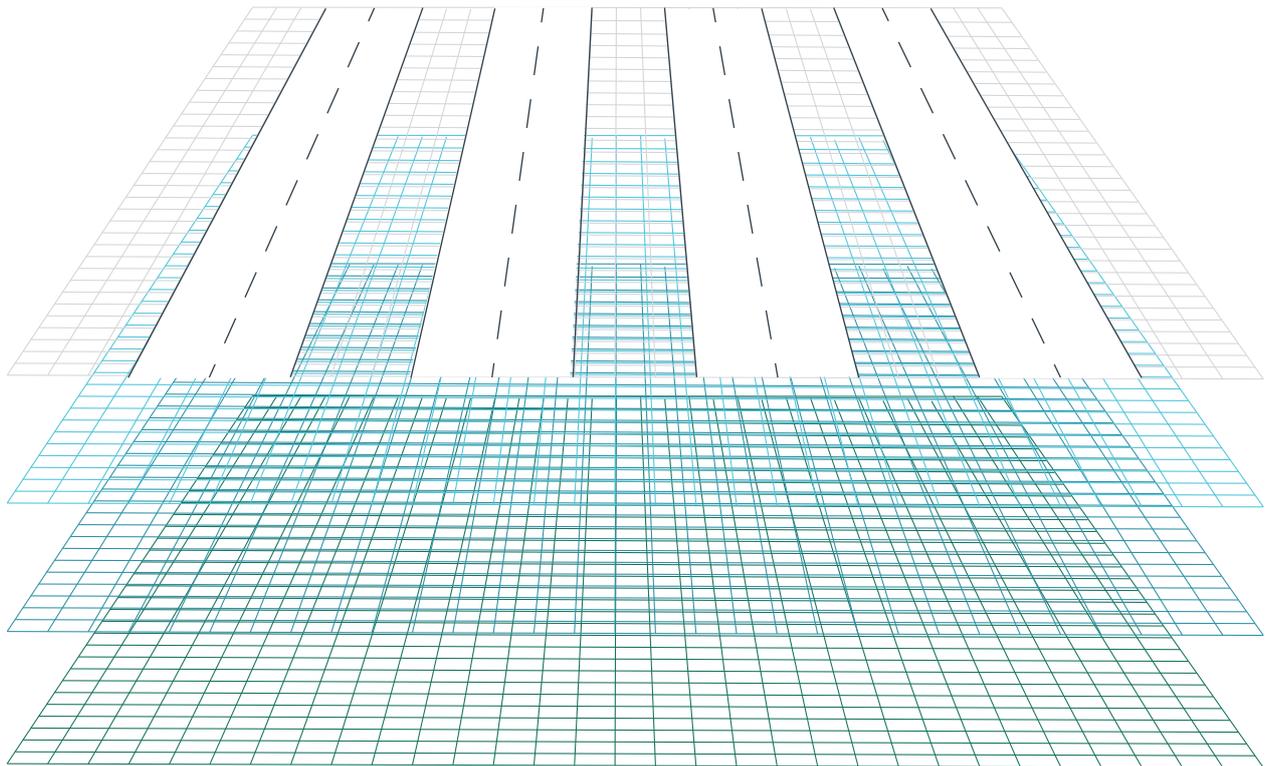
# **INCORPORATING RESILIENCE IN INFRASTRUCTURE PRIORITIZATION:** Application to Japan's Road Transport Sector







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The World Bank Group

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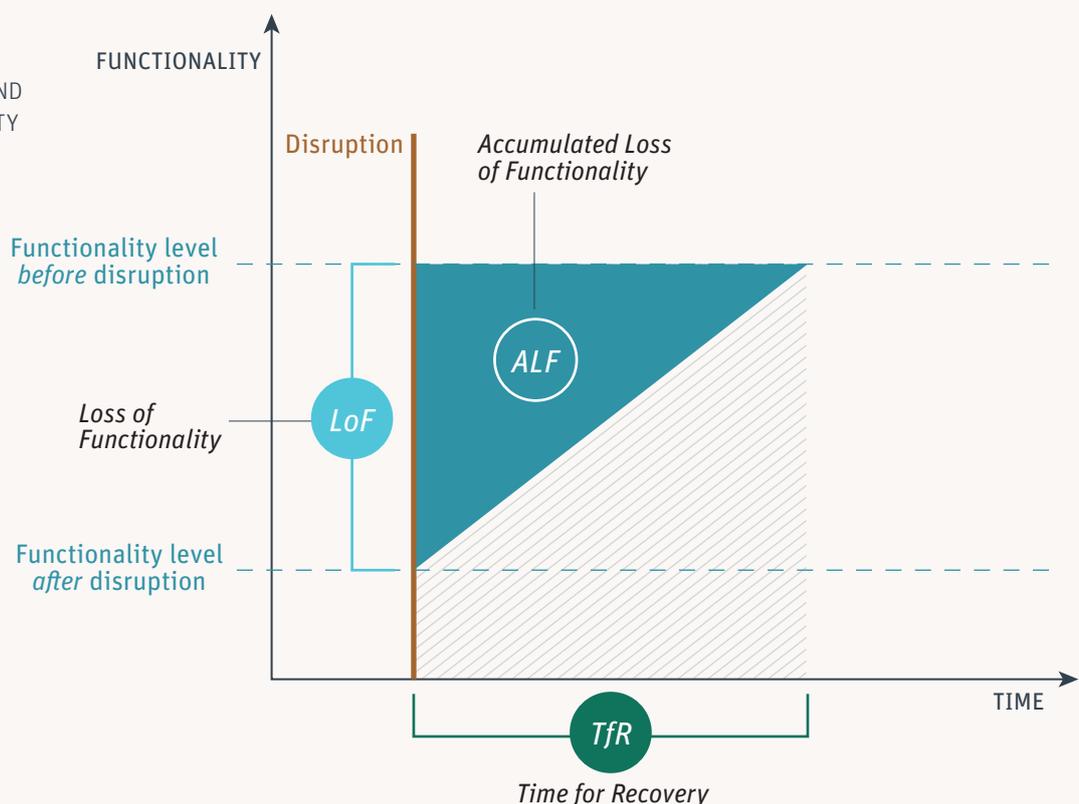
# Executive Summary

Disruption of infrastructure services can cause significant social and economic losses, particularly in the event of a natural disaster. For example, the 2011 Great East Japan Earthquake unleashed a tsunami that left some 20,000 people dead or missing in Japan. The disaster heavily affected Sendai, the capital city of Miyagi Prefecture and a regional economic hub. The Tsunami completely submerged the city's primary wastewater treatment, while some 500,000 residents lost access to water. Also, the tsunami damaged 325 kilometers of coastal railway assets and flooded about 100 kilometers of the national highway in the Tohoku region, leaving devastated towns in need of assistance without inland transport access. This shows the importance of considering resilience to disaster in infrastructure investment decisions.

The World Bank Group and Government of Japan established the Quality Infrastructure Investment (QII) Partnership to focus attention on quality dimensions of infrastructure in developing countries, with a focus on promoting disaster resilience. Moreover, to support infrastructure investment decision making for sustainable and resilient development, the World Bank and Kyoto University have operationalized key resilience concepts at the project level and developed quantitative indicators capturing key aspects of infrastructure resilience. These indicators estimate 'resilience', expressed in terms of functionality loss and recovery time across four dimensions: travel time, economic benefit, provision of life-saving services, and provision of relief goods. The approach is now being tested for transport projects.

The concept of resilience developed here describes an asset's capacity to withstand shock and recover functionality following a shock. **FIGURE 01** illustrates

**FIGURE 01.**  
CONCEPT OF  
RESILIENCE AND  
FUNCTIONALITY



this process. In the event of a disaster, an asset (e.g., a road or bridge) is susceptible to *loss of functionality* (*LoF* ●) measured in terms of four dimensions (k): travel time (t), road utilization (u), provision of relief (p) and access to lifesaving services (l).

Following a disruption (e.g. natural disaster), functionality recovers over the *time for recovery* (*TfR* ●). *Accumulated loss of functionality* (*ALF* ●) is a measure of aggregated functionality loss over the recovery period. Conceptually, ALF relates inversely to resilience (i.e., lower ALF is akin to higher resilience).

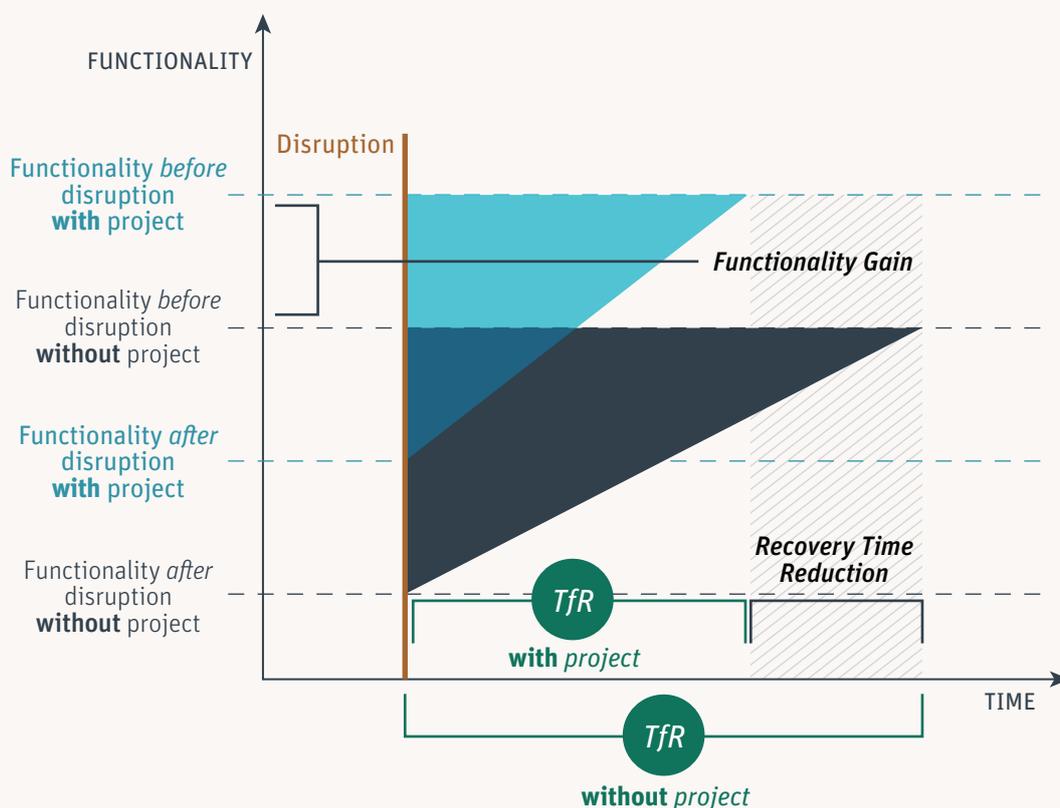
The paper presents a method to calculate estimated LoF associated with each of the above dimensions following a shock, based on several input data gathered from project feasibility studies and available transport data. The calculated LoFs are, in turn, used to estimate the ALFs for each dimension over the estimated recovery time (the area of the

triangle in Figure 1). The resulting ALF calculations can be used to compare projects' expected accumulated functionality losses in the event of the likeliest natural disasters.

Moreover, LoFs and ALFs can be used to compare scenarios with and without a proposed project to estimate variations in ALF ( $\Delta ALF$ )—i.e., how much a project would affect expected ALF as compared to the baseline case. Policymakers may use this information to give higher priority to projects with lower ALFs or to projects with greater reductions to ALF. This concept is illustrated in **FIGURE 2**.

The paper applies indicator calculations to three case studies of proposed bypass roads in Japan and provides an example comparison of calculated indicators across the three projects for each resilience dimension. Piloting the approach will help refine indicators, test their relative utility in decision-

**FIGURE 02.**  
ALF WITH  
AND WITHOUT  
PROJECT



## EXECUTIVE SUMMARY

making, and offer a better understanding of data and analytical demands. Pilots should subject results to expert review, particularly with comparison to alternative approaches for considering project resilience. Piloting should also consider approaches to incorporating sensitivity analysis in indicator construction, explore applications to questions of system-level resilience, and improve approaches to estimating recovery time.

The proposed indicators are designed for application as part of broader prioritization exercises that consider additional economic, financial, social, and environmental factors. One such approach, the Infrastructure Prioritization Framework (IPF) developed by the World Bank, aggregates underlying project-level indicators into composite indices to compare the expected outcomes of proposed projects within a sector. Until now, IPF estimations have assumed an ordinary state of non-disruption. This paper proposes indicators that enable decision-makers to additionally consider potential impacts of disrupted states following disasters such as earthquakes, floods, landslides, or extreme weather events.

