Rail Transportation Vulnerability and Resiliency to Impacts of Climate Change and Recommendations for Objective Measurement Methods

Warren S. Meyers
SYSTRA Inc.
New York, NY

INTRODUCTION

Infrastructure and Climate Change

New York City has experienced within two years two major hurricanes, Irene and Sandy, and an extensive series of snowstorms that paralyzed the region. New York City Transit and commuter rail services were inoperable as were surface transit vehicles. Increasingly, weather conditions are affected by global warming precipitated by the documented global warming caused directly by increases in CO_2 associate with the use of fossil fuels in the industrialized societies of the World. Transportation networks are a critical component of industrial infrastructure that consist of road, rail, marine and pipeline systems that facilitate the transfer of goods and services. Other infrastructure components include; electrical power grid and other forms of power, communications systems, water and sewers, and social systems such as hospitals and health care, public safety and security, and educational systems. These infrastructure systems are required in all civilized and industrialized societies and they must be established and maintained at capacities that meet social needs as well as robustly when challenged by complex variables as weather and climate, national emergency or disaster.

The breakdown of transportation systems can be caused by factors of demand or impacts that prevent the transportation systems to operate or serve demand. Complex infrastructure systems must interoperate in order to allow the system of systems to meet the social needs. Losses of major infrastructure components such as a major bridge, transit mode or roadway, access to water, communications systems or fuels can result in cascading effects that degrade the levels of service that are normally expected by society as a whole.

Global warming, the result of climate change (CC), has resulted in significant impacts across the globe in the recent decade. In fact, extreme weather events have resulted in substantial losses since the 1950s as evidenced by a study by the World Bank in 2001.[1] When the study was written, the certainty of the prediction of CC and warming was far less than it is today, with the benefit of studies and field measurement and observation. Freeman's findings were that infrastructure is directly and seriously impacted by worldwide direct losses and that the impact of different weather events can result in linkage of infrastructure damage.

These cumulative damages caused by one or more causations resultant of CC can result in substantially greater damage that the original construction design standards would account for. In particular, extreme climate events would include; intense precipitation (simple extremes), increased summer drying/drought, increased cyclone and wind speeds, droughts and floods and increased intensity of mid-latitude storms. While the events occur worldwide, Freeman observes that poorer developing countries experience a disproportionate level of human suffering.

---

[1] Freeman, Paul, Warner, K., Vulnerability of Infrastructure to Climate Variability: How Does this Affect the Infrastructure Lending Policies, World Bank and Prevention Consortium, Washington, October 2001.

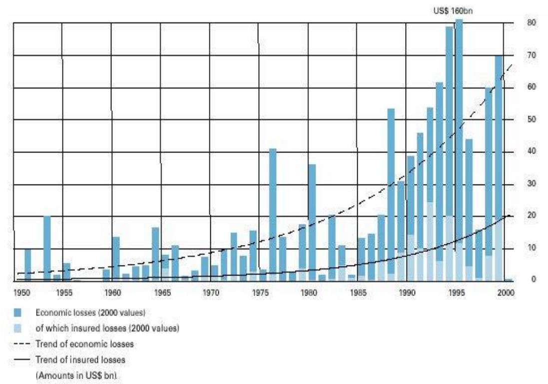

Figure 1- Economic Losses from natural catastrophes in the 20th Century- Freeman

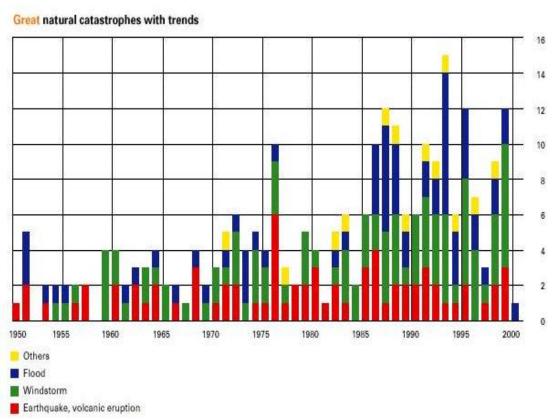

Figure 2- Great Natural catastrophe trends in the 20th century, Freeman

Evidence of Climate Extremes and Climate Change

The evidence of climate extremes and relationship to climate change is most clearly observed in the surface sea temperatures (SST) where the SSTs have been rising by 0.5 to 0.6° since the 1950s and the water vapor in the atmosphere has increased by more than 4%. As a result, the air is on average warmer and moister than prior to 1970s, leading to an increase of 5 to 10% in storm activity and severity. [2] Other evidence of the warming effects of CC include higher signal to noise ratio for weather events that are the typical storming levels of the past historical records, large scale heat and drought (lack of rain in areas), the continued existence of El Nino Southern Oscillation (ENSO), carbon dioxide increases, increased water levels and the buoyancy of air flowing into storms. Lastly, there have been heavy rains and flooding in China, India and Pakistan with strong monsoon impacts on a Russian heat wave and severe heat waves and famine in East Africa. Sea ice breakup in the Arctic and positive Arabian Sea SST anomalies have also been documented. [3]

