

Building Resilient Infrastructure Systems

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The need to provide resilient infrastructure systems will intensify in the coming years. Addressing vulnerabilities requires that citizens, cities and regions, the business sector and governments avoid exacerbating threats to infrastructure systems. In order to ensure availability, quality, safety and security of such infrastructures as transportation networks, a long-term development strategy is needed along with the ability to build on adverse events. Transportation systems owners and operators are compelled to integrate growingly complex challenges within decision-making processes. This includes the impacts of climate change and extreme weather, natural and man-made disasters as well as cyber threats and the structural aging of infrastructures. Highlighting the issues outlined in the TF4 policy brief *Infrastructure Nexus*, we recommend : a) to develop systematic resilience strategies for infrastructure and transport systems at G20 level; b) to establish policies and mechanisms for exchanging knowledge and experiences among G20 countries; c) to promote a socio-political based approach to resilience in order to facilitate the acceptability of infrastructure projects at local and global scales; and d) to set up common methodology for measuring resilience success.

Challenge

It is recognized that transport infrastructure should encompass not only the operational, but also the physical components of interrelated systems, which provide essential services to enable, sustain, or enhance societal living conditions (Fulmer, 2009). Among infrastructure systems, transportation networks play a key role in connecting communities, shaping their economies, and supporting the free movement of ideas, people, goods, and services. International, national, and local transportation is multimodal by design; it benefits from the interrelationships between ground, maritime, air, rail and waterways transport networks.

Among multimodal transport systems, road transport infrastructure and services are major contributors to ensuring the accessibility and mobility of users. In low, middle and high income countries altogether, road transportation accounts for more than 80% of all passenger travel and freight movements, where "Roads are the first social network" (IDRRIM, 2017). By 2030, annual passenger traffic is set to increase by 50%, global freight volumes by 70% and an additional 1,2 billion cars will be on the road by 2050 (Sum4All, World Bank Group, 2017). For these reasons, the "Transport and Traffic" sector is increasingly being classified as a "critical infrastructure" (1).

The deployment of 21st century mobility services depends on the availability of quality infrastructure. Transportation systems and their services need to be affordable, safe, timely, reliable and secure in order to provide optimal societal outcomes and contribute to the UN Agenda 2030 (NZTA, 2013) (2). The lack of quality infrastructure systems will delay the systematic implementation of such services. Low quality infrastructure and services induce extensive economic, social and environmental costs for transit authorities and users (e.g. accident

costs, travel time and freight delays, vehicle operating costs and externalities).

It is estimated that the amount of global investment required for roads will be US\$ 34 trillion between 2016 and 2040, while the current trend of investments for this period does not exceed US\$ 26 trillion (Global Infrastructure Hub, G20). In other words, each country should spend more than 1.27 percent of GDP while current expenditure on average is approximately 1 percent of its GDP only. Many countries, both emerging and advanced, "have paid insufficient attention to maintaining and expanding their infrastructure assets, creating economic inefficiencies and allowing critical systems to erode" (Woetzel & al., 2016). On the contrary, a state of good repair and maintenance of existing infrastructure contributes significantly to increasing "resilience" (see Appendix).

Environment-related risks account for three of the top five risks (by likelihood) and four of the top five risks (by impact) threatening mobility infrastructures (World Economic Forum, 2019)

Cyber-attacks are ranked fifth in term of likelihood, with expected increased risks in 2019, leading to more disruption of operations. The WEF Global Risks Report reflects on new instabilities caused by the deepening integration of digital technologies into every aspects of daily life. In the context of the rapidly advancing digital transformation, digital technologies will also play an increasingly important role in the operation of road infrastructure, whereby the aspects of cyber security, cyber physical security and cyber resilience will play an decisive role in the future. As shown in Figure 1, global risks are interconnected and the levels of vulnerability are increasing.

