Significance of Sustainable and Resilient Critical Infrastructure Systems
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ABSTRACT

Infrastructure can be defined as the set of structural elements that supports our day-to-day lives and influences the direction of humanity. Most of our existing infrastructure (including transportation) are not sustainable and resilient. It is important to understand the significance of sustainable and resilient critical infrastructure systems – an emerging thought in an evolving era where natural and man-made assets are being depleted to provide a sustainable and high quality of life. Sustainable infrastructure refers to the designing, building, and operation of structural elements in ways that do not diminish the social, economic, and ecological processes required to maintain human equity, diversity, and the functionality of natural systems. Moreover, sustainable infrastructure enhances the quality of life, increases positive impacts (benefits), and helps protect our vital natural resources and the environment. Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event. The development of infrastructure systems that are sustainable and resilient is a challenging task, and it involves a broad range of performance indicators over the system lifecycle that affect system functionality and recovery. Sustainability indicators address economic, social, and environmental performance metrics while resilient indicators address strength, functionality, and recovery-time metrics after a hazardous event. Considering these facts, it must be understood that it is vital for our existing infrastructure systems to be sustainable and resilient. The choice of infrastructure development is crucial to sustainable development because the infrastructure we are building today will enable our future communities to remain resilient. By 2050, more than half of the world's population is expected to live in urban areas, bringing huge challenges and opportunities for investment in sustainable infrastructure across every sector of the economy. Transportation systems including railroad systems will need to be smarter, faster, and more focused towards mass transit, electric vehicles, and self-driving vehicles. Rail infrastructure is a critical component of a transportation system that is helping the United States in global markets. America's both freight and passenger railroad industry continues to remain an emblem of innovation and a foundation for economic growth. Disruptions to freight rails inflict serious damage on the economy, cause massive layoffs and affect our supply chain.

INTRODUCTION

Infrastructure can be defined as the set of structural elements that supports our day-to-day lives and influences the direction of humanity. Sustainable infrastructure refers to the designing, building, and operation of these structural elements in ways that do not diminish the social, economic, and ecological processes required to maintain human equity, diversity, and the functionality of natural systems [5]. The integrity of our societies and the social, economic, and environmental systems that underpin them are directly affected by the resilience of infrastructure systems such as transportation, medical facilities, educational institutions, and power. An effective infrastructure system that is successful, consistent, resilient, and fair is essential not only for the economic growth of the region but also for the prosperity of humankind [2]. Resilient infrastructure is about people and the communities for whom infrastructure is a lifeline for improved living conditions such as better education, better health, and better livelihood [9]. Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. According to the World Bank Report, resilient infrastructure is not just about bridges, waste management, roads, power plants, land use planning, and governance. In fact, it is also about unlocking economic opportunities for people [21]. The choice of infrastructure development is crucial to sustainable development because the infrastructure we are building today will enable our future communities to remain resilient.

Resilient infrastructure, is in part, about bridges that can withstand more frequent or stronger floods, water pipes that can resist earthquakes, or electric poles that are tougher in the face of more intense hurricanes. However, it is also about making sure that people can get urgent medical care, children can get to school, and people will not lose their jobs because they are unable to get to work. Disruptions to infrastructure could cost individual households, communities, and the overall nation to great extents. The indirect effects of these disruptions place a further toll on households, businesses, and our societies [9]. Disruptions normally happen due to natural disasters, uncertainty risks, mismanagement, poor choices, and poor maintenance. It is highly crucial to make infrastructure more resilient and more economically robust for the welfare of the people, economy, and environment.

Sustainable and resilient critical infrastructure systems, an emerging thought in an evolving era where natural and man-made assets are being depleted to provide a sustainable and high quality of life, enhances the quality of life for people, increases positive impacts, and helps protect our vital natural resources and the environment. The development of infrastructure systems that are sustainable and resilient is a challenging task, and it involves a broad range of performance indicators over the system lifecycle that affect system functionality and recovery. Sustainability indicators address economic, social, and environmental performance metrics while resilient indicators address strength, functionality, and recovery-time metrics after a hazardous event.

By 2050, more than half of the world's population is expected to live in urban areas, bringing huge challenges and opportunities for investment in sustainable infrastructure across every sector of the economy. Transportation systems including railroad systems will need to be smarter, faster, and more focused towards mass transit, electric vehicles, and self-driving vehicles. [23]. If cities wish to promote sustainable growth, a dramatic growth in public transportation is absolutely essential. Rail infrastructure is a critical component of a transportation network that is helping the United States compete in global markets [6]. America's freight and passenger railroad industry continues to remain an emblem of innovation and a foundation for economic growth. Disruptions to freight rails inflict serious damage on the economy, cause massive layoffs and affect our supply chain. Rail transport has a major role to play in developing the sustainable cities of the future and hence it is imperative to have sustainable and resilient rail infrastructure.

SIGNIFICANCE OF SUSTAINABLE AND RESILIENT CRITICAL INFRASTRUCTURE

Infrastructure services, such as roads, bridges, tunnels, supplies of drinking water and electricity, disposal and treatment of wastewater, mobility of people and goods, and provision of information and communication technologies, are the backbone for economic development, competitiveness, and inclusive growth [11]. The Inter Development Bank has defined sustainable infrastructure as "Infrastructure projects that are planned, designed, constructed, operated, and decommissioned in a manner to ensure economic and financial,

social, environmental including climate resilience and institutional sustainability over the entire life cycle of the project."

Society has traditionally depended on an extensive variety of services as much as on the infrastructures providing them. Over time, some of these infrastructures, or rather their elements considered to be of vital importance to society, began to be regarded as critical [16]. Critical infrastructure is defined as the body of systems, networks and assets that are so essential that their continued operation is extremely vital to ensure the security of a given nation, its economy, and the public health and safety. There are 16 critical infrastructure sectors whose assets, systems, and networks whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a deliberating effect on security, national economic security, national public health or safety, or any combination thereof. Presidential Policy Directive 21 (PPD-21) has identified 16 infrastructure sectors as critical to the United States. They are: Chemical Sector, Commercial Facilities sector, Communication Sector, Critical Manufacturing Sector, Dams Sector, Defense Industrial Sector, Emergency Services Sector, Energy Sector, Financial Services Sector, Food and Agricultural Sector, Government Facilities Sector, Healthcare and Public Health Sector, Information Technology Sector, Nuclear Reactors, Materials, and Waster Sectors, Transportation Sectors & finally Water and Waste Water Sector. [10]

The functioning of a critical infrastructure system is constantly being threatened by extensive range of security threats and they can mainly be categorized into five basic groups as shown below: [2]

- Climate Related threats (Floods, Tornadoes, Heavy Snow, Wild Fire etc.)
- Geological Threats (Earthquakes, Landslide etc.)
- Biological Threat (Pandemic such as Covid-19)
- Technological Threats (Disruptions engineering networks, Cyber Attack)
- Criminal Threats (Terrorism, Criminal Activity etc.)