Infrastructure Vulnerabilities

Military and security practices have developed methodologies to identify and quantify, if possible, the vulnerabilities of systems whether they are a fort or armada, buildings, bridges and tunnels, or pipelines. In recent years, transportation systems or buildings have been targets of terrorism and governments around the globe have improved security and monitoring of these facilities and infrastructure. These activities have resulted in the development of new methodologies that assess infrastructure susceptibility to risks that can lead to an event, threat scenario and outcomes. The methods can be applied to infrastructure systems and develop a clear separation between risk and vulnerability with the latter representing a universal set of the triplet, scenario, protection and importance. While originally developed within a security context, the security event is equally relevant as it pertains to the probabilities of risk and negative outcomes that can affect the serviceability of the asset in question. Developing a list of scenarios, the risk and vulnerability can result in the development of clear parameters that identify the negative impacts of 'events' whether they are related to security or weather or otherwise. [4] Other systems-driven assessments of vulnerability to climate change have developed quantitative to permit the comparison between infrastructure systems or nations using sets of parameters including demographics, climate, agricultural, occupation and geographic vulnerabilities. [5]

The vulnerability of infrastructure systems includes transportation systems across the globe and is not unique to any one nation. Transportation systems can

---

[2] Trenberth, K.E., et al, Observations: surface and atmospheric climate change. Climate Change 2007, The physical science basis, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp. 235-336.

[3] Must Read Trenberth: How to Relate Climate Extremes to Climate Change, ThinkProgress, http://thinkprogress.org/climate.

[4] Ezell, Barry, Quantifying Vulnerability to Critical Infrastructure, US Army School System Directorate.

[5] http://www.icrisat.org/what-we-do/impi/training-cc/october-2-3-2009/vulnerability-analysis-manual.pdf.

be very flexible and robust when the systems are not impacted by stressors as weather, other natural events as earthquakes. However intermodal systems that facilitate commerce and travel can result in serious disruptions of service and all societal order leading to panic or public stress. These impacts are not limited to passenger travel but can equally impact the freight traffic and supply chains can be significantly impacted as was the case with gasoline distribution encountered in the aftermath of Hurricane Sandy.
A recent study funded by the 7th Framework Program of the European Commission, Vulnerability of Transport Systems as completed in 2012 and identified specific levels of stress on the European countries attributed to CC.[6] The studies evaluate CC patterns and validate that northern Europe will be subject to heavier levels of precipitation (rain, snow, fog) and the southern Europe will be subjected to hotter and drier conditions and will include fires, and flash floods that can result in damage to the transportation infrastructures. These include road, rail, maritime and air facilities and infrastructure. The severity of CC related damage is more clearly identified within the intermodal systems largely due to inflexibility of the transport systems for flooding and damage caused by landslides, avalanches and wind. These damages could impact road and tracks, vehicles, ships, harborage, bridges and airline facilities include traffic control systems.

A second study conducted within France examines the vulnerabilities to changes in season and CC using the data developed of two IPCC global climate models (A2 and B2).[7] The study results suggest the increased impact of weather related damage to transport infrastructure within the nation which needs to be addressed through new infrastructure, improvement to existing systems and rethinking of adaptive measures for CC. All transportation modes were examined and all have various levels of susceptibility to damage attributed to CC and efforts to improve tolerance of such weather events would result in improved resilience of transport systems and provision of services. The reliance on the French rail system (both high-speed rail and conventional rail lines), particularly with concentrations of nodes in a limited number of urban centers and the relatively small number of rail corridors in the country, tend to magnify service effecting services. The impact of increased temperatures across the nation can potentially impact rail track movement and fire damage to rail infrastructure and resulting in service levels and safety. The study recommended the development of both short and long-term adaptive measures to meet demand of the country for both passenger and freight requirements. The study further highlights the need for autonomous (on-demand) and planned (ahead of demand) means to address the upgraded infrastructure needs of the rail, as well as all transportation systems, and the improved tolerance of existing systems i.e. the resiliency of the system to withstand the climate change impacts. In the United States, the National Wildlife Federation identified the following impacts across the nation attributed to extreme weather based on the trends from 2000-2009[8]:

