Innovating Infrastructure Planning, Financing, Engineering and Management

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INFRASTRUCTURES

Infrastructures such as transportation, clean and waste water, fuel and energy, communication and many others are complex systems that integrate a myriad of engineered, natural and human elements, serving as the backbones of our built environment. Civil engineers are the principal stakeholders and stewards of the constructed elements of infrastructures, such as buildings, water distribution systems, highway transportation and mass transit. In fact they design, construct and maintain virtually all ***constructed*** elements of critical infrastructures.

Constructed systems remain very different in terms of how they are planned, financed, funded, designed, constructed and operated – especially in terms of the epistemic uncertainty in their as-built properties, loading and response mechanisms and the challenges in understanding and accounting between the empirical and rational ingredients in their design, construction operation and preservation. Civil engineers have not established objective definitions and metrics for condition, performance and risk of non-performance. The reality of how constructed systems actually perform during operational, serviceability and safety limit-states and what their designers, constructors and operators envision regarding performance during the stages of planning, design, construction and operation can be very different, given that each constructed system uniquely interconnects and interacts with its natural environment, site and soil. We have very little factual knowledge of the behaviors, capacity, demands and failure modes of constructed systems under external and intrinsic loading at different windows of time along their lifecycles. This is why every time there is a failure of a building, highway, bridge, levee, pipeline or dam; it catches civil engineers by surprise.

STRUCTURING THE INFRASTRUCTURE SYSTEMS PROBLEM

The 2013 ASCE Report Card for America's Infrastructure graded U.S. Infrastructure as a D+, estimating $3.6 trillion of investment needed by 2020, just to maintain a state of good repair. Meanwhile, the National Academy of Engineering (NAE) identified "restoring and improving urban infrastructures" as one of 14 Grand Challenges of Engineering in the 21st Century. According to the NAE Grand Challenges site "our infrastructure, along with those of many other countries, is aging and failing, and that funding has been insufficient to repair and replace it." "Technology innovations and building better and smarter systems that can be constantly improved" are two measures that have been identified so far by NAE Committee Members.

According to ASCE (2009), the fundamental challenge in virtually every part of the U.S. is persistent underinvestment. Five solutions are advocated: (1) increase federal leadership in infrastructure; (2) promote sustainability and resilience; (3) develop federal, regional and state infrastructure plans; (4) address life-cycle costs and ongoing maintenance; and, (5) increase and improve infrastructure investment from all stakeholders (ASCE 2009: Can we come back from the brink?).

Once we recognize the need to understand infrastructures as complex systems, we also recognize that we cannot expect to formulate effective solutions to infrastructure concerns unless we clearly understand and identify all critical human, natural and engineered elements that make up the infrastructures, the interactions and interdependencies between them and the associated issues. Only after this we may attempt to group and structure the associated concerns to identify and prioritize the most critical issues and the options for their solutions or resolutions.

For example, based on decades of studying the issues and concerns in relation to highway transportation, we may hypothesize that concerns may be arguably categorized and prioritized as:

1. **Stewardship — Culture, history and societal values** driving infrastructure ownership and stewardship, i.e. whether and which infrastructures should be public, quasi-public and/or privately owned; what should be the minimum acceptable infrastructure conditions and service standards provided to the general public? What are the minimum requirements and measures for responsible stewardship – affected by the quality of engineering, efficiency of management, levels of political influence, etc? What are/should be the roles of legislatures, civil engineers, planners, social scientists, domains such as environmental, chemical, industrial, mechanical and electrical engineers; economists and business managers and the public in infrastructure decisions?
2. **Sustainability —** commonly defined as the intersection of society, economy and the environment. However, to define sustainability we cannot ignore the interdependence between **infrastructures**, the **natural and built environments**, **natural resources, energy** and the **economy**. Sustainability requires a complex system-of-systems understanding, and a holistic as opposed to a reductionist approach to all related policy and decisions.
3. **Lifecycle Benefit/Cost Analysis — Planning, feasibility** and **lifecycle cost analysis** methodology – which has to be integrated and consistent at global, national, regional and local levels.
4. **Financing, Funding and Lifecycle Revenue Mechanisms —** related political, legal and organizational issues and especially responsibility and accountability: Who should decide and who will pay, through which mechanisms, and who will gain from access to infrastructures and associated services when the public, various sectors of economy, multiple agencies and multiple governments are involved? How to best leverage Public-Private Partnerships (**PPP**)?
5. **Project Delivery —** Various legal frameworks for project delivery and associated challenges related to both the **financing and funding mechanisms** and the **quality and accountability in the engineering and management** of **project delivery.** Different funding frameworks and organizational models, in conjunction with associated metrics, warranty and assurance considerations.
6. **Lifecycle Management — Cost and effectiveness of lifecycle operation, protection, condition evaluation and preservation management** given the various stewardship models and the associated engineering challenges, quality and performance metrics, accountability, warranty and assurance.
7. **Risk, resilience and fragility —** Challenges related to the mitigation and management of multi-hazards **risks and fragility** – multi-hazards risk mitigation, emergency

planning and management for resilience recognizing intersections and interdependencies between infrastructures.