Critical infrastructure system failures followed by disruptions produce severe negative impacts. These impacts can propagate further not only within the critical infrastructure system and its subsystems, but also the other external systems where they can directly affect our society, national interests, the economy, and basic human needs [16]. Disruptions to functional parameters of critical infrastructure causes a decline in the performance of specific elements (see Figure: 1) where the decline is directly proportional to the intensity of the emergency and the degree of resilience of the respective critical infrastructure element. [16]

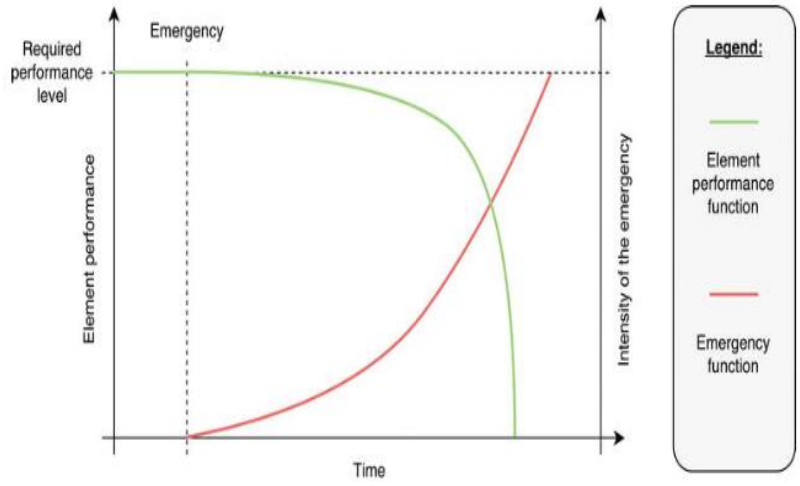

Fig 1: Disruptions to an element in a critical infrastructure system [16]

In order to reduce or nullify the impacts caused by critical infrastructure disruptions, it is crucial to have resilient features integrated into these infrastructure systems. Resilient is the ability of assets, network and systems to anticipate, absorb, adapt to, and recover from a disruptive event or series. In other words, resilience is all about maintaining the continuity of a service in the presence of disruptive events. The resilience actually depends on planning contingencies and effective infrastructure design right from the start.

Resilient Infrastructure should have four major characteristics: Resistance, Reliability, Redundancy, Response & Recovery as shown in Figure 2 [18]. It is really important to have these attributes in place to maintain the resilience.

- Resistance: Provide protection against anticipated events/attacks
- Reliability: Components should be designed to operate under a wide range of anticipated conditions.
- Redundancy: The system should be designed with appropriate backup plans
- Response & Recovery: Should be able to respond quickly to disruptive events by limiting the damage and ensuring public safety.

Figure 2: *Characteristics of Infrastructure Resilience* [18]

INDUSTRY, INNOVATION AND INFRASTRUCTURE

The UN's Sustainable Development Goals (SDGs) are targets for global development adopted in 2015 (Figure 3), set to be achieved by 2030 and will help to put sustainability and resilience on the agenda for both new and ageing infrastructure. All countries of the world have agreed to work towards achieving these goals. This indicates that providers and operators of an infrastructure asset must ensure compliance with pre-determined parameters of the three sustainable development dimensions: social, environmental, and economic dimensions in an integrated manner.

A stunning US$90 trillion is required to finance infrastructure over 15 years for the world to have a chance of meeting the targets set in the Paris Agreement following the global climate change negotiations in 2015 and majority of this infrastructure needs to be sustainable [23]. Hence, Goal 9 of SDG is focused on Industry, Innovation and Infrastructure. It reminds us the importance of investing in infrastructure, industries and innovation because they are the crucial drivers of economic growth and development. Fostering innovation and entrepreneurship are key drivers of growth. With over half the world population living in cities, mass transport has become ever more important.

Figure 3: *Overview of Sustainable Development Goals* [20]

SDG's Goal 9 also reminds us that technological progress is the key to finding lasting solutions to both economic and environmental challenges, such as creating new job opportunities and promoting energy efficiency by protecting the natural resources. Inclusive and sustainable industrialization, together with innovation and infrastructure, can unleash dynamic and competitive economic forces that generate employment and income. They play a key role in introducing and promoting new technologies, facilitating international trade and enabling the efficient use of resources. Building resilient infrastructure, promoting sustainable industrialization and fostering innovation are extremely critical in social, economic and environmental perspective. Critical Infrastructure system resilience must be observed as a cyclic process based on continual strengthening of resilience of subsystems and the four crucial phases are: prevention, absorption, recovery, and adaptation [16] as shown in Figure 4.

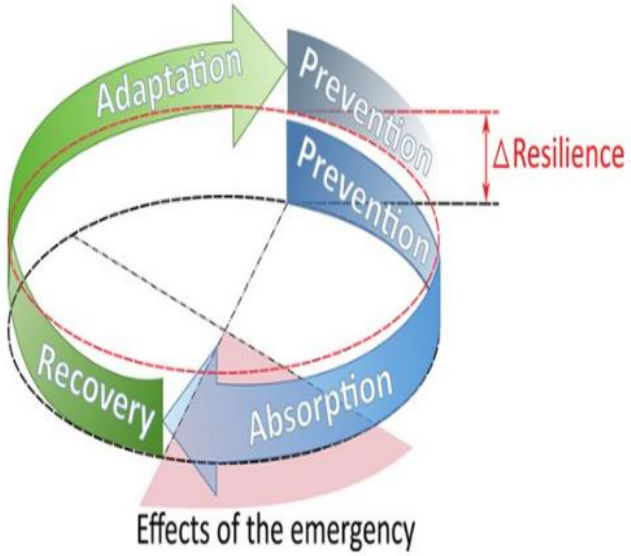

Figure 4: *Cycle of critical infrastructure resilience* [16]

According to Inter-American Development Bank, sustainable infrastructure refers to infrastructure projects that are planned, designed, constructed, operated, and decommissioned in a manner to ensure economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire life cycle of the project [11]. Sustainable infrastructure supports sustainable development.