1. Hotter summers and heat waves
2. Stronger hurricanes
3. More flooding as heavy rainfall increases and snowmelt shifts
4. Water shortages become more common and more severe
5. Increase frequency and duration of power outages
6. Wind, flooding, waves and subsea mudslides and lightning to oil and gas infrastructure production and delivery systems
7. Disruptions of coal transport on railway lines and barge routes
8. Water stress in the southwest impacting power generation
9. Sea-level rise and storm surge impacting coastal areas and flooding of airports, roads, rail lines and tunnels

The United Kingdom Office for Science and the Foresight Project examined the demand for energy and transportation internationally through 2030.[9] The

6 Enei, Riccardo, et al, Weather Extremes: Assessment of Impacts on Transport Systems and Hazard for European Regions, Deliverable 2.
7 Cochran, Ian, Climate Change Vulnerabilities and Adaption Possibilities for Transport Infrastructure in France, Caisse des Depots, Climate Report, Research on the economics of climate change, Issue No. 18, September 2009.

8 http://www.nwf.org/~/media/PDFs/Global-Warming/Extreme-Weather/Final_NWF_EnergyInfrastructureReport_4-8-11.pdf?dmc=1&ts=20121227T2149548219
9 McGee, Anthony, International Dimensions of Climate Change, Report 6.2: Impacts of Climate Change on Overseas Infrastructure (excluding sea-level rise), UK Government Foresight Project on the

report cites an increased demand for energy in the developing countries resulting in increased trans-border infrastructure requirements and specifically energy transportation. This is particularly troubling as much of the world's energy transportation infrastructure is aging for developed nations while new infrastructure will be required for developing nations. [10] Moreover, worldwide passenger travel will double over the next 15 years, with freight traffic outpacing passenger transport. The demand for digital TCP/IP driven telecommunications will increase in virtually all nations. These international trends will require infrastructure interdependencies and will result in acute deficiencies that shall need to be addressed in order to cope with impacts of demand and impacts of CC. As a result, adaptive capacity will be required within the European Community and internationally with substantial costs and impact on the transportation, energy and communications infrastructure. Within the UK, the focus of the study, adaption will be very costly and require extensive infrastructure investment by way if upgrades and new construction.

In the United States, a study conducted by the United States Air Force Counter Proliferation Center identify the critical choke points and for freight rail corridors and passenger rail infrastructure.[11] Common restrictions and congestion points were identified in Chicago, IL, Los Angeles, LA, Salt Lake City, UT and Atlanta, GA, among others. These areas are vulnerable from the standpoint of counterterrorism provide added insight into the complexities of maintaining service levels under stressful states including the impacts of climate change.

Infrastructure Resiliency and Sustainability

The preparations for infrastructure adaption to CC are known to include improved resiliency to the impacts of global warming impacts. These include a set of measures to improve the ability of the infrastructure systems to be tolerant to the impacts. Resiliency consists of three elements; lower probability of failure, less severe consequences and faster recovery times. [12] The challenges of adaption and upgrade of systems are to understand and account for the interdependencies of infrastructure elements and systems. A secondary goal is to provide designs that are sustainable and reduce negative environmental impacts.

Another position relative to resiliency is the role of government in facilitating adaptive infrastructure change since infrastructure is commonly funded by government and private sources.[13] Government has the responsibility of establishing the means to spur economic reinvestment to create infrastructure resiliency which has real costs and necessities for sound societal returns. In India, the approach to resilient and sustainable planning is assumed by the government and requires a proactive infrastructure approach to direct land-use, reduce the exposure of the population, generate compatibility with the environment and foster low carbon development.[14] Another role for the government entity includes recognition of the changing profile of hazards, anticipation of future risks, and disaster response scenarios.

In the United States, Flynn and Burke stress resilience as the ability to deal with change and to maintain continuity of function of the system; develop the means for graceful degradation of services, the ability to recover quickly to a desired level of function and to require the cooperation between the public and private sectors.[15]
Glemare identifies adaption of long-term climate change and intermediate disaster risk management into policies for the planning, design, construction and maintenance by stressing the dimensions of spatial and sectored dimensions followed by the road-mapping of infrastructure adaption:[16]

International Dimensions of Climate Change, July 2010.

[10] Umbach, F, Global energy security and the implications for the EU. ENERGY POLICY, 38, 1229-1240, 2003.

[11] Capra, Gregory, Protecting Critical Rail Infrastructure, The Counter Proliferation Papers, Future Warfare Series No. 38, USAF Counter proliferation Center, Air University, Maxwell Air Force Base, Alabama, December, 2006. http://cpc.au.af.mil/.

[12] Chang, S.E., National Academy of Engineering, Frontiers of Engineering, winter 2009, Infrastructure Resilience to Disasters.