### SUMMARY OF INDICATORS

**I. LoF, TRAVEL TIME:** Let  $t_i^{j(0)}$  denote travel time between an origin-destination (O-D) pair under a non-disrupted state  $s=0$ , and  $t_i^{j(1)}$  the travel time under a disrupted state  $s=1$ .  $j$  captures two possible project statuses: with-project ( $j=1$ ) and without-project ( $j=0$ ). Transport simulation models can offer estimations for  $t_i^{j(s)}$  in each case. For any disaster event  $d$ , the expected LoF resulting from a proposed project  $i$  for the travel time dimension ( $k=t$ ) would correspond to:

$$LoF_{ik}^{j(s)} = Travel\ Time_{i,t}^{j(0)} - Travel\ Time_{i,t}^{j(1)}$$

**II. LoF, ECONOMIC BENEFIT:**  $x=q(t)$  is a traffic demand function  $q(t) = -m \times t + c$ , where slope  $m$  is equal to  $(x^1 - x^0) / (t^1 - t^0)$  and  $c$  is a constant. LoF in terms of lost consumer surplus (using decreased utilization as a proxy of economic loss), for any given disruption  $d$ , corresponds to:  $LoF_{ik}^{j(s)} = (t_i^{j(0)} + t_i^{j(1)}) (x_i^{j(0)} - x_i^{j(1)}) / 2$ , where for project  $i$ ,  $t_i^{j(1)}$  denotes the travel time of a representative O-D pair under a disrupted state ( $s=1$ ) with project status  $j$ , and  $t_i^{j(0)}$  denotes the travel time under a non-disrupted state ( $s=0$ ).

### III. LoF, PROVISION OF EMERGENCY SERVICES:

LoF for S&R is defined as:  $LoF_{ik}^{j(s)} = Pop_{ik}^{j(0)} - Pop_{ik}^{j(s)}$  where  $Pop_{ik}^{j(0)}$  is the population with access to major hospitals within thirty minutes under the ordinary state (with no disruption) and  $Pop_{ik}^{j(s)}$  is the population with emergency access under a specified disaster scenario  $d$ .

### IV. LoF, PROVISION OF RELIEF:

LoF for the functionality of delivery of relief goods is the isolated population under the disrupted state:  $LoF_{ik}^{j(s)} = Pop_{ik}^{j(s)}$  where  $Pop_{ik}^{j(s)}$  is the population living in towns and villages that will become isolated under a specified hazard scenario  $s$  with the project status  $j$  for each project  $i$ .

**V. TFR:** Let  $TFR_{ik}^{j(s)}$  denote estimated time for recovery for a disrupted road ( $s=1$ ) after event  $d$  for project  $i$  with implementation status  $j$ .

### VI. ACCUMULATED LOSS OF FUNCTIONALITY:

$$ALF_{ik} = 0.5 \times LoF_{ik} \times TFR_{ik}$$

### VII. VARIATION TO ALF:

$$\Delta ALF_{ik} = (\Delta ALF_{ik}^w / \Delta ALF_{ik}^{wo}) - 1 \quad (\times 100)$$

# Introduction

Modern society depends extensively on physical infrastructure systems, which serve as the foundation for a wide range of human activities. Given the nature of infrastructure as a critical input to trade and industry, economic productivity, public health, human safety, and quality of life, the disruption of infrastructure services can cause catastrophic economic losses and devastating impacts on health and the operability of the regions they serve. Therefore, the World Bank Group and Government of Japan established the Quality Infrastructure Investment (QII) Partnership with the objective of raising awareness and promoting enhanced attention to the quality dimensions of infrastructure investment projects in developing countries. They identify five aspects that must form the key elements in project design, namely: economic efficiency, safety, environmental and social sustainability, economic and social contribution and resilience against natural disasters.

Due to widespread gaps in infrastructure funding and increasing demands for improved infrastructure services, most countries worldwide face the challenge of having to select from amongst proposed infrastructure projects to develop and fund those most apt to attain developmental goals. To support project prioritization in infrastructure sectors such as transport, water, and energy, the World Bank Infrastructure, PPPs, and Guarantees Group (IPG) developed the Infrastructure Prioritization Framework (IPF) (Marcelo, et al, 2015). The IPF aggregates underlying project-level indicators into two composite indices, the socio-environmental index (SEI) and the financial-economic index (FEI), which characterize the expected relative outcomes of proposed projects within a sector.

Although QII principles recognize resilience as a key aspect of infrastructure project design and planning, the composite indicators considered by the IPF have, until now, only assumed an 'ordinary state' of non-disruption, meaning that they do not consider how infrastructure assets maintain operability and/or recover in the face of disaster events. Moreover, the IPF analyses have not yet considered the potential benefits of infrastructure projects regarding their abilities to contribute to overall resilience at the

local, regional, or national levels. The aftermath of the 2011 Great East Japan Earthquake that unleashed a tsunami and left some 20,000-people dead or missing<sup>1</sup> in Japan, underscores the importance of considering resilience to disaster in infrastructure investment decisions. The disaster heavily affected Sendai, the capital city of Miyagi Prefecture and a regional economic hub. The tsunami completely submerged the city's primary wastewater treatment, while some 500,000 residents lost access to water. Also, the tsunami damaged 325 kilometers of coastal railway assets and flooded about 100 kilometers of the national highway in the Tohoku region, leaving devastated towns in need of assistance without inland transport access.

This paper presents a practical approach to bring the concept of infrastructure resilience to the project level, with direct application to transport infrastructure. The proposed approach complements the IPF and offers additional indicators as potential inputs to the framework that can help decision-makers discern between projects from a resilience perspective. The paper begins with a discussion of the concept of infrastructure resilience and follows with proposed indicators to measure aspects of resilience in transport at the project level.

# Applying the Concept of Resilience to Infrastructure Projects

The concept of *resilience* has been discussed in various academic fields and conceptualized in numerous ways (Cutter et al., 2010). For social sciences, the main interest is the resilience of communities, whereas for engineering fields, the focus is on the resilience and robustness of structures. Organizational resilience, conversely, focuses on the ability of an organization to absorb shocks and to adapt in a changing environment (ISO 22316). In most fields, the concept is recognized to be multifaceted. Bruneau (2003) conceptualizes resilience as the ability of a system to reduce the chances of a shock, to absorb a shock capable of causing abrupt reduction of performance, and to recover quickly after the occurrence of a shock.

In line with these definitions, we present an application of the resilience concept that describes (a) an asset's ability to withstand shocks in such a way that minimizes functionality losses (i.e., robustness or resistance), and (b) the asset's capacity to recover functionality across multiple dimensions following a disaster event (i.e., recoverability). Dealing with the expected functionality of an asset within a transportation system, both pre- and post-shock, inherently considers the asset's connection to a broader network. A network approach to transportation is crucial because transport functionality depends not

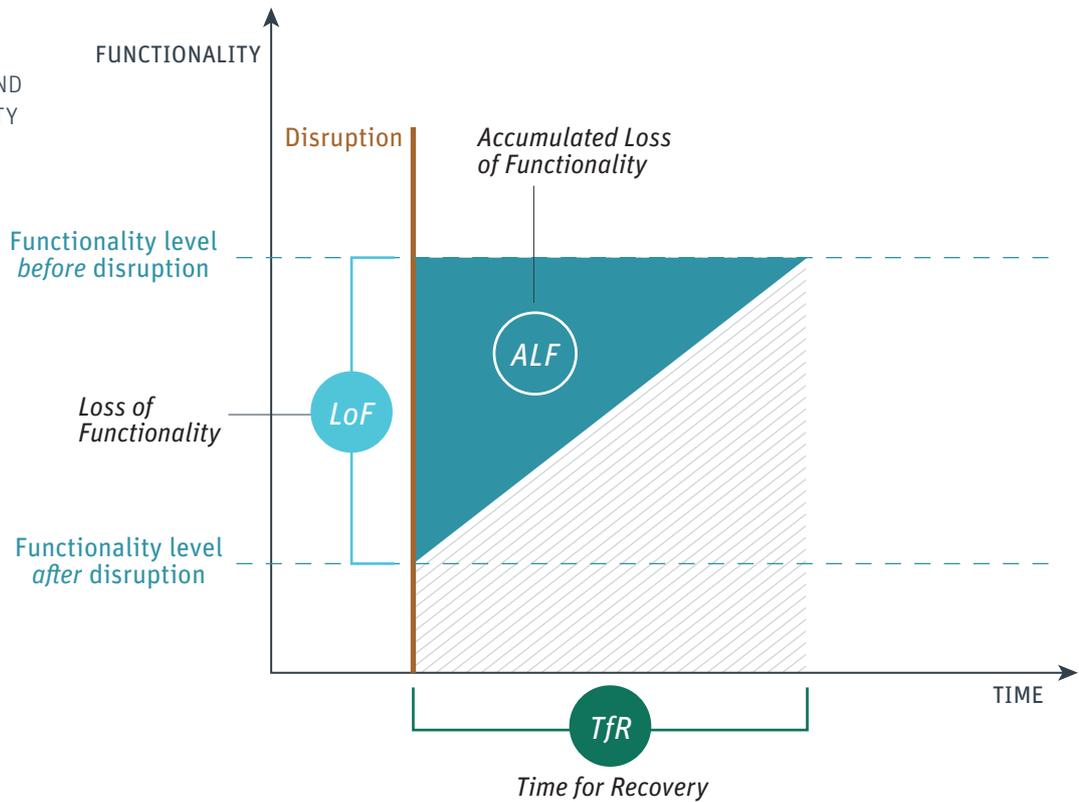
only on the characteristics of individual assets but also on their contributions to the system's overall functionality and performance. That said, while an asset's functionality naturally relates to its locus within a system, the focus here is to encompass (a) the ability to minimize loss of asset functionality (within the system) and (b) the ability to recover asset functionality after a disruption.

**FIGURE 1** illustrates the “recovering of functionality” process of an asset after a disruption (i.e. natural disaster). In the event of a disaster, an infrastructure asset (e.g., a road or bridge) is susceptible to losing some or all of its functionality. We define the decrease in functionality as *loss of functionality (LoF)*. After the disruption, functionality will typically recover, reaching a near-total or total pre-disaster level of performance over time. We term this lapse *time for recovery (TfR)*. The recovery time depends on the systems and processes in place, as well as physical attributes of the asset itself. Therefore, the *accumulated loss of functionality (ALF)* will account for the aggregated functionality loss over the recovery time. Mathematically, *ALF* is equal to the integral of the *LoF* function over the interval between the disruption and the end of the *TfR* period. This integral is the area indicated by the shaded area in Figure 1.

## LOSS OF FUNCTIONALITY

Loss of functionality (*LoF*) accounts for reduced levels of service due to disaster events, most often natural. Since structural robustness helps alleviate or prevent reduced levels of service in the event of a disaster, *LoF* is a function of both 1) the impact of natural disasters and 2) the structural measures taken to resist or absorb the external forces imposed by these disasters.

**FIGURE 1.**  
CONCEPT OF  
RESILIENCE AND  
FUNCTIONALITY  
OF A ROAD



*Source: Authors' illustration. For the sake of simplicity, this illustration assumes that the functionality is recovered in a linear fashion. However, this may not always be the case. In some instances, perhaps the road only opens when full functionality is restored, and, in others, one lane of a many-lane highway may open first, followed gradually by others. Therefore, the ALF's upper bound could take a variety of functional shapes depending on the path of recovery (how much functionality is restored at various stages of repair), such as a straight line (yielding a rectangular ALF are) or even a staggered path. The ALF should then be calculated according to the functional shape that emerges from the specific scenario.*

Moreover, *LoF* relates to the ability of an asset or facility to maintain functionality after a disruption by structurally resisting and/or absorbing the external force by design. *LoF* indirectly captures the notion of capacity to resist, as it measures the magnitude of the reduction in functionality immediately after a natural disaster. The decrease of functionality is the logical result of the occurrence of a disruption, coupled with the intrinsic capacity of the structure to resist or absorb the physical effects of such an event.

In the case of road transport projects, typical disruptions may include earthquakes, volcanic eruptions, floods, cyclones, storm surges, or landslides caused by intensive rainfall. The design of a structure and the materials used in

construction naturally affect its ability to withstand various natural disasters. In the event of a strong earthquake, for example, a road facility can maintain its functionality under most conditions if sufficient structural measures are in place to resist even major earthquakes with the highest seismic intensities.<sup>2</sup> Consequently, an accurate assessment of the *LoF* requires information on (a) the kinds of disruptions that infrastructure projects are likely to face and (b) the expected functionality levels resulting from these disruptions at various levels of intensity.