Sustainable development is the development that is grounded in five dimensions which can expressed as five pillars of sustainable development 5Ps: People, Planet, Prosperity, Peace & Partnership [19]. Resilient infrastructure is a lifeline for sustainable development. Sustainable and resilient infrastructure is generally considered to approach development from a holistic viewpoint: based on global and domestic sustainable development goals, durability and having regard to social, financial, and political issues, public health and wellbeing, as well as economic and environmental concerns [24].

Figure 5: *Five pillars of sustainable development Source [19]*

In terms of physical, environmental, economic, and social perspectives, sustainable critical infrastructure has many overlapping benefits because it promises climate resilience, which in turn helps economic resilience and the welfare of society [24]. From a much wider point of view, sustainable infrastructure investment can be a source of economic growth, environmental gains, public wellbeing, and a positive return of investment (ROI) as shown in Figure 6.

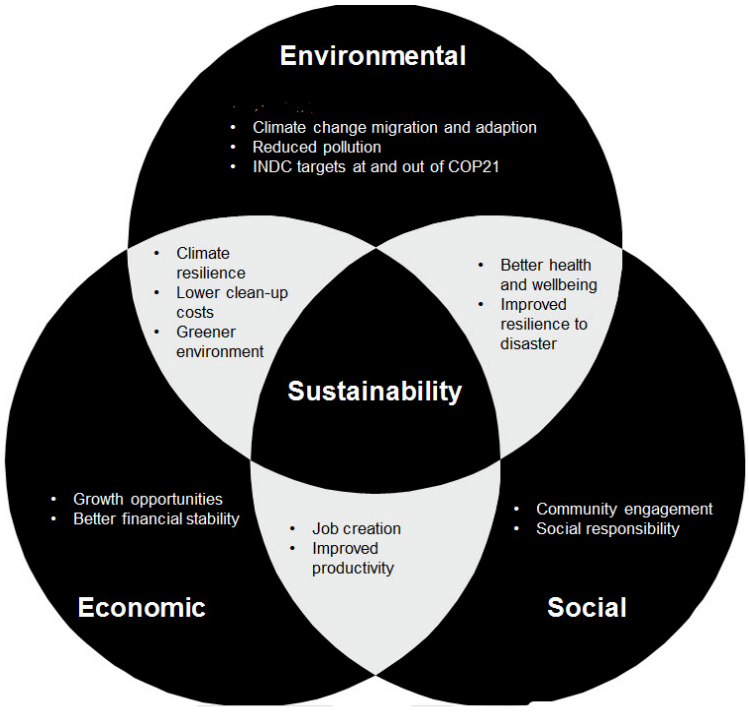

Figure 6: *Benefits of Sustainable Infrastructure Investment* [24]

Almost all infrastructure elements including rail infrastructure elements are mainly depend on power and communication network. Failure or disruptions of these infrastructures would be disastrous for our economy in large and on the society as a whole. Climate change poses great physical risks to critical infrastructure. Apart from climate change, there are several other traditional risks and uncertainties that could bring disruptions to existing infrastructure systems. Natural shocks, economic activities, human wellbeing and infrastructure systems are all interconnected. Figure 7 shows a framework for analyzing how natural shocks affect people and firms through their impact on infrastructure systems. The dotted lines represent how they are directly impacting Firms and people but the red arrow shows how natural shocks affects infrastructure and how people and firms get affected through infrastructure systems [9]. High cost of infrastructure disruptions on people, either directly through their impacts on health-wellbeing or indirectly through their impacts on firms, jobs and income.

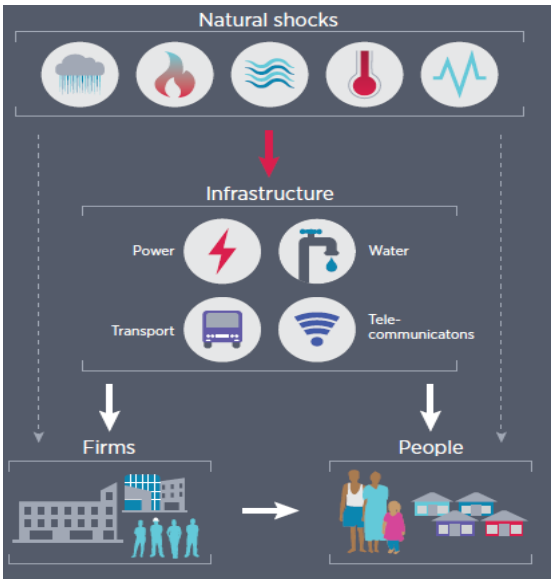

Figure 7: A Sample Framework for analyzing how natural shocks affects communities and firms through their impact on infrastructure [9]

In rail industry, technology helps railroads achieve safety milestones, minimize their impact on the natural environment and maintain a competitive edge in today's fast-paced global economy. Advanced fuel management systems, positive train control, modern tier 4 locomotives, smart sensors and automated inspection equipment are few to mention. The smart mass transit solutions market is estimated to reach $44.78 billion by 2021. Innovation analysts at StartUs Insights have mapped out the nine most impactful innovation areas for the rail transport industry in the near future as shown in Figure 8. The areas include: Artificial Intelligence (AI), Automatic Train Control (ATC), Predictive maintenance, Internet of Trains, Big Data, Cloud Computing, Drones, Smart Sensors and Biometric Ticketing [14].