[13] Secretary of State for Environment, Food and Rural Affairs by Command of the Majesty, May 2011, Climate Resilient Infrastructure; Preparing for a Changing Climate.

[14] Spicer, E., OFID, India, Climate Resilient and Sustainable Urban Development.

[15] Flynn, S. and Burke, S., TR News 275, July-August, 2011, Brittle Infrastructure, Community Resilience and National Security.

[16] Glenmare, Yannick, Official Proceedings International Conference: Strategies for Adapting Public and Private Infrastructure to Climate Change,

- Mapping the present and future climate variability and risk
- Mapping critical socio-technical infrastructure
- Define acceptable risk levels
- Select non-structural and structural risk mitigation strategies

Fiksel addresses the complexities of designing resilient and sustainable systems and cites that sustainable development requires a systems approach and that designers must focus on how complex systems interact and upon interrelationships of infrastructure systems.[17] Resilient systems must be oriented towards dynamic and non-linear relationships in some instance those that are disorderly in nature. These systems must address the need for diversity or redundancy, efficiency and to perform with modest resource consumption and are adaptable to new pressures and requirements. Several works addressing issues of resiliency of the national infrastructure in the United States warrant a closer examination. They are significant in their perspective or depth of coverage and shed further light into the interactions of technologies relevant to the dialog in energy and the transportation infrastructures. The first comes from a multi discipline panel of scientists under the auspices of the National Science Foundation (NSF) in 2007.[18] The objectives were to 1) identify research needs relating to designing systems of interdependent infrastructure that are reliable and resilient over a long-term period, 2) identify critical problems of interdependent infrastructure and what the research priorities should be, and 3) identify research tools and research infrastructure.

The group findings included discussion into the increasingly interdependence of manmade and natural systems that have become less resilient to unanticipated perturbations. Additionally, there was a recognized need to address the complexity of these interdependent systems. Transportation, energy, and water were widely viewed as high priorities. Systems approaches to assessing the higher order interactions among interdependent infrastructure systems is also needed to address complex issues that involving these relationships. A complete assessment of the planning requirements to achieve a sustainable as well as resilient future through the strengthening of disaster response as part of adaption to climate change is provided by O'Brien.[19] Key findings of the collaborative study include the following:

- A combination of incremental and transformation changes are required for reducing risk from weather and climate extremes and change.
- Disaster and adaptive policy can be integrated, enforcing and supportive but careful coordination is required to reach across domains of policy and practice.
- Learning processes are central in shaping capacities and outcomes of resilience in disaster risk management and climate change adaption and sustainable development.
- Questioning assumptions, paradigm changes and stimulating innovation are helpful towards developing resilient and sustainable development to encourage new responses to the issues.
- Multi-hazard risk management approaches provide opportunity to reduce complex and compound hazards.
- Interactions among climate change mitigation, adaption and disaster management are major influences on resilient and sustainable pathways in addressing climate change.
- Multiple approaches and pathways exist and can increase resilience to climate extremes when optimally applied.

To conclude upon this review of the literature, a wide range of research has been performed to identify the various approaches to addressing the need for resilient and sustainable infrastructure required as adaptive measures for climate change, global warming and extreme weather or natural events. The interactions among the various infrastructure systems and a recurring issue that are to be considered by

---

United Nations Development Program, Paving the Way for Climate Resistant Infrastructure, 2011.

[17] Fiksel, J, Designing Resilient and Sustainable Systems, Environmental Sciences and Technology, Vol. 37, No. 23, 2003.

[18] National Science Foundation, Emerging Frontiers in Research and Innovation, Resilient and Sustainable Infrastructure Networks (RESIN), Workshop Report, December 4-5, 2006, National Science Foundation, Arlington, VA.

[19] O'Brien, Karen et al, Towards a Sustainable and Resilient Future, Chapter 8, http://ipcc-wg2.gov/SREX/images/uploads/SREX-Chap8_FINAL.pdf.

planners, engineers, government managers and society ombudsmen.

RAIL TRANSPORTATION AND CLIMATE CHANGE/GLOBAL WARMING AND EXTREME WEATHER

Vulnerability of Rail Systems to Climate Change and extreme weather related events

As previously discussed, transport systems across the globe are susceptible to the negative impacts of climate change, global warming and extreme weather events. Railroad systems are intensively used for both passenger and freight movement across the world and increases in ridership and freight tonnage are increasing in part to the continued growth of emerging nations and demand for 'greener' commuting and travel in the industrialized societies. Studies identifying the relationship between the changes in weather patterns and the rail infrastructure have been emerging from the literature in recent years and do so across the globe. The recurring findings are that CC is increasing the level of precipitation across many parts of the northern hemisphere and also causing record heat in many areas of the earth including the southern United States, southern Europe, the Middle East and many other smaller developing nations.