## RECOVERABILITY

Recoverability refers to the ability of an asset to recover its functionality quickly. Recoverability is associated not only with physical factors, but also

## APPLYING THE CONCEPT OF RESILIENCE TO INFRASTRUCTURE PROJECTS

with social, organizational, resource-related, and managerial factors. Recoverability is dependent on the readiness of resources and preparedness of organizations to respond to disaster events. Recovery of functionality requires the availability of human and capital resources (e.g., machinery) as well as organizational plans and processes required to take necessary actions rapidly and effectively.

For example, the recovery of destroyed road facilities requires construction manpower and equipment in addition to established processes and institutional measures, such as agreements between the public and the private sectors to collaborate in an emergency or the establishment of a clear incident management system. A proxy measurement of recoverability is the duration required to reach a target recovery level.

### PROJECT-LEVEL VERSUS SYSTEM-LEVEL RESILIENCE

When evaluating and measuring resilience, it becomes important to clarify the level of analysis. In other words, the ‘resilience of what’ matters. To apply the notion of resilience in infrastructure prioritization, it is helpful to distinguish between project-level and system-level resilience. Assessment of project-level resilience considers the functionality loss in the event of a shock and the ability of an asset to quickly recover from functionality loss. Asset functionality loss is a function of both the structural robustness of the facility and the level of exposure to a disruptive event. Recoverability depends on the availability of resources for reconstruction and the governance of emergency response management. System-level resilience, on the other hand, refers to the region’s or infrastructure network’s capacity to

absorb and recover from disasters. Infrastructure projects are generally elements of a functional system. This is particularly true for transportation networks. A government, for example, may consider implementing a new road section designated as an emergency transport route instead of a similar project that serves no emergency relief function. Given the nature of road infrastructure assets as network components, the construction of a new road may also enhance resilience by increasing redundancies in the network that allow access to alternative routes and absorb increased traffic in the case of emergency.

The methodology proposed in this paper is intended to estimate project-level resilience and not system-level resilience, though project functionality is inherently dependent on and related to the asset’s relationship to other parts of a system. Further, applied to the transport sector, the goal is to use information that is likely to be available in project feasibility studies for proposed road infrastructure or public datasets to estimate the effect of a disruption on various aspects of functionality. Keeping in line with the nature of the Infrastructure Prioritization Framework (IPF), the analysis at this level is also designed to draw on less complex and less analytically-demanding indicators to make the approach more feasible to apply in information- and capacity-constrained environments.

### DIMENSIONS OF FUNCTIONALITY

Infrastructure services attend to a wide array of interconnected purposes: they facilitate trade, allow mobility of people and goods, provide access to services, and support a host of other human activities. The relationships between assets in different infrastructure sectors are complex, and due to



The 2011 Great East Japan earthquake and tsunami flooded transport networks in the Tohoku region. –KYODO NEWS

sectoral variations with respect to physical structures, locations, and degrees of interconnectivity, natural disasters affect infrastructure assets in different ways. The functionality (and potential loss of functionality) of an infrastructure system is difficult to measure for all sectors within a given region. As such, it is presently more meaningful to make judgments of relative resilience within a sector and for similar types of projects. This paper, therefore, focuses specifically on applying concepts of resilience to road infrastructure projects.

While measurable aspects of functionality may be directly observable in a non-disrupted (normal) state, the *LoF* magnitude can only be estimated prior to a disruption. Moreover, the *LoF* magnitude after a disruption is only partially measurable by examining selected aspects of functionality. For road infrastructure, some of the most important elements of functionality include travel time, road utilization,

provision of emergency services, and provision of relief goods. The first two interrelated dimensions—travel time and utilization—are aspects related to economic impact, whereas the latter two dimensions—provision of emergency services and relief goods—are life-saving aspects.

When a road network faces a disruption, the loss of functionality manifests itself in many forms of economic loss. Damage may be reflected in increased transaction costs, loss of productivity, destruction of resources and wastage, and other negative economic impacts. Most apparent, however, the loss of functionality relates to increased travel times due to inoperability of affected roads. While reduced connectivity (interconnectedness of various areas) has impacts beyond its relationship with travel time, analyses largely center on the increased travel times between areas affected by a disaster event. Therefore, we focus the consideration of economic

## APPLYING THE CONCEPT OF RESILIENCE TO INFRASTRUCTURE PROJECTS

impact on the key feature of increased travel time. Moreover, travel time may be used directly as a measure of functionality, or as an input to a traffic demand function.

When a natural disaster strikes, road infrastructure serves another crucial function, namely to facilitate the preservation of human life. In the aftermath of a disaster, road access is prerequisite to effective search and rescue, conveyance of injured and vulnerable citizens to emergency facilities and shelters, and the supply of relief goods, medical services, and other forms of aid. Also, connectivity to resource depots, emergency shelters, and medical facilities is vital to support lifesaving functionality. While the notion of connectivity relates to travel time and other economic impacts, with respect to the preservation of human lives, the question associated with connectivity is whether affected areas are accessible within a window of time required to

provide life-saving resources or evacuate the critically ill or injured population.

In addition, road infrastructure must also be structurally robust to prevent road users from harm or death associated with the collapse of road structures. While it is recognized that road assets must be made 'safe to fail' (Ahern, 2011), because the intention of this study is to provide an initial basic methodology to calculate a limited—yet essential—set of resilience indicators, other aspects of resilience such as this will remain areas for future study.

To summarize, then, this approach to analyzing infrastructure resilience focuses on four dimensions of road functionality: travel time  $t$ , road utilization  $u$ , access for lifesaving services  $l$ , and provision of relief  $p$ . These functions serve as the basis for the set of calculated resilience indicators in road transport described in the following section.

# Infrastructure Resilience Indicators

This section presents basic infrastructure resilience indicators to support infrastructure investment decision-making. One major concern regarding infrastructure projects is the resilience of constructed facilities, i.e., project-level resistance and robustness that helps minimize loss of functionality. When applied to transport, the proposed indicators directly consider resilience at the project level through the concept of *accumulated loss of functionality (ALF)*. As shown in the next section, *ALF* conceptually relates inversely to resilience. In other words, the lower the *ALF*, the more ‘resilient’ the project is.

## ACCUMULATED LOSS OF FUNCTIONALITY

Consider a proposal for a road project *i*. Let  $ALF_{ik}$  denote a variable that represents the *accumulated loss of functionality* for the project associated with each of the four dimensions *k* mentioned above (*t*=travel time, *u*=road utilization, *s*=life-saving and *r*=relief provision), given the occurrence of natural disaster. In this context, the accumulated loss of functionality  $ALF_{ik}$  for project *i* corresponds to the dotted area in Figure 1. This calculation of the *ALF* follows the formula below:

$$ALF_{ik} = 0.5 \times LoF_{ik} \times TFR_{ik}$$

where  $LoF_{ik}$  measures the loss of functionality for project *i* in dimension *k*, and  $TFR_{ik}$  the time for recovery (time to regain loss of functionality). Alternatively, the formula below offers a measurement of project-level resilience  $Res_{ik}$  conceptualized as the inverse of accumulated loss of functionality:

$$Res_{ik} = 1 / ALF_{ik}$$

## VARIATION IN ACCUMULATED LOSS OF FUNCTIONALITY

*ALF* considers functionality changes before and after a disruption, for example, a land slide or a flood in the case of road transport projects. Policymakers may use this information when comparing infrastructure proposals, giving more priority to projects with lower *ALFs*. Policymakers may also consider the variation in *ALF* with and without the proposed infrastructure project. This variation in *ALF* would represent the project’s contribution to the road connection’s level of resilience—a metric that can also be useful to inform selection from amongst a set of proposed projects.

In this form of analysis, let  $ALF_{ik}^i$  denote the *accumulated loss of functionality* as in equation 1, but now under two possible states: with project (*j=w*) and without project (*j=wo*). From a resilience point of view, the accumulated loss of functionality with project ( $ALF_{ik}^w$ ), is expected to be lower than without project ( $ALF_{ik}^{wo}$ ), especially if the project specifically aims to improve resilience. The resulting  $ALF_{ik}^w$  may, however, be equal or even higher than the without- project  $ALF_{ik}^{wo}$ . The difference between the two results (*with* and *without* project) provides a measurement of the net contribution of any given project *i* to the reduction on accumulated loss of functionality.

$$\Delta ALF_{ik} = (\Delta ALF_{ik}^w / \Delta ALF_{ik}^{wo}) - 1 \quad (\times 100)$$

From a resilience point of view,  $\Delta ALF_{ik}$  is expected to be negative, reflecting a reduction in accumulated loss. Depending on the features of the infrastructure project, however, it may be positive or equal to zero. In the best-case scenario, a proposed project *i* generates zero Accumulated Loss of Functionality

## INFRASTRUCTURE RESILIENCE INDICATORS

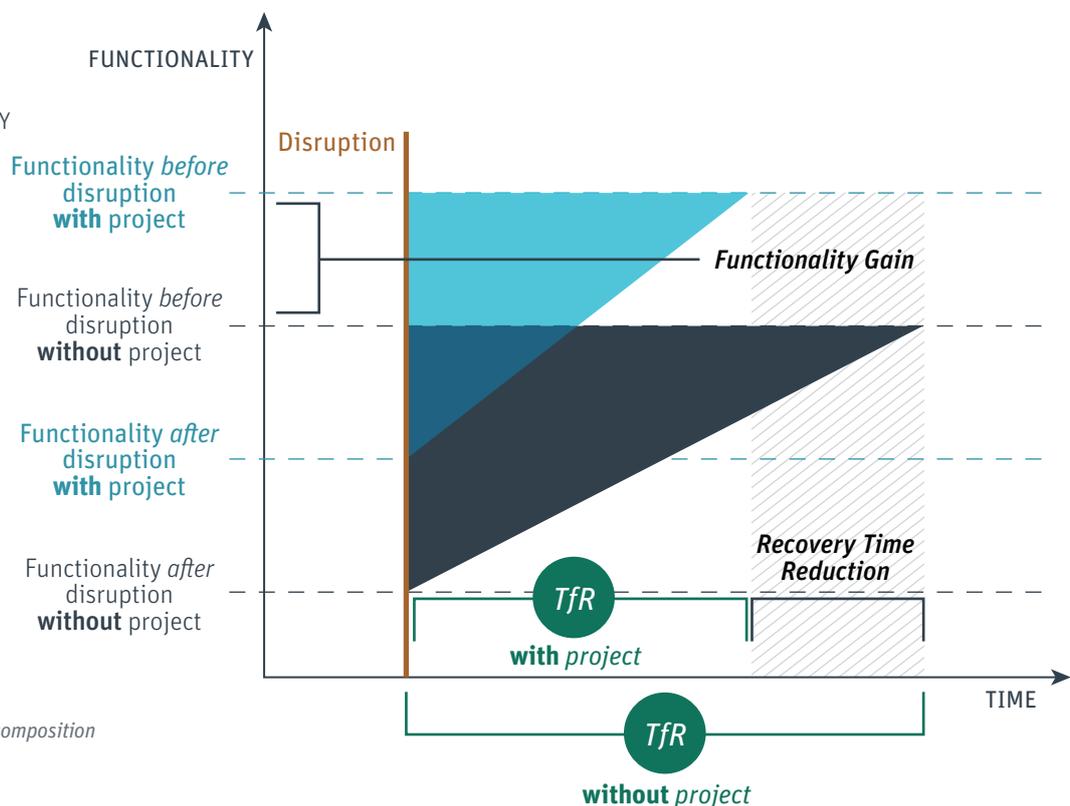
( $ALF_{ik}^w = 0$ ). In this scenario, there would be a 100% reduction in the existing Accumulated Loss of Functionality level. This may be the case, for example, of a road project proposal that, if implemented, guarantees to maintain its level of functionality (e.g. travel time) even after a major disruption (e.g. a magnitude 7 earthquake).

In general,  $\Delta ALF_{ik}$  will be less than zero whenever  $ALF_{ik}^w < ALF_{ik}^{wo}$  since there would be an expected reduction of the existing Accumulated Loss of Functionality level caused by the proposed project. The expected reduction will result from decreases in either  $LoF_{ik}$  or  $TfR_{ik}$  or both. **FIGURE 2** represents a case where, with project, both  $LoF_{ik}$  and  $TfR_{ik}$  simultaneously decrease. The difference in area of the two shaded triangles captures  $\Delta ALF_{ik}$ .