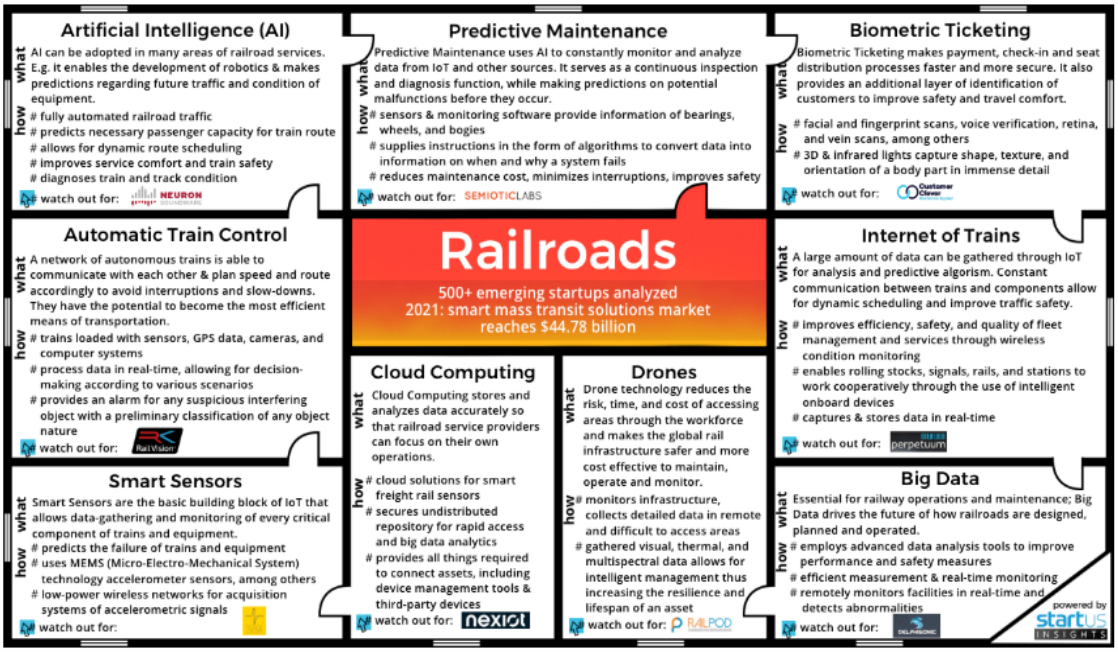

Figure 8: *Nine most impactful innovation areas for the rail transport industry [14]*

EFFICIENT AND EFFECTIVE RISK AND UNCERTAINTY MANAGEMENT TO ACHIEVE SUSTAINABLE AND RESILIENT CRITICAL INFRASTRUCTURE SYSTEMS.

Nearly all development has an economic aspect in the sense of trading off alternatives under certain boundary conditions, and sustainability development is of no exception. The complexities of the economic system in relation to sustainability are such that an effective and efficient risk/uncertainty management is absolutely required to achieve a sustainable and resilient infrastructure system. Infrastructure disruptions are very severe and will impact the economy and people at large. These disruptions can have a range of causes which include manmade external shocks, system failures during which infrastructure breaks down, intentional attacks on infrastructure, and natural shocks such as storms, floods, and earthquakes [9] (Figure 9). Data is key to measure and identify the risks involved in each category. General observations, sense making and judgement calls from experts are also helpful to analyze and isolate the risks involved in each category.

Figure 9 *Classification of causes of Infrastructure disruptions* [9]

Risk is the effect of uncertainty on main objectives and can be seen as the possibility of an unfortunate occurrence. Through the uncertainty assessment process, project teams can evaluate the risks associated in terms of both internal and external context. The purpose of the uncertainty assessment process, as a part of risk management, is to provide evidence-based information and analysis that assists in making

decisions on how to manage the uncertainty associated with threats and opportunities. [13]. Uncertainty identification is a process used to compile a list of opportunities and threats that might contribute to or detract from the achievement of the main objectives. For each opportunity or threat, it is vital to know the what, where, when, why, and how something could happen and the range of possible outcomes that could affect the main objectives. Uncertainty response involves selecting one or more significant opportunities and threats and exploiting the opportunities while avoiding the threats. [13].

Involving stakeholders right from the planning stage of the project has several benefits. These benefits include but are not limited to reduction in project costs, discovery of further opportunities through collaboration, increased reputational value, support from the public, continuous improvement, and operational excellence. Through uncertainty analysis, a risk matrix is developed. A risk matrix is a great tool to evaluate, prioritize, and focus on the risks associated with the infrastructure since it summarizes the main risks and organizes them according to their likelihood and severity of impact.

RESILIENCE OF CRITICAL INFRASTRUCTURE, OBSTACLES AND OVERALL COSTS ASSOCIATED WITH THE HIGH-QUALITY INFRASTRUCTURE SYSTEMS

Resilience of infrastructure can be classified under three levels, as shown in Figure 10 [9]:

- **Resilience of infrastructure assets**
  This refers to assets such as roads, bridges, and power lines that can withstand external shocks, especially natural ones. Here, the benefit of more resilient infrastructure is a reduction in the life-cycle cost of assets.

- **Resilience of infrastructure services**
  Infrastructure systems are interconnected networks, and the resilience of individual assets is a poor proxy for the resilience of services provided at the network level. For infrastructure, a systemic approach to resilience is preferable. At this level, the benefit of more resilient infrastructure is the provision of more reliable services.

- **Resilience of infrastructure users**
  Eventually, what matters is the resilience of users. Infrastructure disruptions can be disastrous or more benign, depending on whether users—including people and supply chains — can cope with them. At this level, the benefit of more resilient infrastructure is a reduction in the total impact of natural hazards on people and economies.

Infrastructure disruptions are the symptoms of chronic shortcomings. Power outages, unreliable and unsafe water supply and travel congestions are just few examples. In most cases the disruptions occur because infrastructure systems are not designed to keep up with the rising demand. Hence to make infrastructure systems resilient, the first step is to make them reliable in normal conditions through appropriate infrastructure design, operation, maintenance, and financing.

Resilience is one of the many determinants of high-quality infrastructure. However, integrating resilience into the design and implementation of infrastructure investments not only helps to manage natural shocks but also complements cost-effectiveness, efficiency, and the quality of infrastructure services [9].

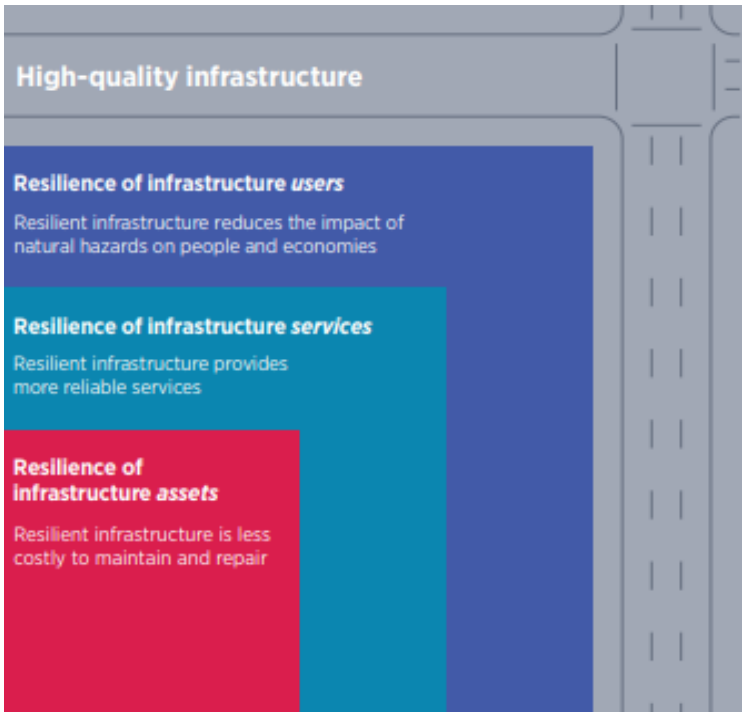

Figure 10 *Resilience of Infrastructure at Several Overlapping and Complementary Levels [9]*

The overall life cycle cost of high-quality infrastructure includes multiple cost components: cost to regulators and government, and Life Cycle cost to infrastructure service providers as shown in Figure 11. As a result, multiple sources of funding are required.