Rossetti conducted in the impacts of climate change on US railroads resulting in increased precipitation and stronger and more frequent storms as well as hotter temperatures and at frequency of hotter days and for longer durations. [20] These impacts take into consideration the complex climate influencers including; El Nino, North Atlantic Oscillation, Pacific Decadal Oscillation, Arctic Oscillations, Pacific-North American Teleconnection, the Madden Jilio Oscillation and finally global warming from greenhouse gases, carbon dioxide, black carbon and methane. The report also finds accident cautions and is evaluated in as far as frequency and severity over time. The link between weather and accident causation is established and recommendations for adaptation of the railroad response and proactive measures are detailed. They include research into the following:

- Analysis of climate records
- Analysis of climate change assessments and forecast scenarios
- Identification of critical climate and weather parameters
- Analysis of climate change effects on railroad operations
- Analysis of climate effects on railroad infrastructure.

The study also notes the increased railroad impacts caused by fluctuations or changes in climate:

- Floods
- Rockslide and avalanche hazards
- Rail damage resulting from track shifting due to temperature extremes
- Winter storm damage to switches
- Damage such as scouring of bridge structures, embankments and ballast

The International Union of Railways (UIC) has established a working group within their sustainability systems unit to develop assessments of the impact of climate change within the European arena. The results of the group have resulted in several studies referred to as the 'Adaption of Railway Infrastructure to Climate Change (ARISCC). [21] The group's objective was as follows:

- Develop best practices for weather/natural event management
- Find good examples of how railways are assessing infrastructure vulnerability
- Understand how railways can incorporate longer term climate predictions into the infrastructure management and planning process
- Develop new management approaches to the issues of climate change and infrastructure

[20] Rossetti, M., the Potential Impacts of Climate Change on Transportation, http://2climate.dot.gov/documents/workshop1002/rossetti.pdf.

[21] Veitch, A., UIC Sustainability Unit, http://www.ariscc.org/.

The group has developed some very helpful methods to document and map weather and other natural hazards, documented good management practice methods for European railways, identified climate models that impact railways and developed adaption strategies. These strategies include the following measures:

- Produce vulnerability and risk maps and link risk to operations and infrastructure
- Develop alarm and monitoring systems, take protective measures in response to CC related infrastructure issues, change standards where appropriate and relocate assets as needed.

Further evaluation of the impacts of climate change within the European Community with particular relevance to cold weather related issues was conducted by the Swedish National Railway and Defense Research Agency.[22] The author had conducted a search of the literature on railway issues and CC and described some of the historical infrastructure issues of the railroads within the country. Operator management attributes some CC events contribute to 'disturbances' after technical failures but have not performed as of the surveys mapped out current or future climate related threats. The findings nonetheless suggest that areas of the Swedish country will result in warmer climate conditions that should serve to reduce the consequences of severe weather on the operation of the railway system. Otherwise in cases where there are consequences, they would be related to rail buckling and failures of the drainage systems. One adaptive measure by the railway is to establish tree-free zones along the railway corridor to reduce tree downing impacts of service. Other improvements considered to be required are with drainage systems. Other issues of CC that the railroad will need to address include; water damage, rail buckling, increased risk of fires, higher water levels of streams and rivers leading to flooding. In response to the certainty of CC, the railway will undertake systematic mapping of climate related vulnerabilities and threats to the system. Increased attention to the planning process for infrastructure, climate change in general as well as improved management oversight and use of technology to better monitor systems and improve response to weather and extreme weather events. The importance in establishing the appropriate planning response to CC was also recognized.

Lastly, within the United Kingdom, Network Rail produced an impact assessment of Climate Change Adaption for its rail system. Network Rail has previously conducted climate change risk assessments and continues to do so. The rail operator has identified an increase in track buckling due to hotter weather and sagging of overhead line equipment. Each contributes to higher maintenance costs and manpower. Additionally there are increased levels of bridge scouring and localized flooding of embankments, culvert washouts, depot flooding and wayside equipment failure and breakdown of railway flood defenses. Uncertainties of other impacts caused by CC are responded to by the need for improved study of CC and its impacts locally as well as globally. Network Rail will work to develop the appropriate adaption measures and strategies and intends to utilize the resources of research laboratories in the universities and study the issues of interdependencies of infrastructure systems as are other transport organizations identified in this paper and by other public bodies evaluating CC and adaptive strategies and has concerns with cascade failure threats within the public transport and other infrastructure services from an operational as well as budgetary levels.