Furthermore the functioning of infrastructure systems in a degraded mode (caused by a lack of adaptation to extreme climate events, of maintenance, by a man-made disaster...) will worsen the impacts of these risks on people and territories. Due to rapidly growing urbanization, with two-thirds of the global population expected to live in cities by 2050, more people will be exposed to infrastructure systems failures in a very near future (3) . In a vicious circle, urbanization does not only concentrate people and properties in areas of potential damage and disruption, but it also exacerbates those risks, for example, by destroying natural sources of resilience.



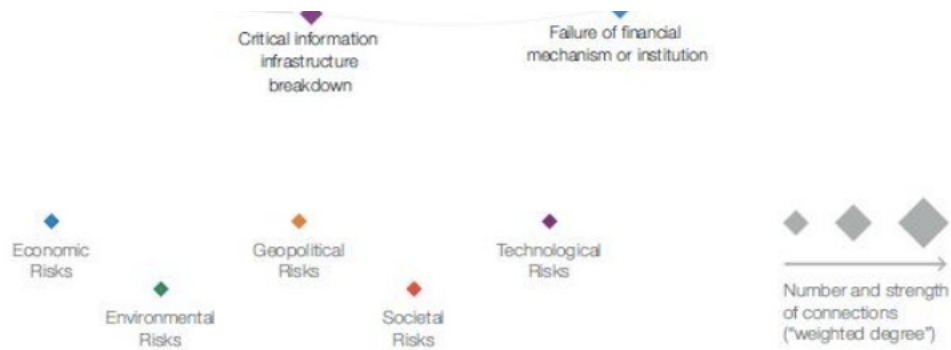


Figure 1 : Global Risk's Interconnections Map (Source: World Economic Forum, 2019)

The importance of more resilient design, construction, and maintenance of infrastructure cannot be understated. This is obvious in high-income countries where the number of infrastructure disasters has increased in recent years – causing severe economic, environmental, and social consequences. The recent collapse of a bridge in Genoa, Italy, on August 14th 2018 claimed 43 lives and caused huge spendings in repair, insurance to damages, properties, buildings, machinery and stocks, and at a regional scale lowered companies' profits. In this context, both a state of good repair and maintenance and suitable design approaches for new and existing infrastructure facilities, taking into account relevant vulnerabilities and criticalities, are basic prerequisites for building resilient infrastructure systems.

Climate change and the associated increased number of extreme weather events are a major global concern

This includes temperature changes, flooding, rising sea levels, storm surges, increased hurricane and cyclone intensity, landslides, drought, and bushfires. Over the last 20 years, the reported economic losses due to extreme weather events has risen by 151% compared to the 1978-1998 period, reaching US\$ 2,245 billion (UNISDR, 2017). Similarly, during 1998-2017, global GNP increased by approximately 200%. As such, a connection can be formed between the increase in population, and increases in damage costs due to climate change exposure. The effects of extreme or highly variable weather on infrastructure is of increasing significance to the transportation community. For example between 2010-2013, El Niño and La Niña combined effects caused major damages to Queensland road network in Australia. As a result, 8,741 km of the state-controlled network required full or partial reconstruction, with a reconstruction budget of approximately US\$ 4.5 billion (Queensland Government, 2016).

The cost of redesigning and retrofitting key road infrastructure elements, such as upgrading roadways to add resilience features, elevating bridges, or relocating roads, is often costly and it requires a strategic risk-based approach for investment decisions. Upgrading road infrastructure to improve resilience includes a risk management challenge that will require national and local governments to 1) identify climate change impacts (e.g. sea level rise, extreme precipitation events, etc.) which are most relevant to their infrastructure, 2) ascertain how those impacts are likely to manifest themselves (e.g. coastal floodings, flash flooding from storm surge, wild fires etc.), and 3) identify which infrastructure assets are the most vulnerable and cause the greatest risks linked with inaction or delay action (TRB, 2019).

Governments and transportation agencies can draw on the experience from partners in other professional fields such as seismic protection agencies, which have a matured risk-based resilience approach in a number of countries (e.g., Japan and the United States). The transportation agencies in these countries have decades of experience with upgrading their infrastructure systems to withstand seismic events. They have been proactive in evaluating the lessons learned from significant hazards, developing solutions and implementing improved design as well as retrofit guidelines and standards for their infrastructure systems.