As mentioned earlier, upgraded or even new infrastructure may not necessarily translate into

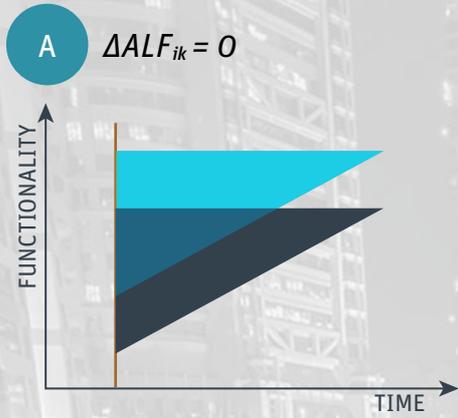
reductions in the accumulated loss of functionality. First,  $ALF_{ik}^w$  may remain the same, even if a project only increases the existing functionality levels (e.g., a reduction in travel time before and after disruption), or if a project reduces the time for recovery (e.g., reduction in flood recovery time) but increases the loss of functionality (see **FIGURE 3**, scenarios a and b). Second, if a project improves the current functionality level only in the ordinary state (e.g., road capacity measured in vehicles per day) but maintains the same  $TfR$  and expected functionality level following a disruption, then the  $ALF_{ik}^w$  will increase, since a greater pre-event functionality is expected to be lost (see Figure 3, scenario c). Less intuitively, a project may increase  $ALF_{ik}^w$  even if it increases the functionality levels (before and after disruption) and reduces the  $TfR$ . This is because the loss of functionality considers the difference between levels of functionality before and after disruption. The levels of functionality may increase,

**FIGURE 2.**  
ACCUMULATED  
LOSS OF  
FUNCTIONALITY  
WITH AND  
WITHOUT  
PROJECT



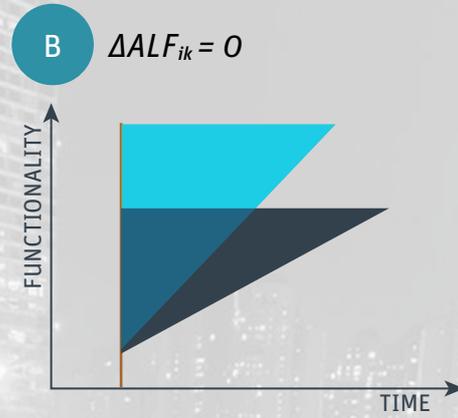
Source: Authors' composition

**FIGURE 3.**  
VARIATIONS ON ACCUMULATED LOSS OF FUNCTIONALITY



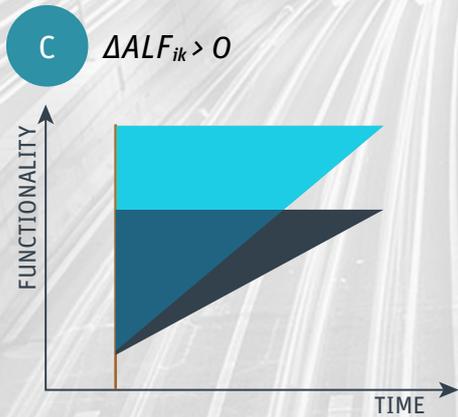
$$\Delta ALF_{ik}^w = \Delta ALF_{ik}^{wo}$$

- Higher functionality *with* project before and after disruption
- **But** same *LoF* and *TfR* *with* and *without* project



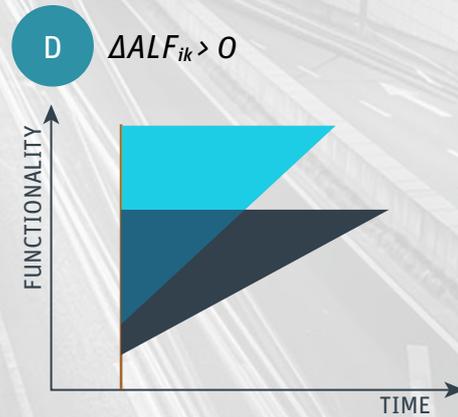
$$\Delta ALF_{ik}^w = \Delta ALF_{ik}^{wo}$$

- Higher functionality *with* project before and after disruption
- Lower *TfR* *with* project
- **But** same functionality *with* and *without* project after disruption
- **But** higher *LoF* *with* project



$$\Delta ALF_{ik}^w > \Delta ALF_{ik}^{wo}$$

- Higher functionality *with* project before disruption
- **But** same *TfR* *with* and *without* project
- **But** same functionality *with* and *without* project after disruption
- **But** higher *LoF* *with* project



$$\Delta ALF_{ik}^w > \Delta ALF_{ik}^{wo}$$

- Higher functionality *with* project before and after disruption
- Lower *TfR* *with* project
- **But** higher *LoF* *with* project

## INFRASTRUCTURE RESILIENCE INDICATORS

while their difference in functionality (pre-and post-disruption) may increase or decrease.<sup>3</sup>

### INDICATORS OF *LoF*

The *LoF* will depend on the type of disruption faced by a road network. Since various disruption scenarios are possible, the *LoF* calculations for each of the *k* dimensions require considering various types of disruptions, their potential intensities, and the likeliest resulting states of the road assets.

Let *S* denote two possible states for a road network, where *s=0* represents a non-disrupted and *s=1* represents a disrupted state.<sup>4</sup> Let *D* denote a set of all possible disruption events  $d \in D$ , such as earthquakes, major storms, or floods with varying scales and intensities.

To facilitate the comparison of project proposals, *LoFs* associated with different types of natural disasters *d* are estimated separately. Note that *LoF* calculations assume that disaster events will, indeed, occur. Further, by calculating baseline functionality levels with- and without-project under hypothesized natural disaster scenarios, *LoF* calculations also provide the inputs to calculate variations in *ALF* resulting from the implementation of a project. Section 4 describes this with examples.

The following sections describe measures to estimate *LoF* in the economic dimension, more specifically, travel time and utilization, and in the life-saving dimension, including the provision of emergency services and provision of relief goods.

### *LoF* INDICATORS FOR ECONOMIC DIMENSION

#### *LoF* Indicator for Travel Time

In terms of functionality loss for road infrastructure, the simplest way to assess the economic impact resulting from a disaster event is by measuring its effect on travel time between a representative origin-destination pair. Ideally, all roads connected to the proposed link should be evaluated using a network model approach. However, given the data intensity and technical capacity limitations in developing countries, for this analysis, the origin and destination are identified as the primary towns that the link is intended to serve.

Let  $t_i^{j(0)}$  denote the travel time between an origin-destination (O-D) pair under a non-disrupted state *s=0*, and  $t_i^{j(1)}$  the travel time under a disrupted state *s=1*. *j* captures two possible project implementation statuses: with project (*j=1*) and without project (*j=0*). Transport simulation models can offer estimations for  $t_i^{j(s)}$  in each case.

For any disaster event *d*, the expected road network *LoF* resulting from a proposed road project *i* for the travel time dimension (*k=t*) would correspond to

$$LoF_{it}^{j(s)} = Travel\ Time_i^{j(0)} - Travel\ Time_i^{j(1)}$$

#### *LoF* Indicator for Economic Benefit

A more direct measure of economic impact associated with increased travel time is the effect on road utilization (road demand). According to standard transport economics theory, the consumer surplus is a key consideration when assessing the economic benefit of a road network (de Palma, Andre, et al, 2011, World Bank, 2005). Calculation of consumer surplus requires specifying a traffic demand function, i.e., the relationship between travel volumes and generalized costs, including time value of users, travel time, and tariff charges.

Traffic demand depends on the generalized cost of transportation, which includes costs to the user such as travel time, safety, vehicle ownership and operation, and taxes, tolls, and other fares (Lee, 2000; Litman, 2017). If the generalized cost of transportation is proportional to travel time, holding other costs constant, transportation volume may be expressed as a function of travel time and vice versa.

We denote  $x=q(t)$  as the traffic demand function corresponding to the relationship between volume (e.g., vehicles per day)  $x$  and travel time  $t$  when assuming no tariff charges and a uniform time value for users. In addition, for the sake of simplicity, we assume that the function  $q(t)$  is linear as shown below:

$$q(t) = -m \times t + c$$

where the slope  $m$  is equal to  $(x^1 - x^0) / (t^1 - t^0)$  and  $c$  is a constant.

Disruption of a part of road network implies increased travel time resulting in the loss of economic benefit. In this specification, the economic loss due to disruption is equal to the difference between the consumer surplus of the ordinary (no disruption) state and that of the disrupted state (see shaded area, **FIGURE 4**).

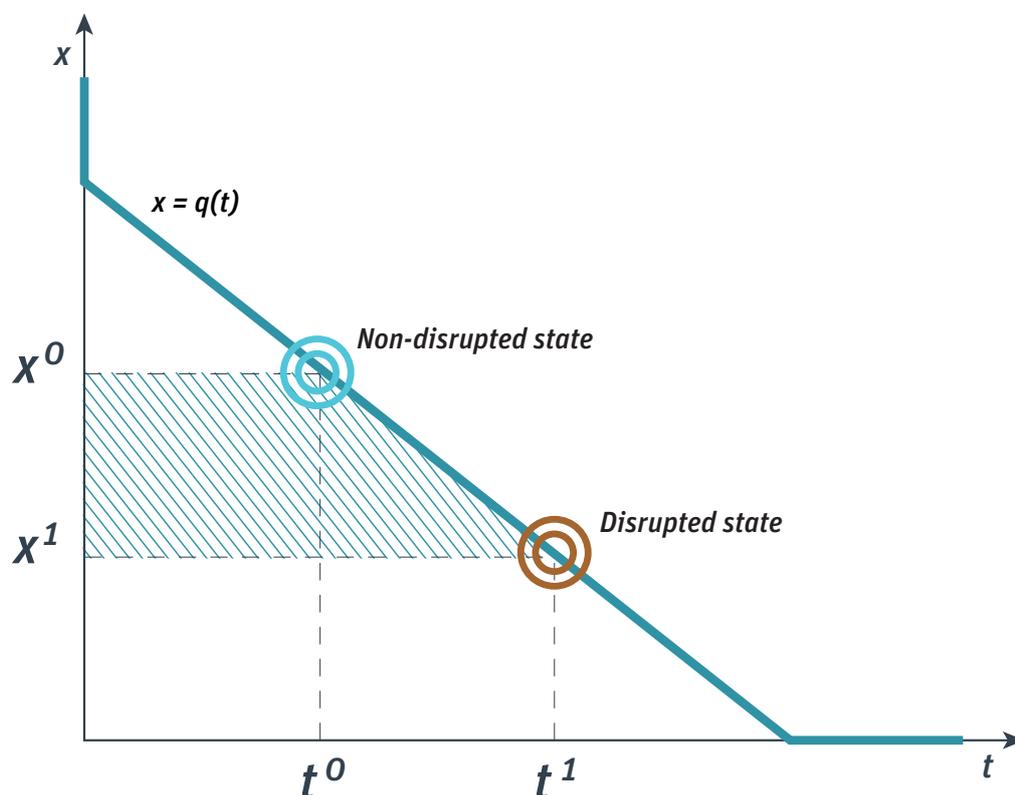
Therefore, *LoF* associated with a proposed project  $i$  in terms of lost consumer surplus (using decreased utilization as a proxy of economic loss), for any given disruption  $d$ , corresponds to:

$$LoF_{iu}^{j(s)} = (t_i^{j(0)} + t_i^{j(1)}) (x_i^{j(0)} - x_i^{j(1)}) / 2$$

For project  $i$ , the variable  $t_i^{j(s)}$  denotes the travel time of a representative O-D pair on a road under a disrupted state ( $s=1$ ) with project status  $j$ , and  $t_i^{j(0)}$  denotes the travel time under a non-disrupted state ( $s=0$ ). A simpler specification of equation 6 is as follows:

$$LoF_{iu}^{j(s)} = (t^0 + t^1) (x^0 - x^1) / 2$$

**FIGURE 4.**  
ROAD DEMAND  
FUNCTION



# INFRASTRUCTURE RESILIENCE INDICATORS

This approach may be appropriate if data on utilization is available or possible to estimate, as it gives a better indication of the economic losses associated with decreased road use.