8. **Education** **—** Capable and competent **workforce education** and training – including K-PhD education, continuing education, stakeholder outreach, public outreach. Promoting a **culture of ownership** by citizenry for crowd-sourcing of infrastructure services quality control.

Table 1: Paradigms, Knowledge and Technology Needs for Infrastructure Renaissance

Complex Systems-Id, Performance & Health Monitoring	1. Wide-area, multi-scale, real-time, multi-modal, integrated ***sensing, communication, computing and decision-assist*** systems 2. ***Drone and robot-supported*** inspection, evaluation and prognosis 3. Multi-resolution ***modeling, identification*** and ***control*** of complex (CLIOS) systems by ***leveraging living infrastructure*** *laboratories* 4. Design of ***intelligent interventions*** and renewal materials, processes and systems to mitigate performance deficiencies
Infrastructure Services Delivery, Performance and Risk Based Asset Management	1. ***Policy, planning, financing & revenue scenario analyses*** 2. ***Stewardship models (PPP)*** for more effective services delivery; lifecycle operation and preservation 3. Decision under uncertainty and risk - ***unexpected consequences*** 4. ***Network level simulations*** of interdependent multi-domain infrastructure assets at sufficient resolution for multi-objective constrained optimization for asset maintenance and renewal
Performance – as opposed to process – Based Engineering	1. ***Competitive Valuation of infrastructure systems and services*** stewarded by *different organizations and revenue mechanisms* 2. ***Performance metrics*** at different resolutions and time-scales for interdependent infrastructures and individual asset classes 3. What should be a ***minimum and free*** level of infrastructure conditions and service; and how should a society pay for this? 4. ***Lifecycle cost*** *and* ***cost/benefit*** definitions and ***metrics*** 5. Definitions and ***metrics for sustainability and resiliency***

9. **Transformative paradigms** **—** Research and innovation challenges – **transformative paradigms** such as those listed in Table 1, integration and leveraging challenges; Basic, problem-focused and applied research and demonstrations; standards and specifications; best practices.

10. **Managing the Unknowns, Uncertainty and Risk** **—**Understanding, identifying and proactively managing the known and unknown **intersections and interdependencies** between various infrastructures, and optimum frameworks for multi-sector "asset management" based on risk. The known as well as unknown intersections and interdependencies between the above topics that may lead to **unexpected consequences** as infrastructures deteriorate, unable to meet the demands for services, and changes to the status quo are explored.

Table 2 illustrates the linkages between performance limit-states and criteria, associated return periods and how lifecycle asset management should assure that performance throughout the lifecycle of an infrastructure system should be satisfied at any limit-state. Table 2 further illustrates that asset management should be considered as the assurance of performance criteria at various limit-states of an infrastructure throughout its lifecycle, in view of the vastly different return periods of critical limit events. Metrics for the performance criteria for various limit-states along the lifecycle of an infrastructure are needed in order to enable asset management to reach its potential. Given that infrastructure decisions are often governed by decisions based on heuristic-empirical knowledge, research focused on measures of performance of actual infrastructures is pressing. Research on actual operating infrastructures is possible by transforming them into living field laboratories. Incentives, funding and standards for this type of research are critical if we expect to move forward with meaningful research on performance-based asset-management with realistic and objectively measured performance criteria at each and every limit-state.

Table 2: Performance Limit-States, Return Periods, Criteria and Lifecycle Asset-Management

Managing the Lifecycle Performance of Infrastructures				
Limit State *Return Period*	**Utility and Functionality** *Every day throughout the Lifecycle*	**Serviceability and Durability** *5 – 20 years*	**Life Safety and Stability of Failure** *100-500 years*	**Substantial Safety at Conditional Limit States** *2,500 – 5,000 years*
ASSET management	LIFE-CYCLE MANAGEMENT			***Disaster response Planning and Emergency Management***
	⇔ ***Operational Management*** ⇔	***Maintenance Management*** ⇔	***Risk Management*** ⇔	
Performance Criteria	***Operational efficiency, safety and security; robust and predictable revenue stream***	***Effective and economical inspection, maintenance, repair and rehabilitation during lifecycle***	***Assurance of life-safety,*** quick recovery of normal operations following any Hazard (days-months)	***Minimizing Casualties*** Protection of escape routes, evacuation, search and rescue needs Assuring economic Recovery (years)

INFRASTRUCTURE PROJECT FINANCING, FUNDING AND LIFECYCLE REVENUE MECHANISMS

Guidelines for Successful Public-Private Partnerships issued by the European Community (EC, March 2003) indicate that "PPP arrangements come in many forms and are still an evolving concept which must be adapted to the individual needs and characteristics of each project and project partners. Successful PPPs require an effective legislative and control framework and for each partner to recognize the objectives and needs of the other."