The development of a holistic risk-based approach to climate change resilience of transportation infrastructure will require the translation of available scientific climate projections into engineering guidance and standards that practitioners can use when planning and designing future infrastructure projects (Stahl et al., 2016), (GAO, 2015). This involves consideration of a multidimensional approach of sustainability (Fig. 2).

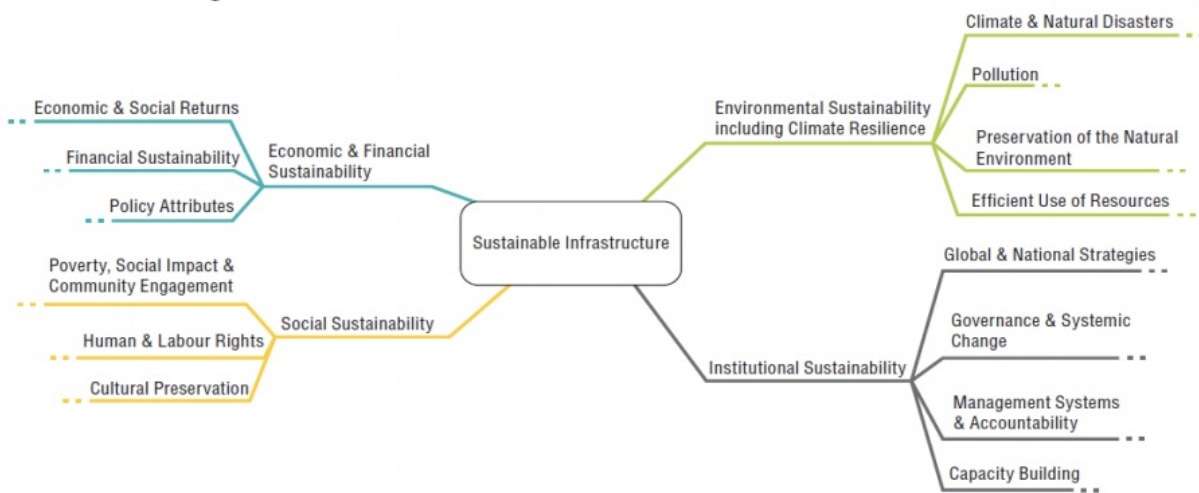


Figure 2 : The IDB's four dimensions of sustainable infrastructures (Source: IDB, 2018)

Transportation infrastructure is vulnerable to a wide range of threats, including man-made events

In the last decade, direct intentional attacks on infrastructure users and/or cargo have increased (Theocharidou et al., 2018). Transport infrastructure systems and services are an attractive target for radical activists and terrorist groups, who often act with the explicit intention to disrupt transport flows and harm passengers and people. Other motivations can be to make a political statement, or to make economic profit by blackmailing the affected country. For this reason too, transportation and energy infrastructure is increasingly being classified as a "critical infrastructure" (European Programme for Critical Infrastructure Protection).

As a consequence, the management of transport infrastructure should include security considerations at all levels ranging from the infrastructures' strategic importance and criticality, their different uses, and their proximity with and access to other assets and public spaces. The extent of the impact of the loss of, or damage to, a targeted transportation network depends, of course, on the degree of resilience built in the underlying infrastructure.

This leads to question how to mitigate negative impacts and how to adapt and improve the resilience of transport systems

The answer lies in the interconnection between several professional spheres of operation, including planning and design, asset management, materials science, structural engineering, emergency procedures, investment, and others. Resilience management and resilience engineering are suitable ways to tackle the above-mentioned challenges.

Owners and managers of transport infrastructure systems play a major role in fostering resilience. Their investments in mitigation (through risk-based design and construction) and incident planning (through proper operations) are key to minimize risks and improve infrastructure resilience. Given the growing number of man-made extreme events, transportation infrastructure owners and operators need to include security issues among their top priorities. Embedding and managing security as part of business-as-usual becomes mandatory. This requires dedicated budgets and new collaborative processes between government, infrastructure owners, managers and operators.