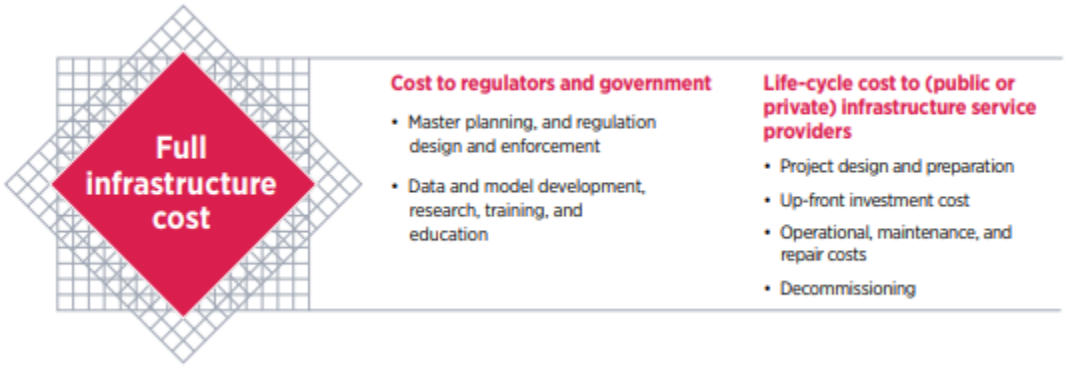

Figure 11 *Overall Life Cycle Cost of Infrastructure [9]*

SUSTAINABLE TRANSPORT IN THE CITIES OF THE FUTURE AND RAIL TO BENEFIT FROM SUSTAINABLE AND RESILIENT INFRASTRUCTURE INVESTMENT

By 2050, more than half of the world's population is expected to live in urban areas, bringing huge challenges and opportunities for investment in sustainable infrastructure across every sector of the economy [23]. Transportation systems including railroad systems will need to be smarter, faster, and more focused towards mass transit, electric vehicles, and self-driving vehicles. Buildings will need to be higher, greener, more energy efficient, and more secured. Investment and expertise will be needed in urban planning, water and waste management, construction practices and materials, roads and bridges, and provisions pertaining to sustainable energy. Advanced technology and innovation would play a vital role in the switch to a low carbon economy with sustainable infrastructure.

If cities around the world wish to promote sustainable growth a dramatic growth in public transportation is absolutely essential. The development of mass transit, particularly metro and light rail projects goes hand-in-hand with sustainable urban growth. Rail transport has a major role to play in developing the sustainable cities of the future and hence it is imperative to have sustainable and resilient rail infrastructure. Population Growth & Growing middle income families who cannot afford living in the city center makes rail transport more desirable due to: Ease of accessibility, Reduced travel time, Improved quality of life and Reduced environmental footprint. Rail transportation is seen as the most attractive option by many and seen as the backbone of an urban transport system in many countries including the United States. Figure 12 shows the railways, passengers carried (passenger-km) between 2005 to 2016 within the United States. Passengers carried by railway are the number of passengers transported by rail, multiplied by the kilometers traveled.

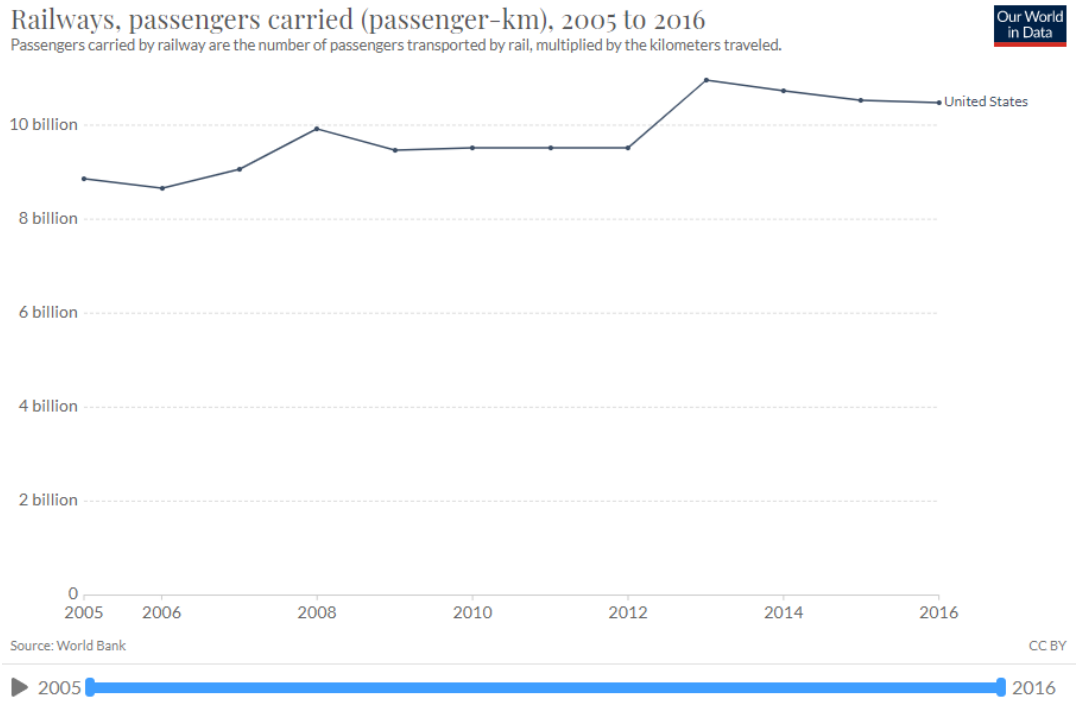

Figure 12 *Railways, passengers carried 2005-2016 in the United States [23]*

Freight rail drives economic growth from small towns to global market. U.S. freight railroads helped spur nearly $220 billion of economic activity and supported approximately 1.1 million American jobs in 2017. This included $71 billion in wages and close to $26 billion in tax revenue — more than the annual tax receipts of 30 states [1]. The freight railroads' extensive and improved network enables connectivity between buyers and sellers and facilitates trade both within the United States and between the United States and other countries. A global marketplace and strong domestic economy are possible, in part, because of decades of private spending by American freight rail. A global marketplace facilitated by freight rail also serves American consumers. America's freight railroad industry continues to remain an emblem of innovation and a foundation for economic growth. Disruptions to freight rails inflict serious damage on the economy, cause massive layoffs and affect our supply chain [1]