Quantitative Metrics of CC Risk, Vulnerability and Costs

Through the research of the literature and reporting of transit agency investigations of the cost and vulnerabilities of infrastructure to climate change and extreme weather events, there are very limited quantitative methods to assess adaptation costs and risks associated with its progression. Metrics are limited the following Table 1.

Metric Parameter	Derivation	Value
Cost	Estimates of capital & expense	Strong relative to exposure
Climate Data	Scientific measurement of global CC	Critical requirement and suitable for trend analysis and quantification
Risk	Probability of negative impacts and magnitudes	Strong method of evaluating potential for impacts.
Vulnerability	Combination of factors from environment and	Strong for comparative analysis and combined with

[22] Lindgren, Johan et al., Climate Adaption of Railways: Lessons from Sweden, European Journal of Transport and Infrastructure Research, Issue (2), June, 2009, pp. 164-181, ISSN: 1567-7141, www.ejtir.tbm.tudelft.nl.

	professional observation	non-parametric tools
Statistical	Evaluation of Hypotheses	Determination of significance of data, random vs. non-
Physical attribute of civil and electronic systems	Measurement of stress, wear, faults or conditions	Static vs. dynamic analysis of physical infrastructure and materials
Economic and financial models	Development of cost benefit ratios, IRR and NPV	Used to allocate scarce resources and prioritize projects

Table 1- Quantitative Methods for Evaluating Climate Change

Each of these quantitative methods can provide valuable and critical insight into the impact of CC and the adaptation and remediation as well as potential for serious long-term harm to the infrastructure and socioeconomic systems. Used in conjunction with one another, these metrics can create a composite of view of risk; severity or scale of potential impact, cost, vulnerability, scientific collection and analysis of earth science data; tests if statistical significance and physical monitoring of all systems that may be affected by CC. These quantitative measures can be sued on conjunction with subjective data based on opinions of social or economic impact to develop a consensus of the inputs and the subsequent development of appropriate actions to be taken. There is a need to exercise caution however as the uses of disparate data sources can be overwhelming and reduce the significance of the value of any input model to a higher level model. This adds a level of complexity when making determinations that involve multiple complex systems and their interactions. The cost of funds to make improvements to these infrastructures is great and the funds are limited. Man has coexisted with the planet for 40,000 to 50,000 years and the enormous development of public infrastructure has been around for only a few hundred and unfortunately there are so many costly improvements that can be addressed in a short interval. Fortunately for man, the impact of global warming will occur most heavily, and over the vastness of the earth, over a few generations or a few hundred years into the future. It is largely understood now by scientists and government bodies that CC will alter our infrastructure and that changes will have to be planned. Timing could not come worse as the industrialized societies have built excess economic capacity and public revenues are increasingly limited and stretched over many competing projects and programs. The necessity of scientific, public and academics to address these complex problems will be necessitated and additional insight is gained into the problems of addressing CC. The efforts to mitigate the impact of CC and global warming are noble and necessary and the hopes of holding the impacts to present day conditions. The odds are however, that an enormous upgrade in infrastructure systems will be required to minimize losses of societies around the world.

Vulnerability Metrics for Rail Transportation Systems

As it has been presented, the global railroad systems operators will have to assess the impact of CC to the cost of operations and infrastructure to relate to their rail systems. These metrics will, as has been discussed, require data aggregation and development of composite indexes to allocate scarce funds and invest for the future. The railroad and other transit systems are of paramount importance to society and the global economies. The absence of a working transportation system for anything beyond a two day period, places the economies of the region at risk with severe impacts to corporations and the pubic-at-large. This cause and effect scenario was witnessed by the impact of Hurricane Sandy on the New York and New Jersey region. It was very fortunate that the transit lines were restored - in some cases in very little time - as opposed to months on some limited lines such as the PATH system. The filling of tunnels around Manhattan were unprecedented in modern history and the reality of CC has made a very stark and dangerous impact on the way we think about the resiliency of the transportation infrastructure as well as that of water, power, and communications. Faced with the daunting task of planning for the impacts of CC, civic leaders, engineering organizations and firms, academics and students alike are or will be working to take serious and bold steps to assessing the infrastructure systems and allocation of resources to fortify our systems, reduce their vulnerability to such events and increase their resilience to absorb the long term and acute impacts.

Central to allocation and prioritization of funds, civic leaders will need to document their systems strengths, weaknesses, exposure to risk, impact of loss or marginalized service and develop a rational means by which to optimize our short and long-term prospects for minimizing the detrimental impact of CC upon our infrastructure. To facilitate the rational sorting of priorities and needs, risks and benefits, a survey method to gauge the appropriateness of the capital investment into infrastructure systems. Insight into the considerations and methods are aptly described in the following selection as written by A. J. Holmgren.[23]

"The author argues that studies or critical infrastructures must rely on both detailed engineering modeling, and course modeling that focus on generic mechanisms. Existing methods for risk analysis can, to some extent, be adjusted and used in vulnerability analysis of infrastructure systems, but a major challenge is further develop methods for analysis of complex systems." In view of the need for some form of metrics within the rail transportation sector, a starting point for assessment of vulnerability and risk must be taken seriously.