The affordability of resilience for infrastructure systems is set to become an increasingly important issue. Robust risk financing strategies will be required, both to fund investments in adaptation and to pay for recovery when failures occur. At present, the total fundings of post-hazard recovery is globally almost nine times higher than prevention. Reaching a proper balance will require dialogue and planning between all the stakeholders.

Proposal

"Infrastructure planning must be improved at all levels of government to create pipelines of sustainable infrastructure projects aligned with long-term climate and development objectives. Priority actions include: ... Make resilience the norm to limit vulnerability to climate damages." (OECD/TheWorldBank/UN environment, 2018).

We suggest to establish strategies that include a unified and holistic risk-based approach for the assessment, quantification and investigation of the possibilities for improving the resilience of infrastructure, in general, and transport systems, in particular.

Develop resilience strategies for infrastructure and transport systems at G20 level

It is recognized that an integrated systems approach connecting all levels and scales is required, which focusses on emerging markets and clients in urbanized and regional locations. This involves the development of internationally consistent strategies to ensure that appropriate planning is in place to address disruptions to road infrastructure and operations. Road assets must therefore be able to adapt to future events and the most economically efficient investment options must be used. These objectives will require determining when and where the most appropriate adaptation measures are required and how much this would cost for specific infrastructure systems and assets. This includes identifying the economic benefits of improving the ability for transport systems to withstand events using life-cycle costing, adaptation pathways and other approaches. The Audit of the French State Roads Network and its Maintenance Policy (IMDM and Nibuxs, 2018) was inspired by such a concept.

The resilience policy that could be developed within G20 should take into account existing resilience strategies as well as face new challenges such as combined changing demographics, security risks and weather events. This includes more emphasis on additional vulnerability introduced to transport systems, such as the application of automated solutions. Automated transport will influence the management of emergency situations, hence there is a need to take on board those associated influences in the development of holistic resilient strategies.

One such example is the PIARC International Climate Change Adaptation Framework for Road Infrastructure, which was developed to guide road authorities through identifying relevant assets and climate variables for assessment, identifying and prioritising risks, developing a robust adaptation response and integrating findings into decision making processes. Another example is the ASCE Manual of practice on adaptive design and adaptive risk management currently being developed by the American Society of Civil Engineers (Committee on Adaptation to a Changing Climate).

A key focus is to consider asset management in terms of a "whole of organization" approach to creating and maintaining assets which deliver services valued by an agency's customers in the most cost-effective and efficient manner. In such an organization, the needs of road users and expectations are defined in the context of both community, stakeholder, and organizational objectives (see for example the Austroads Guide to Asset Management, 2018).

Policy Options:

- Develop strategies at State level for resilient (road) transport systems that could make a significant contribution to solutions in the future, such as to create the foundations for a proactive and holistic resilience engineering/resilience management.
- Introduce educational initiatives that focus on comprehensive resilience centered operation, maintenance and adaptation of (road) infrastructure including risk-based elements and cost-benefit analyses.

Establish policies and mechanisms for exchanging knowledge and experiences related to the the resilience efforts for the infrastructure and transport systems among G20 countries

Adopting resilient infrastructure systems requires planners, asset designers, owners, and operators to communicate and determine the following resiliency factors:

- maintain infrastructure, rather than just build more;

- promote a flexible development of new services to rehabilitate and existing infrastructure;
- identify assets likely to suffer from future events and potential vulnerabilities (exposure and sensitivity);
- assess and prioritize risks according to the level of risk probability (likelihood of future impacts on the asset) and severity (consequence of the impacts on the asset);
- identify those assets that are approaching the end of their design life;
- adapt existing transport infrastructure to the consequences of climate change and the associated increases in extreme weather events;
- retrofit or build new resilient infrastructure.