Preserving the Natural Environment is a responsibility railroads take seriously. For example: Freight rail is well ahead of other modes of transportation when it comes to limiting greenhouse gas emissions, increasing fuel efficiency and reducing its carbon footprint. From advanced locomotive technology to zero-emission

cranes, freight railroads leverage technology in all aspects of their operations. If just 10% of the freight that moves by Class 7 or Class 8 (the largest) trucks moved by rail instead, fuel savings would be close to 1.6 billion gallons per year and annual greenhouse gas emissions would fall by more than 17 million tons — equivalent to removing around 3.45 million cars from the highways for a year or planting 266 million trees. U.S. Freight railroads, on average, move one ton of freight more than 470 miles per gallon of fuel. U.S Environmental Protection Agency data show freight railroads account for only 0.6% of total U.S. greenhouse gas emissions and only 2.0% of the transportation-related sources, while accounting for 40% or more of long-distance freight volume [1].

Privately Owned freight railroads are the most sustainable way to move freight over inland locations. Several Innovative technologies are being adopted by private freight rail carriers [1].

- Fuel Management Systems – Through real-time cutting-edge software guides engineers how to operate locomotives to maximize fuel efficiency.
- Tier 4 Locomotives - Using sensors to produce data that helps to prioritize maintenance, minimize the impact of poor performance.
- Anti-Idling Technologies - reduce the amount of fuel wasted during down periods and limit pollution.
- Enhanced Operating practices through advanced technologies
- Zero-Emission Cranes - The electric cranes recharge their own batteries each time they lower a load.
- Redesigned railcars - In 2017 the average freight train carried 3,630 tons, up from 2,923 tons in 2000.

According to Greiff, [8] the United States has a massive rail infrastructure problem and it is costing the country billions of dollars every year. With around 140,000 miles of track, rail infrastructure is a critical component of the country's economic efficiency and growth. In order to compete with ever expanding freight and passenger markets, rail industry has a lot of catch up to do and to meet the projected future demand, it is estimated that the U.S.'s rail industry will require an additional $200 billion in investments by 2035. Greiff also pointed out that the U.S.'s rail infrastructure problem is most noticeable in the "Northeast Corridor," (NEC) an electrified railroad line owned by AMTRAK. The Acela Express, the U.S.'s fastest high-speed train, only averages about 90 miles an hour when it *could* be averaging more than 125 mph because tracks are not designed to sustain the speed of 125 mph. There are also not enough tracks laid out and due to this trains are often slowed down causing traffic congestion and delays. Disruption caused on the tracks have a severe impact on the freight and passenger sectors. Slowly but surely improvements and programs are being made to help fast track the massive redevelopment projects. Amtrak's 'NEC Vision and Track modernization program" is a good example [8].

Amtrak is focused on running their business efficiently, modernizing infrastructure and enhancing customer service, promoting innovation through partnership and technology and investing in the future, all on a foundation of safety and security.

Figure 13 *AMTRAK's sustainability Initiatives* [3]

According the Amtrak's sustainability report [3], the company will invest $2.45 billion on their multifaceted modernization program, which will include the new trainsets and infrastructure improvements and thereby improving customer experience through reduced service interruptions and improved travel time [3]

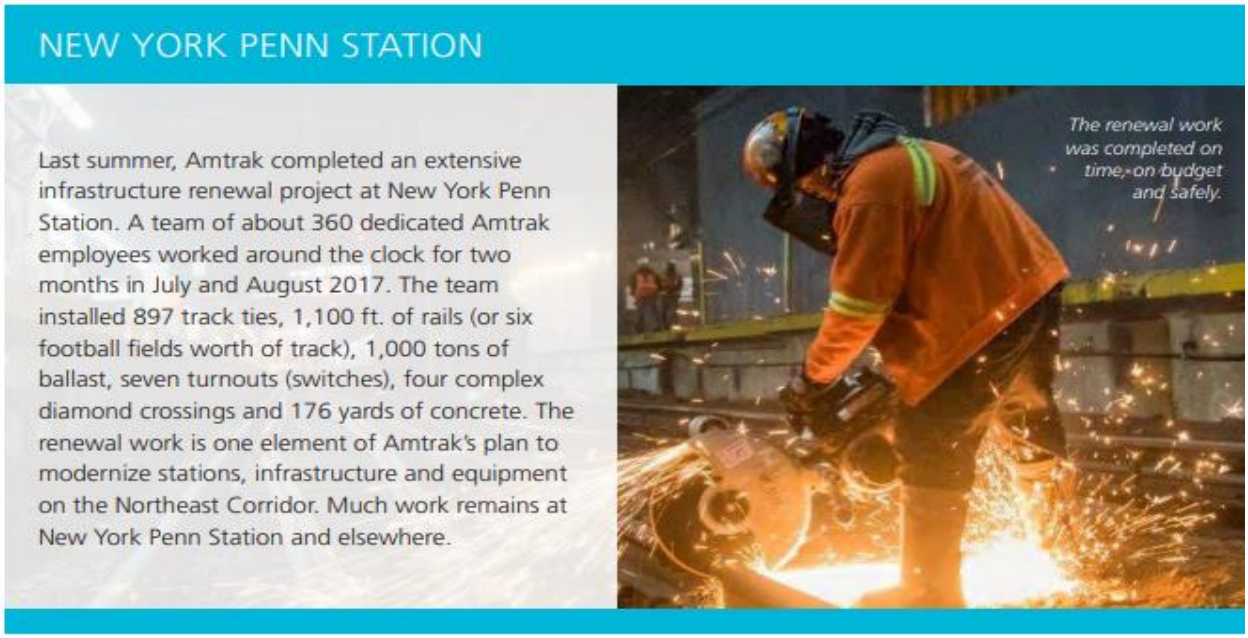

Figure 14 *AMTRAK'S Infrastructure Improvement Project, NEW YORK Penn Station* [3]

In conjunction with Amtrak's NEC Vision program, the federal government has taken steps towards creating a more competitive, efficient, but most of all, effective U.S. rail network. The U.S. High-Speed Rail

Association has started a four-phase project which aims to lay 17,000 miles of new track over the next few decades [22]. The new project would allow future high-speed trains to travel at speeds averaging upwards of 220 mph (four times faster than current rail travel). But again, it is crucial to make these projects a sustainable and resilient one to meet the future challenges in social, economic and environmental aspects. [12].