## Conceptualization of Economic Dimension *LoF*

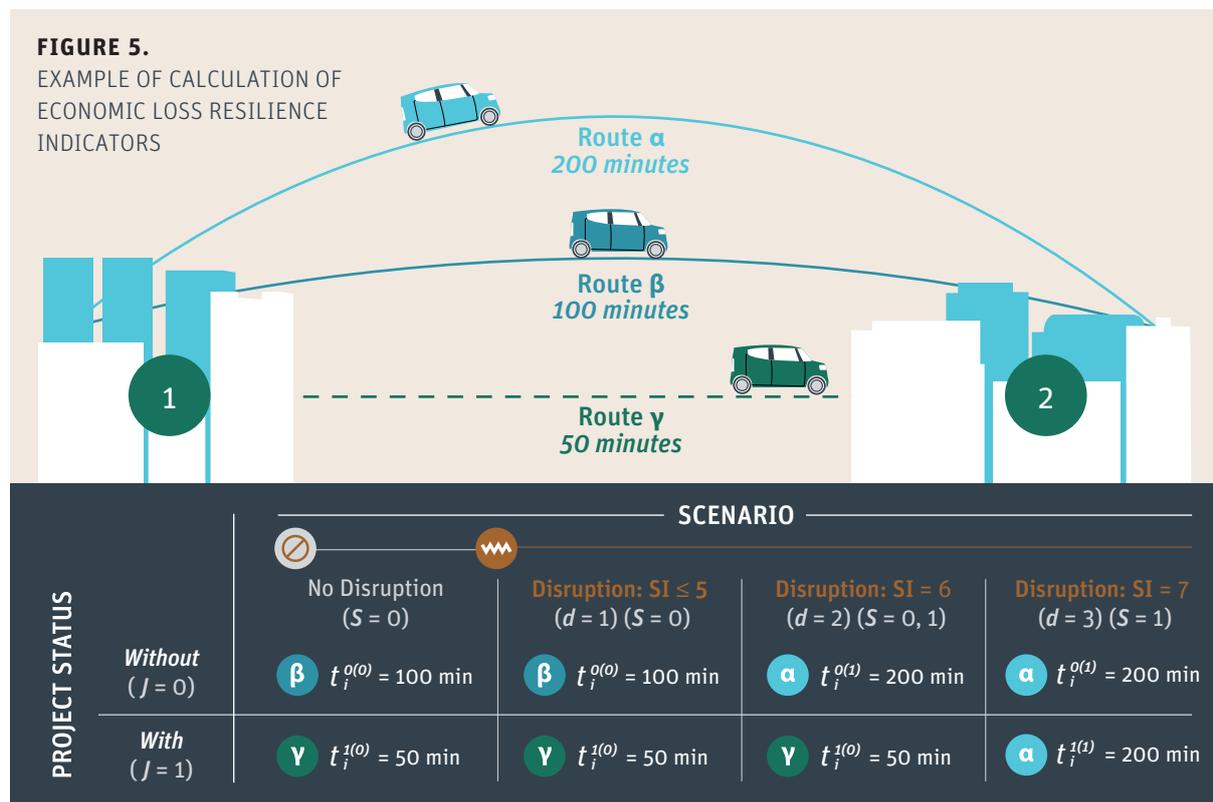
**FIGURE 5** illustrates the concepts of *LoF* for travel time and utilization. Suppose there are two existing road links, Route  $\alpha$  and Route  $\beta$ , between cities A and B. The construction of a new road “Route  $\gamma$ ” is under investigation. Route  $\alpha$  does not pass through areas prone to earthquakes and connects the two cities in a travel time of 200 minutes. By design, Route  $\beta$  allows to maintain a functional service level, with a reduced travel time of 100 minutes, even after an earthquake with a level-5 seismic intensity (SI), but not beyond that level. The proposed Route  $\gamma$  could maintain operability after a level 6 earthquake, but not a level 7.

both with and without the proposed project Route  $\gamma$ . These include the non-disrupted state and three possible disruption scenarios: a level-5 SI earthquake, a level-6 SI earthquake, and a level-7 SI earthquake.

Each potential disaster event will have an impact on the travel times between the A-B origin-destination pair. This is due to the designs and locations of the proposed Route  $\gamma$  and the existing routes  $\alpha$  and  $\beta$ . Without Route  $\gamma$ , if Route  $\beta$  is disrupted, Route  $\alpha$  would be the only available way to connect cities A and B. After a level 6 or 7 earthquake, the travel time would increase to 200 minutes.

The proposed Route  $\gamma$  is more resistant than Route  $\beta$  and could operate after a level 6 earthquake, but not after a level 7 (Route  $\beta$  would collapse under both scenarios). If implemented, Route  $\gamma$  would keep the connection between the cities functional even after a level 6 earthquake.

Figure 5 illustrates potential disruption scenarios,



The functionality of the road network will result from the combination between project status ( $j=0|1$ ) and disruption scenario ( $d=1|2|3$ ). The travel time of a representative O-D pair is the minimum travel time the available routes. The travel times with and without the project Route  $\gamma$  with no disruption and the three hazard scenarios are as follows:

No disruption:	$t_i^{o(o)} = 100$	$t_i^{1(o)} = 50$
Scenario 1 (d=1):	$t_i^{o(o)} = 100$	$t_i^{1(o)} = 50$
Scenario 2 (d=2):	$t_i^{o(i)} = 200$	$t_i^{1(o)} = 50$
Scenario 3 (d=3):	$t_i^{o(i)} = 200$	$t_i^{1(i)} = 200$

In this example, if  $d=2$  (SI 6 earthquake), the economic *LoF* would double, because the travel time without the Route  $\gamma$  project would increase from 100 to 200 minutes, whereas no travel time loss would arise with the project implemented, since no disruption (in terms of travel time) would occur.

The *LoF* calculation requires making assumptions of future, yet uncertain scenarios. One way to incorporate uncertainty is by defining the probabilities for each disruption scenario. In practice, however, obtaining reliable probabilistic distributions is complicated or costly to determine. Moreover, the calculations presented here do not require them. For the purposes of project comparison, the *LoF* and *TfR* calculations assume that each modelled disaster scenario will occur and compare their relative resilience in those hypothetical scenarios. This approach is consistent with construction practice, as required levels of structural robustness are typically specified and incorporated into design code.

For these reasons, we propose a deterministic approach that does not directly incorporate

probabilities of disaster scenarios in the calculations of potential losses and rather assumes disaster scenarios as if they effectively occurred. If known, however, probabilities of such disaster scenarios may guide the assumptions under this approach. Moreover, if available, these probabilities may provide inputs to calculate an indexed *ALF* via a weighted average.

The framework can also be applied to the upgrading or improvement of an existing road section. The example in **FIGURE 6** presents the case of a structural robustness upgrade for an existing road section. The logic is basically the same. Now suppose there are two links between cities A and B called Route  $\alpha$  and Route  $\beta$ . Route  $\alpha$  passes through an area free of earthquake risks, whereas Route  $\beta$  does not. A project  $i$  to structurally reinforce Route  $\beta$  is under investigation. Assume three disaster scenarios: (1) the occurrence of a level 5 earthquake ( $d=1$ ), (2) the occurrence of a level 6 earthquake ( $d=2$ ) and (3) the occurrence of a level 7 earthquake ( $d=3$ ). Route  $\beta$  can withstand an earthquake of SI less than 6, but not one of SI 6 or 7. If Route  $\beta$  is upgraded with project  $i$ , it could withstand an earthquake of SI less than 7 but not one of SI 7.

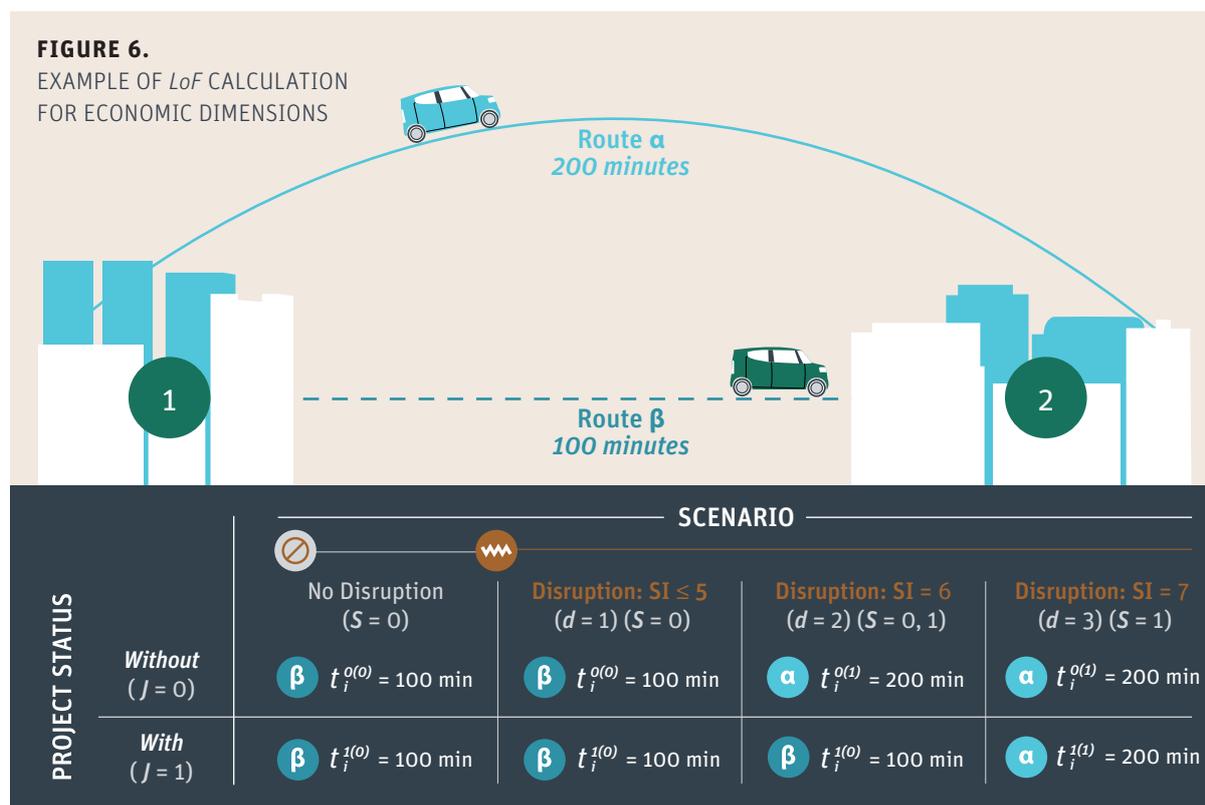
Figure 6 summarizes the various configurations resulting from the combination between project status and disaster scenarios. The associated travel times of the representative O-D pair for each state of network are:

No disruption:	$t_i^{o(o)} = 100$	$t_i^{1(o)} = 100$
Scenario 1 (d=1):	$t_i^{o(o)} = 100$	$t_i^{1(o)} = 100$
Scenario 2 (d=2):	$t_i^{o(i)} = 200$	$t_i^{1(o)} = 100$
Scenario 3 (d=3):	$t_i^{o(i)} = 200$	$t_i^{1(i)} = 200$

The travel times of the with-case and without-case are different under scenario 2 ( $d=2$ ). The travel time

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**FIGURE 6.**  
EXAMPLE OF *LoF* CALCULATION  
FOR ECONOMIC DIMENSIONS



between the O-D pair doubles if scenario 2 occurs in the without-project case, whereas no change in travel time would occur in the with-case since the proposed project would withstand a level 6 earthquake. Given scenario 2, then, *LoF* (the economic loss due to the increase of travel time) arises in the without-project case, but does not in the with-project case. This *LoF* savings over the period of recovery would account for the project’s contribution to resilience.

## LoF INDICATORS FOR LIFESAVING

The functionality of a road network in terms of the dimension of saving lives refers to the facilitation of emergency services, including search and rescue (S&R) and the provision of relief services and goods.

### LoF Indicator for Provision of Emergency Services

With respect to emergency services and S&R, roads

must provide quick access to major hospitals. Standard emergency practice assumes higher rates of mortality if emergency care is not offered within the “golden hour” following mass trauma (Lerner & Moscati, 2001). While research outcomes are mixed with respect to the veracity of this window, McCoy et al. found a significant increase in mortality rates following trauma after twenty minutes of emergency response time in urban settings (2013). Therefore, we assume a critical window of thirty minutes for emergency medical service response time.

*LoF* for S&R is defined as follows:

$$LoF_{ii}^{(s)} = Pop_{ii}^{j(0)} - Pop_{ii}^{j(1)}$$

where  $Pop_{ii}^{j(0)}$  is the population with access to major hospitals within thirty minutes under the ordinary state (with no disruption) and  $Pop_{ii}^{j(1)}$  is the population with emergency access under a specified

disaster scenario  $d$ , for each project  $i$ .