It is essential to determine how to ensure that these strategies have a real holistic positive impact – or spillover effect (Yoshino et al., 2018) – and do not produce any negative side effect to the territories (biodiversity, accessibility or social inclusion...). Relevant stakeholders and G20 members may work together to establish a framework for a communication structure with regard to resilient infrastructure and transport systems. This structure would report systematically on adverse events that have a significant impact on the availability, safety and security of transport systems. In addition, training initiatives may be initiated that focus on resilience-centered approaches and that include risk-based elements into cost-benefit analysis, and other economic valuation approaches.

Policy Options:

- Assist LMIC4s in the long-term strategic planning of road infrastructure and in the implementation of efficient and cost-effective road development and maintenance measures, through their taking part in knowledge sharing measures and through actual implementation of remedial measures on roads.
- Develop a post G20 Summit strategy to monitor and coordinate policies and initiatives with regards to resilient transport systems e.g., the international conference agenda (International Transport Forum, World Road Congress, Intelligent Transport System World Congress, World Congress on Railway Research, etc.).

Promote a socio-political based approach to resilience in order to facilitate the acceptability of infrastructure projects at local and global scales

Transport infrastructure systems always involves a political dimension, either openly addressed or hidden behind the technological frontscreen.

Infrastructure projects engage in political and geographical relationships with communities. There are different engineering and architectural traditions among G20 countries, such as the Japanese “above-of-the-ground model” for transport infrastructure, or the French traditional requirement for a proper “excavation-and-backfill balance”, or the German “low flyheight” that dates back to the first Autobahnen. These techniques all shape different responses to the same problem : how to connect the infrastructure with the landscape ?

Be it geographical, political or sociological, all infrastructure systems imply an element of discrimination, and this is often a hardened, long standing issue. For project planners, architects, engineers, practitioners and even politicians, it is necessary to cross the borders shaped by infrastructure, to share experience and best practices, to build places where people can live in and transform infrastructure drawbacks into a common good. These are important prerequisites for achieving infrastructure resilience. This collaboration can also provide a stronger base to enable future investment decisions to be made.

Policy Options :

- Advocate the need that transport infrastructure systems should be closely tied with territories. This will address more than the functionality of systems, but will also encourage the development of a proposed “knowledge-sharing Academy”, involving inputs from engineers, architects, urban planners, economists, social and human scientists.

Set up common methodology for measuring resilience success

This approach seeks to build on the outputs of internationally recognized organisations in their worldwide knowledge-sharing mission, such as (non exhaustive list) the World Road Association (PIARC), "100 Resilient Cities", the International Federation for Structural Concrete ("fib"), the World Business Council for Sustainable Development (WBCSD), the International Association for Bridge and Structural Engineering (IABSE), the ASCE, ICLEI local governments for sustainability... G20 members should validate, improve and disseminate approaches for evaluating the success of resilience indicators and resilience solutions.

Policy Options:

- Establish mechanisms for the collection and evaluation of efficient and cost-effective solutions.
- Improve interaction between policy makers and owners and operators of road infrastructure in order to raise awareness with regard to resilient road infrastructure.
- Encourage the adaptation of existing technical guidelines and standards in order to integrate resiliency to infrastructures (design, building, operation, maintenance).

References

- Austroads (2018). Guide to Asset Management, AGAM01-18, Austroads, Sydney, NSW.
- Brunau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A. and von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities, Earthquake Spectra, 19(4), 733-752.
- Fulmer, J. (2009). What in the world is infrastructure? PEI Infrastructure Investor (July/August): 30–32.
- General Accountability Office (2018). A National System Could Help Federal, State, Local, and Private Sector Decision Makers Use Climate Information. GAO-16-37: Published: Nov 23, 2015. Publicly Released: Dec 8.
- IDB (2018). What is sustainable infrastructure ? A framework to guide sustainability across the project cycle, Inter-American Development Bank.
- IDRRIM, Institut des routes, des rues et des infrastructures de mobilité (2017). Annual Report. Paris.
- IMDM and Nibuxs (2018). Audit externe sur l'état du réseau routier national non concédé et la politique d'entretien de ce réseau, MTES/DGITM.
- OECD / The World Bank / UN Environment (2018). Financing Climate Future, Rethinking Infrastructure, OECD Publishing, Paris.
- NZ Transport Agency (2013). The New Zealand accessibility analysis methodology, report no. 512, NZTA, Wellington, NZ.
- Queensland Government (2016). Reconstruction program – Transport Network Reconstruction Program, Department of Transport and Main Roads (TMR), Brisbane, Qld.
- Scharte, B., Hiller, D., Leismann, T., Thoma, K., (2014). Introduction – Thoma, Klaus (Hrsg.): Resilien Tech. Resilience by Design: Strategy for the technology issues of the future (Acatech STUDY). München: Herbert Utz Verlag.
- Stahl, L., Filosa, G., Lawless, E., and Poe, C. (2016). Surface Transportation Systems Resilience to Climate Change and Extreme Weather Events: First International Conference. Transportation Research Board Circular E-C204.