Railroads have many advantages over other forms of transport, especially for moving bulk goods across large territories. Few advantages of Rail Transport over Road Transport are:

- Cost Effective
- Environment friendly
- Capable of hauling large loads
- More reliable & better performance Efficiency
- Better safety records
- Play an important part in meeting rising sustainable regulations & goals

With such a long history and so much at stake, we are wise to consider the state of infrastructure as critical and the requirements to make rail services fit for purpose by investing and building a sustainable and resilient rail infrastructure.

THE ROLE OF GOVERNANCE FOR SHAPING SUSTAINABLE AND RESILIENT CRITICAL INFRASTRUCTURE

Resilience is a dynamic concept without a fixed endpoint. It is a never-ending journey that operates within a risk landscape that may be traditional or caused by uncertainty and is conditioned by people, knowledge, and technology [13]. Good governance is vital to the financial and economic success of sustainable and resilient infrastructure.

Governing bodies, such as policy makers and regulatory authorities at national, regional, and city levels, have greater roles to play and will be instrumental to the shaping of sustainable infrastructure goals. They are also crucial in closing the finance gap mainly in three ways: policy measures, information flow, and mobilizing finance [23].

1. Policy measures

- Developing clear and supportive policy and regulatory frameworks that enable environments to ensure that sustainability and resilience have become embedded in the planning and investment criteria - both for public spending and as a signal for private investment
- Following Intended Nationally Determined Contributions (INDC) commitments through implementation of domestic legislation to make emission reductions and reporting them mandatory.
- Overall Procurement and Investment plan should contain a defined set of sustainability criteria.
- Anti-corruption, service delivery, cost evaluation, improving transparency, and management in the public sector

2. Information flows

- Issuing long-term infrastructure plans to help develop a clear pipeline of projects for investors
- Communicating the benefits of sustainable infrastructure in a well-structured manner to all stakeholders right from the planning to commissioning stages
- Engaging collaboratively with other governing bodies vertically and across jurisdictions to develop common standards and collect performance data periodically to improve project comparability, future proof of investments, and sharing information about successes and failures.

3. Mobilizing investment

- Diverting fossil fuel subsidies to sustainable infrastructure development and putting a price on carbon.
- Introducing financial and tax incentives and financial support options.
- Leveraging credit enhancement mechanisms and public funding to attract private sector investment
- Funding the upfront costs, because sustainable infrastructure projects initially more expensive than conventional projects
- Boosting capital markets and developing standards for green bonds

Table 1 shows the key obstacles, along with their underlying causes, that are encountered when trying to provide more resilient infrastructure services [9]. Most of these obstacles can be overcome by having a good governance system in place.

Table 1 *Key Obstacles to More Resilient Infrastructure Services*

Obstacles to good infrastructure management	Obstacles to infrastructure resilience			
Poor design, operation, and maintenance of infrastructure systems	**Political economy challenges and coordination failures**	**Lack of incentives to increase resilience**	**Inadequate data, models, skills, or tools**	**Affordability and financing constraints**
• Absence of local standards, codes, and regulations (or lack of enforcement) • Underfinanced or understaffed regulators • Insufficient resources for the early-stage design of the infrastructure system and assets • Borrowing constraints and affordability issues • Lack of financing and capacity for asset maintenance	• Invisibility of resilience benefits • Interdependency of infrastructure systems • Synergies and trade-offs across different risks or infrastructure systems • Narrow mandates of institutions	• Infrastructure service providers not bearing the full cost of disruptions • Lack of incentives to protect or restore ecosystems	• Lack of data, methodologies, or technical skills • Designs often based on historical data and not on future hazards and climate change • Overconfidence in model results and historical data • Insufficient consideration of low-probability scenarios	• Lack of resources for risk-informed planning and risk assessment at early stages of project design • Lack of resources in postdisaster situations • Lack of information and transparency on infrastructure asset resilience

Note: *Adapted from (Hallegatte et al., 2019)*

RECOMMENDATIONS

Making the infrastructure more resilient requires a consistent strategy through the life cycle of the project or process. The World Bank's recommendation to investors is to invest in the early stages of regulations, planning, and maintenance in order to avoid significant costs of repair/reconstruction after a disaster [9]. The World Bank endorses five key recommendations to promote resilient infrastructure systems. First, it emphasizes a focus on "getting the basics right," underscoring the importance of tackling poor governance and management of infrastructure systems. Second, it recommends building institutions for resilience by addressing wider political economic challenges and identifying critical infrastructure assets and systems. Third, it suggests using regulations and financial incentives to account for the full social cost of infrastructure disruptions. It also suggests to encourage service providers to go beyond mandatory standards. Fourth, it calls for improved decision making and stresses that access to better data, tools, and skills can be "a gamechanger in building resilience." Finally, it emphasizes the importance of the "right kind of financing at the right time." At the early stages of infrastructure design, minimum amounts of resources can support regulators while in the aftermath of a catastrophe, billions of dollars of investments may be needed for repair and recovery.

1. Make the foundation for Resilient Infrastructure

Many infrastructure systems are poorly designed/operated/maintained and are quite vulnerable. Hence, it is vital to make them reliable by ensuring suitable designs, operations, and maintenance. Introduction of appropriate regulations, construction codes, and procurement rules are a must, apart from providing adequate funding. Table 2 has captured the obstacle, recommendation and required action associated with making the foundation.