The contribution to resilience of a project from a life-saving standpoint can be captured by the difference in  $LoF_{ir}^{j(s)}$  for the with- and without-project cases.

### **LoF Indicator for the Dimension of Relief Goods**

The functionality of a road network in terms of human safety and lifesaving also includes the delivery of relief goods. With regards to the delivery of relief goods, accessibility is the key issue of functionality, as relief goods will not reach villages and municipalities isolated by the impacts of natural disasters. While  $LoF$  is a difference calculation for other aspects of functionality (i.e., the difference between the ordinary and disrupted states),  $LoF$  for the functionality of delivery of relief goods is simply defined as the isolated population under the disrupted state, since there is no (zero) isolation under the ordinary state. This calculation, therefore, is as follows:

$$LoF_{ir}^{j(s)} = Pop_{ir}^{j(s)}$$

where  $Pop_{ir}^{j(s)}$  is the population living in towns and villages that will become isolated under a specified hazard scenario  $s$  with the project status  $j$  for each project  $i$ . Again, the contribution to resilience of a project, with respect to access for provision of relief goods, can be captured by utilizing the difference in  $LoF_{ir}^{j(s)}$  for the with- and without-project cases and the time for recovery.

### **INDICATOR OF TFR**

Time for Recovery ( $TfR$ ) depends on the degree of damage as well as the level of emergency preparedness, including the existence of an emergency management plan and the pre-emptive establishment of cooperative agreements for road

clearance works and reconstruction between road administrators and contractors. Let  $TfR_{i^j}(s)$  denote the estimated time for recovery for a disrupted road network ( $s=1$ ) after a natural disaster  $d$  for each proposed project  $i$  with implementation status  $j$ .

To determine  $TfR$ , it also becomes necessary to establish the point in time at which recovery can be considered 'complete'. Reconstruction of roads to fully restore pre-event service levels may require extensive time and resources. Therefore, in the emergency period, road administrators often make disrupted roads available by provisional methods of construction that restore service, but not to full pre-event standards. This state of 'temporary recovery' is the state to which  $TfR$  applies.

The recovery time estimation requires assessing the state of existing assets, evaluating possible damages, and estimating the construction works capacity and availability of financial and human resources. In addition, damage assessments and other estimations can be used to calculate the workforce needed in the event of a disaster. Furthermore, the gap between the workforce needed to recover functionality and actual available personnel provides essential inputs to estimate the time for recovery. If damage assessments are not available or not possible to estimate, proxies using historical data may provide an estimate of the likely resource demands and time required for recovery. Any of these cases will require empirical data obtained through expert interviews and by examining the input requirements for recovery in similar historical cases.

The time for recovery ( $TfR$ ) associated with the various dimensions of functionality (i.e., lifesaving, relief, and economic) may be different. For lifesaving,

## INFRASTRUCTURE RESILIENCE INDICATORS

functionality is reestablished with a minimal level of restored access (e.g. if one lane of a highway clears for passage of emergency vehicles). However, pre-event traffic demand cannot be restored to a functional level until the disrupted road is open to the public again. The time for recovery in terms of the economic dimension of functionality is often longer than that of lifesaving and relief.

In Japan, for example, a post-tsunami road clearance plan is currently under development that specified required recovery times. The plan focuses on highways threatened by a potential large-scale tsunami resulting from an expected Nankai Trough Earthquake with 9.0 SI. At Wakayama Prefecture, the plan requires the clearance of at least one lane

of the connecting highways leading to the coastal areas from inland highways within 24 hours after a tsunami. Within 48 hours, important places (e.g., city halls) in coastal areas are to be connected with inland highways by clearing at least one lane of coastal highway. All coastal highways required to provide life-saving services, conduct search and rescue activities, and deliver emergency relief must be cleared within 72 hours. To implement this plan, having in place an inland highway and connecting highways to coastal areas is critical. Also, ensuring the provision of key power and economic resources is essential. Pre-event treaties between government and key stakeholders, especially with local contractors, are crucial to guarantee the availability of resources for recovery.

# Japan Case Studies

## CASE 1: CONSTRUCTION OF BYPASS ROAD IN A FLOOD-PRONE AREA

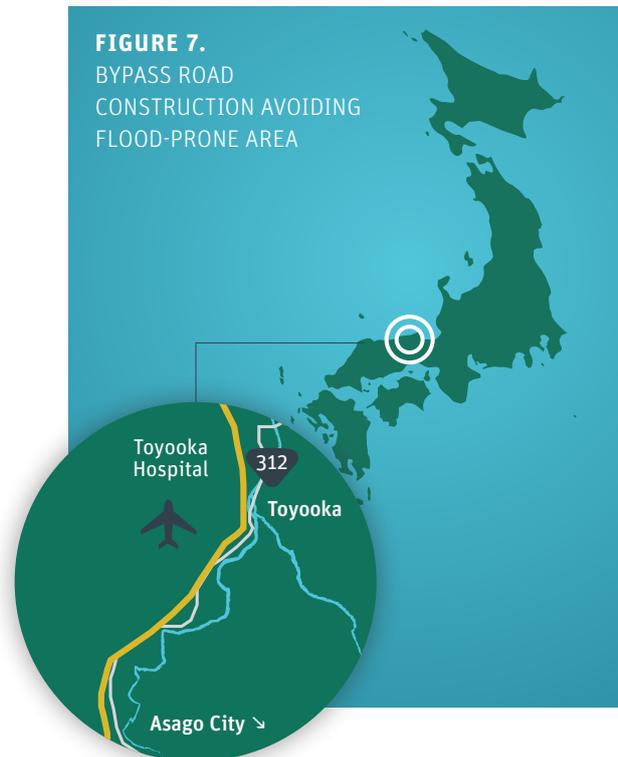
The first case project for testing the calculation of resilience indicators is a proposed construction of a new bypass road intended to save travel time and to develop an alternative route for the existing route, which is located in a flood-prone area (see **FIGURE 7**).

The existing route of National Highway No. 312 experienced a major flood of Maruyama river when Typhoon No. 18 hit in October 2004. This road section is a major highway connecting two local cities in the northern Hyogo prefecture, Toyooka City and Asago City. Toyooka City is a regional base in the North Tajima region wherein a first-aid station hospital, Toyooka Hospital, is located. Some residents in the flooded area are isolated and lose access to the first-aid station hospital. Moreover, the increase in travel time between the two cities due to necessary detouring is not negligible. The proposed bypass route passes through a mountainous area with some tunnels and, hence, is not exposed to flood risk.

### Indicator Data

Table 1 shows a list of necessary data for the calculation of resilience indicators for each dimension. The historical record of flooding in 2004 is set as an expected scenario for the disrupted state of the existing route.

The return period of this expected scenario is estimated to be 40 years by the MLIT (Ministry of Land, Infrastructure, Transportation and Tourism). Regarding the indicator for the economic loss dimension, ordinary-state traffic volume is assumed to be the design traffic volume for that road section. There is no valid data for the traffic volume in the disrupted state, but based on expert opinion of



professionals who observed the 2004 flooding, it is assumed to be half that of the ordinary state. Travel time between the representative O-D pair can be estimated by route navigation systems such as Google Maps, for example. For travel time in the disrupted state, it is assumed that inundated road sections are unavailable.

Regarding the indicator for saving lives, the population of the coverage area is assumed to be that of Tajima Area, which Toyooka Hospital covers as the primary first-aid station. By using a route search system such as Google, the area accessible to Toyooka Hospital within 30 minutes can be estimated for the both of ordinary and disrupted case. The population of that area can be determined by local demographics; therefore, the ratio of population who can access Toyooka Hospital within 30 minutes can be estimated.

**Table 1: Case 1 Resilience Indicator Data**

LoF Indicators	Relevant Data	Data Source	Content
Economic Loss	Traffic volume per min under the ordinary state ( $x_0$ )	Design traffic volume	13.68 pcu/min (19,700 pcu/day)
	Traffic volume per min without the project under the disrupted state ( $x_1$ )	Simulation	6.84 pcu/min
	Travel time between representative OD (Asago – Toyooka) without the project under the ordinary state ( $t^{wo(0)}$ )	Route search system	50 mins
	Travel time between representative OD (Asago – Toyooka) with the project under the ordinary state ( $t^{wo(0)}$ )	Route search system	42 mins
	Travel time between representative OD (Asago – Toyooka) without the project under the disrupted state ( $t^{wo(1)}$ )	Route search system	79 mins
	Travel time between representative OD (Asago – Toyooka) with the project under the disrupted state ( $t^{wo(1)}$ )	Route search system	42 mins
Saving Lives	Population of coverage area (Tajima Area) ( $Pop_s^{(0)}$ )	Population statistics	180,607
	The percentage ratio of population who can access major hospitals in 30 minutes <i>without</i> the project under the <i>ordinary</i> state	Route search system	45.1%
	The percentage of population who can access major hospitals in 30 minutes <i>with</i> the project under the <i>ordinary</i> state	Route search system	52.2%
	The percentage of population who can access major hospitals in 30 minutes <i>without</i> the project under the <i>disrupted</i> state	Route search system	35.7%
	The percentage of population who can access major hospitals in 30 minutes <i>with</i> the project under the <i>disrupted</i> state	Route search system	47.3%
Relief Goods	The number of isolated population <i>without</i> the project under the <i>disrupted</i> state $Pop_r^{wo(1)}$	0	8162
	The number of isolated population <i>with</i> the project under the <i>disrupted</i> state $Pop_r^{w(1)}$	0	8162
TfR	Estimated necessary time for temporal recovery <i>without</i> the project	Length/Speed	1.25 days (30 hours)
	Estimated necessary time for temporal recovery of existing road section <i>with</i> the project	Length/Speed	0.625 days (15 hours)
	Estimated necessary time for temporal recovery <i>with</i> the project	Bypass is risk free	0 days

Residents in the flooded-area are isolated and, therefore, are unable to access the first-aid station hospital. The new bypass would be free from flood risk, but the existing road section is not. Regarding Time for Recovery, *TfR*, the record of road clearance work of the Great Eastern Japan

Earthquake shows it took an average of 0.1 km per hour. For the existing road section in the case study, since clearance work can occur from the two edges of the road, the time for recovery is estimated to be  $6/0.2=30$  hours or 1.25 days. This *TfR* would get affected if the bypass is built because

it would allow for clearance work to start from two additional edges (as seen in **FIGURE 8**), making the necessary time to complete the road clearance work equal to  $6/0.4 = 15$  hours or 0.625 days.<sup>5</sup> The new bypass is not vulnerable to flood risk and so, there is no associated  $TfR$ .

### Numerical Calculation of Indicators

As described earlier, economic loss associated with utilization is calculated as follows:

$$LoF_{iu}^{j(s)} = (t^0 + t^1) (x^0 - x^1) / 2$$

This case considers only one disrupted scenario.

Therefore,

$$LoF_{iu}^{wo} = (50+79) \times (13.68 - 6.84) / 2 = 441.18$$

and

$$ALF_{iu}^{wo} = 0.5 \times LoF_{iu}^{wo} \times TfR^{wo} \\ = 0.5 \times 441.18 \times 1.25 = 275.74$$

$LoF_{iu}^w = ALF_{iu}^w = 0$  as the bypass route is free from flood risk and so, the inter-city transport route remains unaffected. Therefore, the variation in  $ALF$  is as follows:

$$\Delta ALF_{iu} = \Delta ALF_{iu}^{wo} - \Delta ALF_{iu}^w \\ ALF_{iu}^{wo} = 275.74 - 0 = 275.74$$

Likewise,  $LoF$  for the saving lives dimension and for the relief goods dimension is calculated as follows.