In recent months, New Jersey Transit (NJT) enlisted a study of "Resilience of NJ Transit Assets to Climate Impacts" as prepared by an outside consulting firm.[24] This study identified NJT exposure levels to flood hazards, coastal vulnerability and storm surge and forested areas. The study identified the general consensus of the impact of CC and the frequency or intense storms and specific resilience measures were recommended. Costs were aggregated to the cost per track mile as the primary metric.

The public report however did not disclose the costs potential or the specific recommendations to NJT. The complexity of the issues and the lack of a well-defined risk and vulnerability method that is sufficiently quantitative demonstrate the complexity and difficulty of the task. On this base, a proposed framework for a quantitative methodology that may be used by transit agencies follows. It relies upon the parameters cited in Table 1 and uses a combination of objective and subjective evaluation criterion.

The data collection and study methodologies are a composite of the findings examined and assessed in this document and opens up a newer horizon of opportunity to provide a deeper understanding of the causation of infrastructure damage, means to remediate and improve resilience and lower vulnerability of the transportation assets. A combination of on-demand/head of demand and qualitative and quantitative methods in conjunction with a deep routed understanding of the transit organization can establish a means test with which to provide clearer direction to public executives while enlisting the technical analysis of engineering professionals and urban/transit and system planners. Similar to the means by which civil engineering associations have ascribed letter grades to the condition of American highways and bridges, a composite valuation and determination upon infrastructure investments and measures to counter global climate change can be of significant and lasting benefit. The refinement of the methodology is to be developed and shaped into actionable recommendations and applied to the types of infrastructure and the classification of climate impact that may affect its availability, reliability, capacity and maintainability.

Risk, Vulnerability and Cost Assessment Model for Metropolitan Area Transit/Rail Agencies

1) Model Characterization ________________

2) Volume/Service Levels ________________

3) Hazard associated with Weather Impact____

4) Climate Change Agent ________________

5) Replacement Cost____________________

6) Remediation/Adaption Strategy and Cost ___

7) Probability and Impact Severity __________

8) Expert panel of subject matter expert's ________

9) Statistical determinations of event and impact on pubic activity ______________________________

10) Appropriate technology for monitoring of infrastructure ______________________________

11) Cost benefit, NPV or IRR means testing of adaption strategy ___________________________

12) Service level requirements or targets ________

13) Infrastructure Interdependencies ____________

14) Innovations in Infrastructure Technologies ____

15) Service Life/Technology Refresh of Systems __

16) Existing and desired levels of redundancy and resilience _______________________________

17) Long-term public needs and benefits _______

Table 2- Risk/Vulnerability Assessment Methodology

---

[23] Murray, A.T., Grubesic, T.H., Critical Infrastructure, Reliability and Vulnerability, Springer Press, New York ISBN 978-3-540-68055-0. p. 31-55.

[24] Thomson, Barbara et al, Resilience of NJ TRANSIT Assets to Climate Change Impacts, A report from First Environment, Inc., Boonton, NJ.

An expanded description of the types of infrastructure as well as those weather effects impact by CC can be further developed in the next stage of development for the model. Typical risks would include: flooding, storm surge, loss of embankments, scouring, bridge damage, rail buckling, terminal damage or loss, communications and information technology systems, signaling, traction and power, safety systems, revenue or repair/service vehicles and support infrastructure.

FURTHER RELEVANT CASE METHODOLOGIES AND CONCLUSIONS

A review of the specific climate change adaptation strategies for three very large transit agencies of the world. They include that of London, United Kingdom, New York Metropolitan Transportation Authority and the Los Angeles Metropolitan Transportation Authority, in the US. Their summaries of CC adaptation are provided below.

Transport for London

The following actions were taken by the Transport of London in response to the CC challenge:

- Passage of a U.K. Climate Change Act of 2008 to require government agencies to report on how they have evaluated their systems and planned for CC impacts
- Development of CC risk assessment of the transit authority
- Demonstrated use of relevant and appropriate CC data
- Explicit consideration of uncertainty and response
- Risk assessments that generate priorities for actions and identifies opportunities for action
- Clear demonstration of an adaptive management approach to adoption of measures and
- Monitoring and evaluation of adaption effectiveness
- Evaluation of all transport assets for all combinations of CC impacts
- Development of main risk assessment methodology for all levels of risk and development of assessments of probability, cost, time to implement, customer and reputation.
- Development of climate change impact risk map methodology
- Development of a formal tracks and civil risk assessment methodology

New York Metropolitan Transportation Authority [25]

The NYC Transportation Authority has constructed a well-developed risk identification and causation model for critical systems and high probabilities of flooding and system damages. In response, the Authority has developed improved drainage system programs and has encouraged improvements in development and use of energy efficient modes such as bicycle.