Table 2 *Make the foundation for Resilient Infrastructure*

OBSTACLE	RECOMMENDATION	ACTIONS
Poor design, operation, and maintenance of infrastructure systems	Get the foundation for resilient infrastructure right	• Introduce and enforce regulations, construction codes, and procurement rules • Create systems for appropriate operation, maintenance, and post-incident response • Provide appropriate funding and financing for infrastructure planning, design, construction, and maintenance

Note: Adapted from (Hallegatte et al., 2019)

2. Building Institutions for Resilience

Oftentimes, the disasters that make headlines force an in-depth analysis of what actually went wrong, but extreme incidents that cause no or minor damages go unnoticed and do not attract people. Multiple political economic challenges and coordinating failures obstruct public action on resilience. Understanding the benefits of adding resilience to infrastructure requires recognizing the crises that are avoided – something that is extremely hard to do and even more difficult to communicate to the public. However, on the other hand, the cost of making infrastructure more resilient is much easier to recognize and contest. Mutual coordination is needed to make sure that actions by stakeholders are consistent because lack of coordination among actors could potentially be a greater challenge. Since modern infrastructures are running on automated processes and controlled by computer networks, they have become more vulnerable to cyberattacks and cyber-disasters. The most important step of risk management is to scan the environment, both in terms of the internal and external context, to identify traditional and uncertain risks and threats associated with each one of them. Table 3 shows the obstacle, recommendation and required action associated with building institution for resilience.

Table 3 *Building Institutions for Resilience*

OBSTACLE	RECOMMENDATION	ACTIONS
Political economic challenges and coordination failures among stakeholders	Build institutions for resilience	• Implement a whole-of-government approach to resilient infrastructure, building on the existing regulatory system • Identify critical infrastructure and define acceptable and intolerable risk levels • Ensure equitable access to resilient infrastructure

Note: *Adapted from (Hallegatte et al., 2019)*

3. Create Regulations and Incentives for Resilience

Technically speaking, the providers of infrastructure services and the parties that design, build, operate, and maintain infrastructure assets are expected to accept the full cost of infrastructure disruptions. Full cost

would include covering the cost of the repairs and the additional maintenance required after natural shocks, such as earthquakes, floods and storms, as well as the full cost of disruptions forced upon the users of the infrastructure services. Service providers then would have the incentives required to reduce the disruptions, including natural perils. In most cases, infrastructure owners or its operators have no incentive to reason for how the infrastructure would affect the risk exposure of its stakeholders and their ability to manage infrastructure disruptions. In addition to it, the overall expectation that the government will provide the ad hoc support, if an unexpected disaster occurs, may diminish the incentives to act by the providers. The recommendation to cop-up with these obstacles is to create a consistent set of regulations and financial incentives for resilience by bringing in line the interests of providers with public interests. Table 4 has listed the obstacles, recommendation and action points associated with creating regulations ad Incentives for resilience.

Table 4 *Create Regulations and Incentives for Resilience*

OBSTACLE	RECOMMENDATION	ACTIONS
Lack of incentives to avoid disruptions and increase resilience	Create regulations and incentives for resilience	• Consider resilience objectives in master plans, standards, and regulations and adjust them regularly to account for climate change • Create financial incentives for service providers to promote resilient infrastructure services • Ensure that infrastructure regulations are consistent with risk-informed land use plans and guide development toward safer areas

Note: *Adapted from (Hallegatte et al., 2019)*

4. Improve decision Making

The fourth recommendation is to improve decision making, but the obstacle is that public and private players often lack data, models, and capacity. In the absence of natural hazard and climate change data and models, operators are unable to improve resilience and regulators are not able to create robust regulations and incentives to deal with the uncertainties. The proposed recommendation is to invest in reliable data sources, make robust decisions, and build the knowledge and skills needed to use the data and models. It is critical to promote innovation and usage of new technologies to make data collection and processing much easier. Computer models can be used to simulate future scenarios so that to some extent, the anticipated risks associated with the specific infrastructure can be predicted through models. Table 5 has captured the obstacle, recommendations and action plans associated with improve decision making.

Table 5 *Improve Decision Making*

OBSTACLE	RECOMMENDATION	ACTIONS
Inadequate consideration of natural hazards and climate change	Needs to improve decision making	• Invest in freely accessible natural hazard and climate change data • Make robust decisions and minimize the potential for regret and devastating failure • Build the knowledge and skills needed to use data and models and mobilize the expertise of the private sector

Note: *Adapted from (Hallegatte et al., 2019*)

5. Provide Financing

Sometimes, making an infrastructure asset more resilient causes an absolute increase in its total life-cycle cost, leading to affordability challenges since the cost borne by the government, regulators, and the providers will increase. To ensure good project designs and a regular flow of resources for resilient infrastructure, it is vital to allocate resources and upfront investments toward the early phases of the project.

There are obstacles associated with providing financing. The recommendation is to make financing available and design appropriate action plans to overcome the obstacle as shown in Table 6.

Table 6 *Providing Financing*

OBSTACLE	RECOMMENDATION	ACTIONS
Infrastructure sector faces affordability and financing constraints	Make financing available	• Provide adequate funding to include risk assessments in master plans and early phases of project design • Develop a government-wide contingency plan and financial protection strategy • Encourage transparency to better inform investors and decision makers

Note: *Adapted from (Hallegatte et al., 2019)*

CONCLUSION

By 2050, more than half of the world's population is expected to live in urban areas, bringing huge challenges and opportunities for investment in sustainable and resilient infrastructure across every sector of the economy. Transportation systems including railroad systems will need to be smarter, faster, and more focused towards mass transit, electric vehicles, and self-driving vehicles. Infrastructure can be defined as the set of structural elements that supports our day-to-day lives and influences the direction of humanity. Hence, it is important to understand the significance of sustainable and resilient critical infrastructure systems – an emerging thought in an evolving era where natural and man-made assets are being worn-out to provide a sustainable and high quality of life. The effectiveness of a resilient infrastructure system depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event. Sustainable and resilient infrastructure is generally considered to approach development from a holistic viewpoint and based on global and domestic sustainable development goals and durability, having regard to social, financial and political issues, public health and wellbeing, as well as economic and environmental concerns. The development of infrastructure systems that are sustainable and resilient is a challenging task, and it involves a broad range of performance indicators over the system lifecycle that affect system functionality and recovery. Rail transport has a major role to play in developing the sustainable cities of the future. The choice of infrastructure development is crucial to sustainable development because the infrastructure we are building today will enable our future communities to remain resilient. Rail infrastructure is a critical component of a transportation system capable of helping the United States compete in global markets. With such a long history and so much at stake, we are wise to consider the state of infrastructure as critical and the requirements to make rail services fit for purpose by investing and building a sustainable and resilient rail infrastructure.

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