EC Guidelines continue: "There is a broad range of options for involving the private sector in the financing, physical development, and operation of transport and environment projects traditionally the domain of the public sector. As depicted in Figure 1, Public-Private Partnership (PPP) approaches are arrayed across a spectrum. At one end, the public sector retains all responsibility for financing, constructing, operating and maintaining assets, together with the responsibility for assuming all associated risks. At the other end, the private sector assumes all of these responsibilities. The vast majority of PPP approaches fall in the middle of spectrum, with risks and responsibilities shared between the public sector and its private partners according to their strengths and weaknesses."

Given the wide spectrum of procurement options that share public and private responsibility, each option comes with various advantages and disadvantages as shown in Table 3 from the EC Guide below. The first row of the Guide describes various advantages and disadvantages with the Design-Build approach and indicates that this mechanism does not provide incentive for whole-life or lifecycle cost concerns in design. Indeed according to Wenzel (PC) a large number of bridges that were procured in the EC through design-build proved to have their lifecycles limited by durability concerns and required replacing at an average age of only 40 Years.

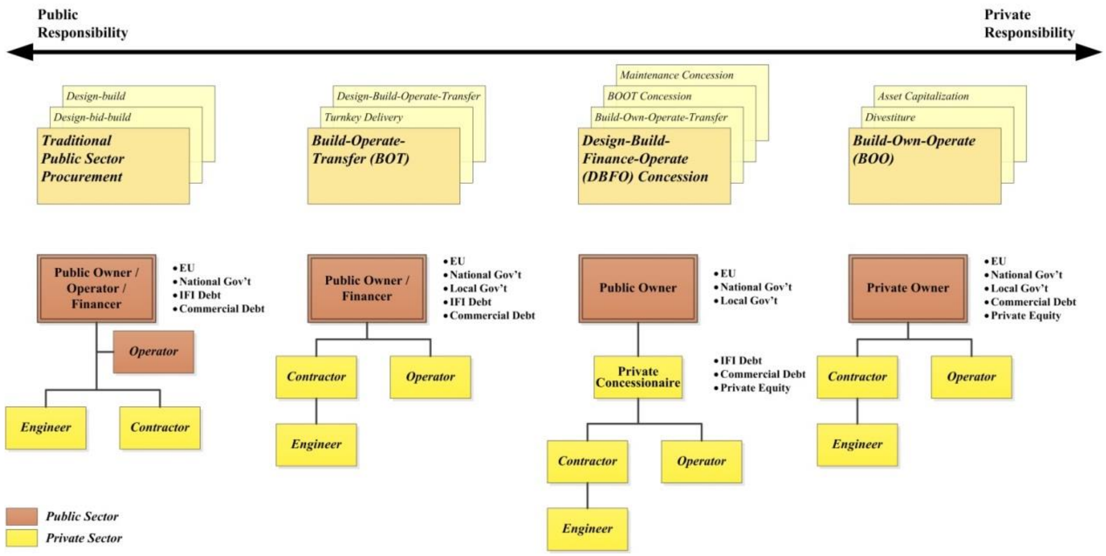

Figure 1: The Spectrum of Infrastructure Procurement Options including PPP (from EC, 2003)

In November 2012 the Federal Highway Administration (FHWA) in U.S. issued "Establishing a Public-Private Partnership Program: A Primer" that explores key issues involved in establishing a PPP program at a public agency with a focus on PPPs for new capacity for highway infrastructure. The Primer indicates: *"Building the organizational capacity needed to develop (PPP)s while protecting the public interest presents a major challenge to transportation agencies. Transportation agencies will need capabilities they have not traditionally possessed in order to identify and develop projects and negotiate and manage agreements with private partners. Agencies will need to acquire or develop new policy, legal, technical, financial and managerial skills and establish processes and structures, such as specialized (PPP) units, that allow them to apply those skills in a multidisciplinary way."*