- Theocharidou, M., Galbusera, L., Giannopoulos, G. (2018). Resilience of critical infrastructure systems: Policy, research projects and tools. In Trump, B. D., Florin, M.-V., & Linkov, I. (Eds.). IRGC resource guide on resilience (vol. 2): Domains of resilience for complex interconnected systems. Lausanne, CH: EPFL International Risk Governance Center.
- Transportation Research Board, (2019). Special Report 329: Renewing the National Commitment to the Interstate Highway System: A Foundation for the Future. National Research Council, Washington, D.C.
- UNISDR, Economic Losses, Poverty & Disasters 1998-2017. • Woetzel, J., N. Garemo, J. Mischke, M. Hjerpe, and R. Palter (2016). Bridging Global Infrastructure Gaps. McKinsey Global Institute.
- World Bank Group. Sum4All (Sustainable Mobility for All), Global Mobility Report, 2017. • World Economic Forum (2019). The Global Risks Report 2019, 14th Edition.
- World Road Association (PIARC) (2015). PIARC International Climate Change Adaptation Framework for Road Infrastructure.
- Yoshino, N., Taghizadeh-Hesary, F., Nakahigashi, M. (2018). Modelling the social funding and spill-over tax for addressing the green energy financing gap. Economic Modelling. 10.1016/j.econmod.2018.11.018.

Appendix

Resilience plays a key role in maximising the economic, social and environmental aspects of transport infrastructure and network operations and has multiple definitions. There are a number of levels encapsulated in 'resilience'. It spans the ability of infrastructures to plan/prepare, withstand, recover and adapt according to a cyclical, proactive and holistic risk management system.

Important aspects include:

- Robustness – the inherent strength, or resistance, to external damage without degradation or loss of functionality;
- Redundancy – system priorities that allow for alternative options, choices, and substitutions under stress;
- Resourcefulness – the capacity to mobilise needed resources and services in emergencies;
- Adaptability and Ability to Recover quickly – the speed with which disruption can be overcome and safety and services restored (Bruneau et al. 2003).

Resilience can therefore be considered as follows: "Resilience is the ability to repel, prepare for, take into account, absorb, recover from and adapt ever more successfully to actual or potential adverse events. Those events are either catastrophes or processes of change with catastrophic outcome which can have human, technical or natural causes" (Scharte et al., 2014).

Increasing the resilience of an infrastructure network requires:

- to better predict the intensity and frequency of the actions to which the infrastructure network can be subjected, be it "climate" actions (wind, snow, flood, ground movements...) or traffic loads (increase in road traffic, passage of truck convoys, increase of weight);
- to evaluate at best the resistance of the structures under the effect of these actions, considering the aging of the materials constituting these structures;
- strengthen surveillance and possibly use real-time instrumentation of the most vulnerable infrastructure to detect any major failure in time;
- prioritize maintenance and reinforcement work by using the most relevant technical solutions to optimize short- and medium-term expenses.

Facing a critical event or a modification of its environment, a resilient infrastructure system will have to resist the crisis, to absorb the constraints and recover while diminishing its inherent vulnerability. Resilience should therefore be seen as holistic combining the robustness at both the infrastructure and organisational level.

Existing Initiatives & Analysis