Therefore,

$$LoF_{li}^{wo} = [180,607 \times (0.451 - 0.357)] = 16,977.06$$

and

$$ALF_{li}^{wo} = 0.5 \times LoF_{li}^{wo} \times TfR^{wo} \\ = 0.5 \times 16,977.06 \times 1.25 = 10,610.66$$

Because of the bypass route, the  $TfR$  reduces as explained earlier and therefore,

$$LoF_{li}^w = 180,607 \times (0.522 - 0.473) = 8,849.74$$

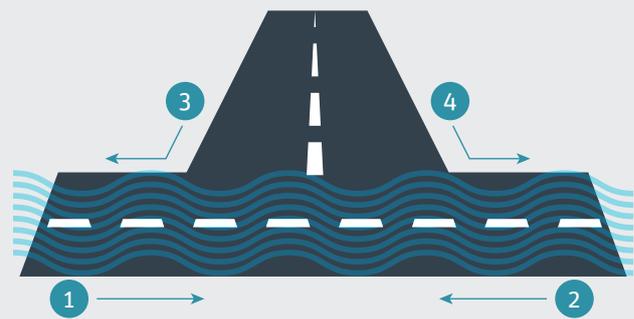
And,

**FIGURE 8.**  
ROAD CLEARANCE WORK PROCEDURE  
AND BYPASS PROJECT

**without the bypass project**  
existing road in inundated area



**with the bypass project**



Note: Arrows show direction of road clearance work.

$$ALF_{li}^w = 0.5 \times LoF_{li}^w \times TfR^w \\ = 0.5 \times 8,849.74 \times 0.625 = 2,765.54$$

Therefore, the contribution to resilience associated with the variation to  $ALF$  for lifesaving is:

$$\Delta ALF_{li} = \Delta ALF_{li}^{wo} - \Delta ALF_{li}^w \\ = 10,610.66 - 2,765.54 = 7,845.12$$

Residents in the flooded area are counted as population of isolated villages. These do not change in the with or without case, making

$$LoF_{ri}^w = LoF_{ri}^{wo} = 8,162$$

The  $TfR$ s under with and without project are different, and so, the corresponding  $ALF$ s are calculated as

## JAPAN CASE STUDIES

$$ALF_r^{wo} = 0.5 \times LoF_r^{wo} \times 1.25 = 5,101.25$$

$$ALF_r^w = 0.5 \times LoF_r^w \times 0.625 = 2,550.625$$

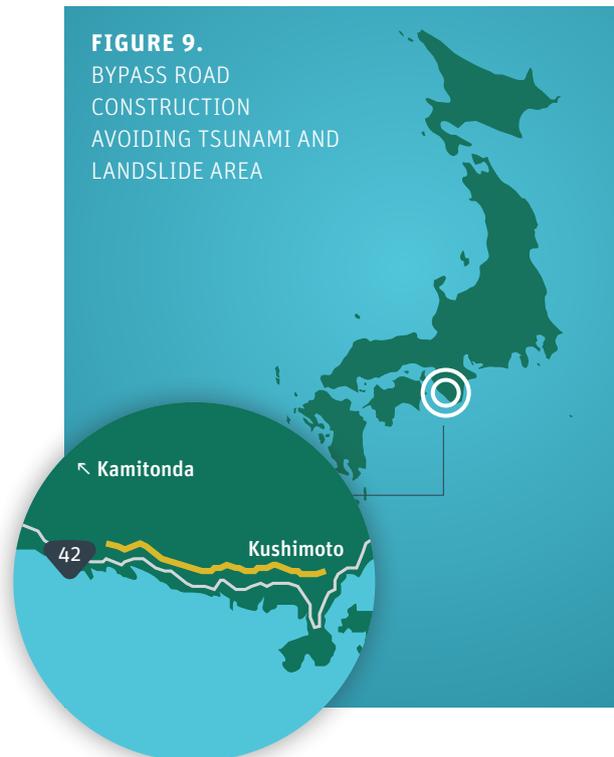
Therefore, the variation to the *ALF* indicator for relief goods,

$$\Delta ALF_r = \Delta ALF_r^{wo} - \Delta ALF_r^w = 2,550.63$$

### CASE 2: CONSTRUCTION OF BYPASS ROAD IN A TSUNAMI-PRONE AREA

The second case project is another bypass road intended to reduce travel time and provide an alternative route to avoid a tsunami-prone area (see **FIGURE 9**). The existing National Highway No. 42 runs through the nearby coastal area along the Pacific Ocean, which is characterized by steep slopes and serves as the only primary route available to connect cities along the coastal area. If the existing highway is disrupted, there is no alternative route available for the coastal cities it serves. This road section is exposed to the high possibility of a tsunami caused by the Nankai Trough Earthquake which is expected to occur in next few decades. The proposed bypass runs outside the tsunami-prone area, and, therefore, works as the alternative route during the disruption of existing national highway. Most residents live along the existing national highway and would lose access to the major hospital if the road is obstructed. Therefore, even with the bypass, the population suffering due to the tsunami would remain the same. However, the critical impact of the bypass would be on the recovery time since it allows for additional points to start road clearance work.

Table 2 lists the data in Case 2. The economic loss calculations required knowing the traffic volume



**FIGURE 9.**  
BYPASS ROAD  
CONSTRUCTION  
AVOIDING TSUNAMI AND  
LANDSLIDE AREA

of the ordinary and disrupted states between the representative O-D pair (Kamitonda-Kushimoto). The existing national highway is the only primary route connecting towns in the coastal area. If the existing highway is disrupted, the only available detour is a secondary route including narrow roads in the mountainous area. While it usually takes 60 minutes between Kamitonda and Kushimoto under the ordinary state, the disruption of the highway would result in a 119-minute travel time. The bypass consists mostly of tunnels and runs through areas away from the coast and hence, is free from the risk of a tsunami. The travel time between Kamitonda and Kushimoto using the bypass is 49 mins. The traffic volume between Kamitonda and Kushimoto is assumed to be the design traffic volume in the ordinary state whereas, the volume in the disrupted state is assumed to be zero, based on expert opinion. The expected time for recovery in

**Table 2: Case 2 Resilience Indicator Data**

LoF Indicators	Relevant Data	Data Source	Content
Economic Loss	Traffic volume per min under the ordinary state ( $x_0$ )	Design traffic volume	5.14 pcu/min (7,400 pcu/day)
	Traffic volume per min without the project under the disrupted state ( $x_1$ )		0 pcu/min
	Travel time between representative OD (Kamitonda – Kushimoto) without the project under the ordinary state ( $t^{wo(0)}$ )	Route search system	60 mins
	Travel time between representative OD (Kamitonda – Kushimoto) with the project under the ordinary state ( $t^{wo(0)}$ )	Route search system	49 mins
	Travel time between representative OD (Kamitonda – Kushimoto) without the project under the disrupted state ( $t^{wo(1)}$ )	Route search system	119 mins
	Travel time between representative OD (Kamitonda – Kushimoto) with the project under the disrupted state ( $t^{wo(1)}$ )	Route search system	49 mins
Saving Lives	Population of coverage area (Kinan Area) ( $Pop_k^{(0)}$ )	Population statistics	243,025
	The percentage ratio of population who can access major hospitals in 30 minutes <i>without</i> the project under the <i>ordinary</i> state	Route search system	78.1%
	The percentage of population who can access major hospitals in 30 minutes <i>with</i> the project under the <i>ordinary</i> state	Route search system	78.5%
	The percentage of population who can access major hospitals in 30 minutes <i>without</i> the project under the <i>disrupted</i> state	Route search system	52.8%
	The percentage of population who can access major hospitals in 30 minutes <i>with</i> the project under the <i>disrupted</i> state	Route search system	52.8%
Relief Goods	The number of isolated population <i>without</i> the project under the <i>disrupted</i> state $Pop_r^{wo(1)}$	Population of inundated area	61,571
	The number of isolated population <i>with</i> the project under the <i>disrupted</i> state $Pop_r^{wo(1)}$	Population of inundated area	61,571
TfR	Estimated necessary time for temporal recovery <i>without</i> the project	Length/speed	10.625 days (255 hours)
	Estimated necessary time for temporal recovery of existing road section <i>with</i> the project	Length/speed	126 hours (5.25 days)
	Estimated necessary time for temporal recovery <i>with</i> the project	Bypass is risk free	0 days

the case of a disruption of the existing route is 255 hours (10.625 days), based on the road clearance plan for a tsunami disaster prepared by MLIT.

**Numerical Calculation of Indicators**

Applying the calculation formula, the indicator for

the dimension of economic loss in the case of a disruption without the proposed bypass is calculated as follows.

$$LoF_u^{wo} = (60+199) \times (5.14-0) / 2 = 4,60.03$$

and

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$$ALF_u^{wo} = 0.5 \times LoF_u^{wo} \times Tfr^{wo}$$

$$= 0.5 \times 460.03 \times 10.625 = 2,443.91$$

$LoF_u^w = ALF_u^w = 0$  as the bypass route is free from flood risk. Therefore,

$$\Delta ALF_u = \Delta ALF_u^{wo} - \Delta ALF_u^w$$

$$ALF_u^{wo} = 275.74 - 0 = 2,443.91$$

Likewise,  $LoF$  for the saving lives and relief goods dimensions are calculated as follows:

$$LoF_l^{wo} = [243205 \times (0.781 - 0.528)] = 61,530.87$$

and

$$ALF_l^{wo} = 0.5 \times LoF_l^{wo} \times Tfr^{wo}$$

$$= 0.5 \times 61,530.87 \times 10.625 = 326,882.72$$

With the bypass, most residents living in areas expected to be inundated will be affected, however, the  $Tfr$  would be less, leading to the following functionality loss:

$$LoF_l^w = [24,3205 \times (0.785 - 0.528)] = 62,503.69$$

And,

$$ALF_l^w = 0.5 \times LoF_l^w \times Tfr^w$$

$$= 0.5 \times 62,503.69 \times 5.25 = 164,072.17$$

Therefore,

$$\Delta ALF_l = \Delta ALF_l^{wo} - \Delta ALF_l^w$$

$$= 162,810.55$$

For the indicator for the dimension of providing relief, areas that would be isolated in a hazard event and their accumulated populations can be identified. The isolated population does not change with or without the project and, therefore

$$LoF_r^{wo} = LoF_r^w = 61571$$

$$ALF_r^{wo} = 0.5 \times LoF_r^{wo} \times Tfr^{wo}$$

$$= 0.5 \times 61571 \times 10.625 = 327,095.94$$

$$ALF_r^w = 0.5 \times LoF_r^w \times Tfr^w$$

$$= 0.5 \times 61571 \times 5.25 = 161,631.75$$

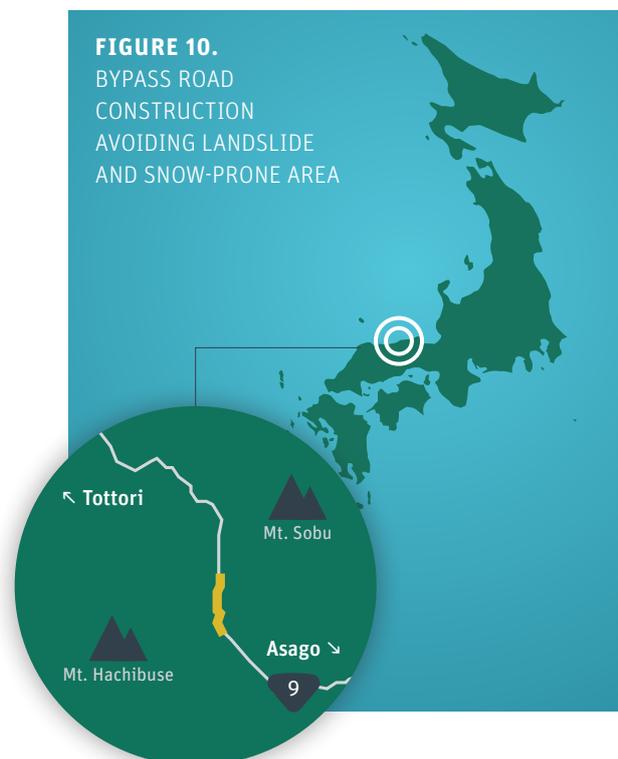
Therefore,

$$\Delta ALF_r = \Delta ALF_r^{wo} - \Delta ALF_r^w$$

$$= 165,464.19$$

### CASE 3. CONSTRUCTION OF BYPASS ROAD IN LANDSLIDE-PRONE AND HEAVY SNOW AREA

The third case project is the construction of a bypass road intended to avoid a landslide-prone area. National Highway No. 9 is a major route along the north shore of western Honshu, the main island of Japan. The particular road section of interest is located in an area where large scale landslides can occur. In addition, this road section includes a pass vulnerable to snowy weather. The risk considered in this analysis is only that of landslides, since the impact is expected to be heavier as compared to a snow storm in terms



**Table 3: Case 3 Resilience Indicator Data**

LoF Indicators	Relevant Data	Data Source	Content
Economic Loss	Traffic volume per min under the ordinary state ( $x_0$ )	Design traffic volume	6.11 pcu/min (8800 pcu/day)
	Traffic volume per min without the project under the disrupted state ( $x_1$ )	Simulation	3.06 pcu/min
	Travel time between representative OD (Asago – Tottori) without the project under the ordinary state ( $t^{wo(0)}$ )	Route search system	109 mins
	Travel time between representative OD (Asago – Tottori) with the project under the ordinary state ( $t^{wo(0)}$ )	Route search system	109 mins
	Travel time between representative OD (Asago – Tottori) without the project under the disrupted state ( $t^{wo(1)}$ )	Route search system	113 mins
	Travel time between representative OD (Asago – Tottori) with the project under the disrupted state ( $t^{wo(1)}$ )	Route search system	109 mins
Saving Lives	Population of coverage area (Tajima Area) ( $Pop_{is}^{(0)}$ )	Population stats	180,607
	The percentage ratio of population who can access major hospitals in 30 minutes <i>without</i> the project under the <i>ordinary</i> state	Route search system	45.1%
	The percentage of population who can access major hospitals in 30 minutes <i>with</i> the project under the <i>ordinary</i> state	Route search system	45.1%
	The percentage of population who can access major hospitals in 30 minutes <i>without</i> the project under the <i>disrupted</i> state	Route search system	45.1%
	The percentage of population who can access major hospitals in 30 minutes <i>with</i> the project under the <i>disrupted</i> state	Route search system	45.1%
Relief Goods	The number of isolated population <i>without</i> the project		0
	The number of isolated population <i>with</i> the project		0
TfR	Estimated necessary time for temporal recovery <i>without</i> the project for landslide	Professional opinion	2 days
	Estimated necessary time for temporal recovery <i>with</i> the project for landslide	N/A	N/A

of recovery time required. The national highway is the major corridor in this area, though a detour route is still available. The proposed bypass tunnel would run through the landslide-prone area and allow for this road section to remain free from the risk of landslides.