Los Angeles Metropolitan Transportation Authority[26]

The LA MTA has undertaken a CC adaptation program as summarized below:

- Formulation of an articulated adaptation plan identifying the nature and magnitude of risks, planning and operational options for reducing risk along with a financial analysis of costs vs. benefits
- Development of an detailed methodology that includes the following actions:
    - Identify critical assets and services
    - Analyze historical climate and projected future climate

[25] Dutta, Projjal, Director of Sustainability initiatives, Climate Change Adaptation and the MTA, FTA Climate Change Adaptation Webinar, August 8, 2011.
[26] Liban, C.B., LA MTA, Progress Towards a Climate Adaption Plan at LAMTA, FTA Transit Climate Change Adaptation Webinar, August 8, 2011.

- Identify vulnerability to impacts
- Evaluate potential adaptation options

- Identification of critical assets and services and provide a preliminary analysis of the service levels for transit services and the development of a framework for determining criticality for stations and service locations/facilities

- Documentation and articulated understanding of the CC impacts in Southern California and develop adaptation changes to infrastructure to address future climate change

- Documentation of detailed adaptation options for consideration including:
  - Improved weather collection information and technologies
  - Exploring the use of more heat resistant track and wayside materials
  - Improving flood defense systems
  - Develop improved construction practices to reduce the impact of adaptation upgrades

- Develop an evaluation process and methodology related to the pursuit of adaptation strategies

Strategies Recommended by the American Association of State Highway and Transportation Officials (AASHTO)

The AASHTO has developed a Workshop Whitepaper on the topic of adaption transportation infrastructure to extreme weather events in 2012.[27] The objective of the workshop was to publicize the potential impact of CC impacts upon current and aging transportation infrastructure. AAHSTO further identify the key impacts of CC including temperature increases, elevated precipitation and storm activity, sea level rise and hurricanes. The impact to transportation infrastructure and the change to operations and maintenance methodologies are detailed. Specific activities in a number of states are reviewed including California, Iowa, Massachusetts, Michigan and Washington and the resulting damage associated with Hurricane Irene was particularly detailed along with warnings of the impacts of future hurricanes along the eastern US seaboard. The whitepaper further details changes in planning considerations to accommodate CC along with other measures including more flexible design standards, retrofitting of infrastructure to improve resiliency and lower vulnerabilities, alterations in maintenance programs and emergency response. Additional adaptation strategies were provided with respect to materials and the strength of materials and design adequacy.

Conclusions and Additional Research

The impact of global climate change in the transportation sector is of paramount importance. Specific areas of concern are for the transport systems infrastructure including tracks, power, and facilities attributed to flooding, storm surge, wind, heat, hurricanes and tornados. The infrastructure systems are complex and will require advanced levels of analysis and design review to ensure service and operability when stressed by future weather impacts of CC and global warming. Many transportation authorities in the United States and internationally are proactively addressing the assessment and engineering of infrastructure and increasingly engaged in the appropriate response to CC. New quantitative methods can incorporate existing conventional methodologies and potentially examine the complex interdependencies between factors and provide a framework for assessment of infrastructure requirements in response to climate change. Additional work will be done into using the methods and survey methodologies to establish a working and meaningful model to index the risk/vulnerability infrastructure and tested with surveys of New York, New Jersey and Los Angeles, CA transit officials to begin to populate the methodology and refine it for further testing and use. The outcome of this work will be presentation to the American Public Transportation Association annual Rail Conference in June, 1013. A draft of the topic has been submitted and Abstracts are due January 4th, 2013. Further applicable to railroad network communications and Information Technology platforms will be examined as well with recommendations for improving resiliency, availability, reliability and fault tolerant to minimize future electronic systems consequences for major storm incidents like Hurricane Sandy.

---

[27] Meyer, M., Choate, A., Adapting Infrastructure to Extreme Weather Events: Best Practices and Key Challenges, Background Paper, AASHTO Workshop, Traverse City, Michigan, May 20, 2012.

About the Author

Warren Meyers **is Communications** Manager at SYSTRA in New York. He has a background in Traffic and Transportation Engineering Systems, Telecommunications, Technology Management and Urban Sustainability and Sustainability of Infrastructure Systems.