**Indicator Data**

Table 3 shows the necessary data for the calculation of resilience indicators for each dimension in Case 3. As with the above cases, the traffic volume in

the ordinary state is taken to be the design traffic volume. The travel time is calculated by a route search system like Google Maps. Since alternate routes to Nation Highway No. 9 exist, a disruption to the road section causes only a 4-minute increase in travel time between Toyooka and Tottori. Using a route search system, areas accessible to the major hospital can be determined and, hence, the population with access can be calculated by drawing on demographic statistics. Because the disrupted

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section is just a single point, none of the population is isolated, even in the disrupted state.

The expected time for recovery depends on the type of hazard events. A landslide event requires 2 days for recovery, on average.

### Numerical Calculation of Indicators

Again, applying the formula for economic loss of functionality loss, the  $LoF$  indicator without the proposed bypass is calculated as follows:

$$LoF_u^{wo} = (109 + 113) \times (6.11 - 3.06) / 2 = 338.55$$

Therefore,

$$ALF_u^{wo} = 0.5 \times LoF_u^{wo} \times TfR^{wo} \\ = 0.5 \times 338.55 \times 2 = 338.55$$

$LoF_u^* = ALF_u^* = 0$  as the bypass tunnel is free from landslide risk. Therefore,

$$\Delta ALF_u = \Delta ALF_u^{wo} - \Delta ALF_u^* \\ = 338.55$$

Likewise,  $LoF$  for the dimension of saving lives and for the dimension of providing relief goods can be calculated as follows: because the ratio of population who can access the major hospital is same in the ordinary and disrupted state,  $\Delta ALF_l = 0$ . And finally, because the flood scenario does not cause any isolation of villages,  $\Delta ALF_r = 0$ .

### COMPARING PROJECT RESILIENCE

The calculations in the above cases can be used to compare the projects' variations in accumulated loss of functionality (Table 4) by analyzing the projects' contribution to both, the percentage of functionality losses reduced in the three dimensions, and the absolute amount of  $ALF$  reduced. Because the above three cases are specifically intended to mitigate

exposure to particular hazards, they are designed to eliminate functionality losses, thus making their respective  $\Delta LoF^w$  and  $\Delta ALF^w$  calculations equal to zero.

**Table 4: Comparing loss reductions due to bypass projects**

Case Project/ Dimension	Case 1	Case 2	Case 3
$\Delta ALF_u^w$	100% (275.7)	100% (2,443.91)	100% (338.55)
$\Delta ALF_l^w$	73.94% (7,845.12)	49.81% (162,810.5)	—
$\Delta ALF_r^w$	50% (2,550.625)	50.59% (165,464.2)	—

*Note: Percentage reduction is presented with the  $\Delta ALF$  in parenthesis*

Table 4 suggests that the second project will make the greatest contributions to reducing loss in the event of an extreme event. This is because, first, even though all three projects reduce functionality losses in terms of utilization by 100%, the bypass in Case 2 would impact a greater amount of traffic volume. Second, while the functionality loss for saving lives is reduced only by 50% in Case 2 as compared to 74% in Case 1, again, the absolute number of people whose access to lifesaving services is preserved is greater. Similarly, for the last dimension, even though the percentage loss is the same between the first two cases, the absolute number of people saved from potential isolation is greater in the second. In other words, the Case 2 project makes the greatest contribution to resilience among the three proposed bypass projects in absolute terms.

### SENSITIVITY ANALYSIS

In this section, we test the results of the analysis by varying some of the underlying assumptions to ensure that results are not highly sensitive to minor variations. To do so, the saving lives indicators were re-estimated. The assumption underpinning

**Table 5: Assessing  $\Delta ALF_i^w$  changing assumption of access to lifesaving services within 60 minutes**

Dimension - Saving Lives (60 mins)	Case 1	Case 2	Case 3
The percentage of population who can access major hospitals in 60 minutes <i>without</i> the project under the <i>ordinary</i> state	90.20%	99.50%	90.20%
The percentage of population who can access major hospitals in 60 minutes <i>with</i> the project under the <i>ordinary</i> state	93.60%	99.50%	90.20%
The percentage of population who can access major hospitals in 60 minutes <i>without</i> the project under the <i>disrupted</i> state	79.80%	74.10%	90.20%
The percentage of population who can access major hospitals in 60 minutes <i>with</i> the project under the <i>disrupted</i> state	89.00%	74.10%	90.20%
$\Delta ALF_i^w$	77.9% (9,143.23)	50% (33,2035.62)	—

the calculations changed, from the percentage of the population that can access a major hospital within 30 minutes (as in the original calculation), to the percentage that can access emergency care within 60 minutes.

Comparing the results in Tables 4 and 5, we find that there is a negligible variation in the results even when the time assumption is doubled. This suggests that the results of the analysis are sufficiently robust for project comparison.

## Discussion and Conclusion

The proposed indicators offer a starting point for calculating and applying resilience indicators to support project selection. Moreover, the World Bank’s Infrastructure Prioritization Framework (IPF) can use the resilience measurements presented in this paper in two ways. First, if the data to calculate the proposed resilience estimates is available or acquirable at the project-level, it can be directly inputted into the IPF as additional criteria in the social-environmental index (SEI). In most countries, however, required data is likely to be sparse. In that case, the aim should be to measure infrastructure resilience for only those

projects that emerge as “high priority” from the prioritization analysis, and use resilience indicators as complementary information to support final project selection, but not as a part of the SEI.

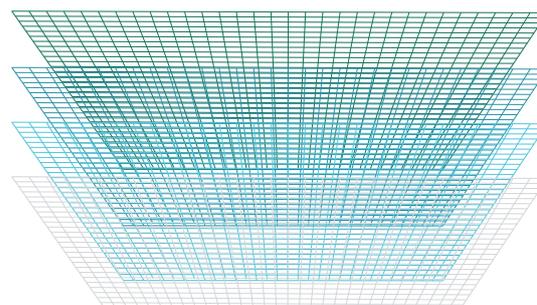
While this approach is not intended to ‘solve’ problems of resilience or determine sector-wide or regional strategies for mitigating disaster, the proposed indicators introduce considerations of resilience that can guide infrastructure investment decisions. Moreover, the indicators offer two potential approaches to consider resilience with respect to infrastructure investments. On the one hand, the proposed transport asset’s expected Accumulated

## DISCUSSION AND CONCLUSION

Loss of Functionality (*ALF*) may be considered in isolation to better understand the ‘resilience’ of road projects. In this case, the question at hand is how much functionality various proposed projects will lose in the event of a disaster. On the other hand, if projects are pursued specifically to improve a region’s overall resilience, a more important metric would be an *ALF* variation ( $\Delta ALF$ ) that measures a project’s impact on the overall road system.

The proposed indicators also address four interrelated dimensions of resilience: travel time, utilization, provision of emergency services, and provision of relief goods and services. What measures are included in resilience calculations and what approach to measurement is taken (*ALF* or  $\Delta ALF$ ) will depend on the policy goals associated with the proposed projects, as well as the information available to inform considerations of functionality and resilience.

Piloting application of these approach in real-life contexts will help further develop the indicators themselves and improve their application to infrastructure decision-making. Also, piloting these indicators will lead to a better understanding of the different approaches’ and dimensions’ relative usefulness for decision-making. Also, the results should be subject to expert review and compared to alternative (possibly qualitative) approaches to assessing the relative ‘resilience’ of proposed projects. In addition, since there are likely to be uncertainties related to data used for estimating functionality as well as the assumptions employed, it is essential to test results with a range of specifications during the piloting of this work. This would not only test the sensitivity of the results but also their robustness.



**“Piloting application of these approach in real-life contexts will help further develop the indicators themselves and improve their application to infrastructure decision-making.”**

Piloting should also aim to develop guidance for applying the  $\Delta ALF$  indicator where investments follow the specific policy goal of improving system or regional resilience. Further guidance should be developed to understand the prevalence of and develop approaches to deal with the special cases described in section 3.2, wherein projects may improve functionality in the ordinary state but make relatively lower or no improvements to post-hazard functionality. In these situations, there may be calculated increases to *ALF* due to the relatively higher losses of functionality due to overall gains in functionality. A potential option to deal with this, which should be tested in piloting, is to compare estimated post-hazard functionality with a proposed project to the estimated post-hazard functionality without the project.

Further, piloting will also lead to a better understanding of the informational and analytical demands associated with estimating loss of functionality and time for recovery. Since these resilience indicators are intended to support infrastructure decision-making under various informational conditions, it is important that the input data required to calculate resilience indicators be reasonably accessible. Piloting should focus on improving approaches to estimating time for recovery.

## Endnotes

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2. The Japan Meteorological Agency uses a seismic scale of zero to seven to describe the degree of shaking at any given time during an earthquake.
3. Note that the *ALF* estimate is meant to be used in conjunction with other indicators included in the Infrastructure Prioritization Framework. This means that projects that may have strong beneficial effects to society such as time savings, gains in productivity, higher number of beneficiaries, etc. would be not penalized because they lead to greater loss of functionality during a disruption (since a disruption might represent a small percentage of the time the road is usable for the rest of the year).
4. While a disaster event could potentially result in a variety of disrupted states with associated probabilities, we choose for the sake of simplicity to model only the *LoFs* for an observed non-disrupted state ( $s=0$ ) and an estimated disrupted state ( $s=1$ ) associated with a potential disaster event  $d$ .
5. While *TfRs* are likely to be different for the different dimensions of functionality, we assume the same *TfR* across dimensions (based on available data for resumed traffic) for the purposes of demonstrating indicator calculations.

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### **World Bank Infrastructure, PPPs & Guarantees Group**

The World Bank's Infrastructure, PPPs & Guarantees Group (IPG) has staff co-located in Washington, DC and Singapore. It acts as a 'connector' on PPP and infrastructure finance and policy issues across the World Bank Group as well as the wider development community. IPG provides research and advice, including specialized support to projects that involve infrastructure development and planning. IPG also creates and promotes tools and standards to improve infrastructure planning, mobilize commercial financing for infrastructure and, as appropriate, help governments determine when and how to use PPPs.

### **World Bank DRM Hub Tokyo**

The World Bank Tokyo Disaster Risk Management Hub supports developing countries to mainstream DRM in national development planning and investment programs. As part of the Global Facility for Disaster Reduction and Recovery, the DRM Hub provides technical assistance grants and connects Japanese and global DRM expertise and solutions with World Bank teams and government officials. The DRM Hub was established in 2014 through the Japan-World Bank Program for Mainstreaming DRM in Developing Countries—a partnership between Japan's Ministry of Finance and the World Bank.

### **GFDRR**

The Global Facility for Disaster Reduction and Recovery (GFDRR) is a global partnership that helps developing countries better understand and reduce their vulnerabilities to natural hazards and adapt to climate change. Working with over 400 local, national, regional, and international partners, GFDRR provides grant financing, technical assistance, training, and knowledge sharing activities to mainstream disaster and climate risk management in policies and strategies. Managed by the World Bank, GFDRR is supported by 36 countries and 10 international organizations.

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