"To design partnerships that are both in the public interest and attractive to private investors, public agencies will need to gain a better understanding of private sector interests and *perspectives and become comfortable transferring a greater degree of responsibility to the private sector – a cultural shift. With a (PPP), risks that are traditionally retained by the public sector are transferred to the private sector. Managing the organizational changes needed to develop, implement, and monitor (PPP)s will require agencies to involve and educate agency staff and external project stakeholders and build committed leadership at multiple levels that can champion (PPP) policies and projects.*

Because (PPP)s are long term agreements, they require greater flexibility and trust than traditional contractual arrangements. The private sector brings equity to the table, creating opportunities that might not otherwise exist, from which both partners can share in the benefits and returns. Public organizations have different interests, values, cultures, competencies and processes than private sector organizations."

Table 3: Strengths and Weaknesses of Various PPP Mechanisms (from EC, 2003)

PPP Type	Main Feature	Application	Strengths	Weaknesses
Contracting	• Contract with Private party to design & build public facility • Facility is financed & owned by public sector • Key driver is the transfer of design and construction risk.	• Suited to capital projects with small operating requirement. • Suited to capital projects where the public sector wishes to retain operating responsibility.	• Transfer of design and construction risk. • Potential to accelerate construction programme.	• Possible conflict between planning and environmental considerations. • May increase operational risk. • Commissioning stage is critical. • Limited incentive for whole life costing approach to design. • • Does not attract private finance
BOT *build-operate-transfer*	• Contract with a private sector contractor to design, build and operate a public facility for a defined period, after which the facility is handed back to the public sector. • The facility is financed by the public sector and remains in public ownership throughout the contract. • Key driver is the transfer of operating risk in addition to design and construction risk.	• Suited to projects that involve a significant operating content. • Particularly suited to water and waste projects.	• Transfer of design, construction and • operating risk • Potential to accelerate construction • Risk transfer provides incentive for adoption of whole life costing approach • Promotes private sector innovation and improved value for money. • Improved quality of operation and maintenance. • Contracts can be holistic • Government able to focus on core public sector responsibilities.	• Possible conflict between planning and environmental considerations. • Contracts are more complex and tendering process can take longer • Contract management and performance monitoring systems required. • Cost of re-entering the business if operator proves unsatisfactory. • Does not attract private finance and commits public sector to providing long term finance
DBFO *design-build-finance-operate*	• Contract with a private party to design, build, operate and finance a facility for defined period, after which the facility reverts to the public sector. • The facility is owned by the private sector for the contract period and it recovers costs through public subvention. • Key driver is the utilisation of private finance and transfer of design, construction & operating risk. • Variant forms involve different combinations of the principle responsibilities.	• Suited to projects that involve a significant operating content. • Particularly suited to roads, water and waste projects.	• As for BOT plus: • Attracts private sector finance; • Attracts debt finance discipline; • Delivers more predictable and consistent cost profile; • Greater potential for accelerated construction programme; and • Increased risk transfer provides greater incentive for private sector contractor to adopt a whole life costing approach to design.	• Possible conflict between planning and environmental considerations. • Contracts can be more complex and tendering process can take longer than for BOT. • Contract management and performance monitoring systems required. • Cost of re-entering the business if operator proves unsatisfactory. • Funding guarantees may be required. • Change management system required.
Concession	• As for DBFO except private party recovers costs from user charges. • Key driver is the Polluter Pays Principle and utilising private finance and transferring design, construction and operating risk	• Suited to projects that provide an opportunity for the introduction of user charging. • Particularly suited to roads, water (nondomestic) and waste projects.	• As for DBFO plus: • Facilitates implementation of the *Polluter Pays Principle*; and • Increases level of demand risk transfer and encourages generation of third party revenue.	• As for DBFO plus: • May not be politically acceptable • Requires effective management of alternatives / substitutes, eg alternative transport routes; alternative waste disposal options)

TECHNOLOGY AND PPP

Given the important cultural differences between public and private sectors as well as between legal, financial, structural, operations and preservation demands for ensuring a successful lifecycle performance of a major infrastructure project, it is necessary to transform our definitions of success to quantitative performance measures. Technology is a critical element for ensuring the success of any PPP effort. Stiffness, mass, vibration frequencies, mode shapes, damping and displacements, strains, stresses and accelerations under known live loads, as well as material properties and their variability are measurable attributes which can describe structural conditions and performance objectively and may complement visual condition indicators. However, recovering such measurable performance indicators requires technology leveraging.

The current state-of-the-practice in technology leveraging for infrastructure management is evolving ever since the dual-use strategy was adopted after the fall of the Berlin Wall in 1989. Without associated guidelines and frameworks, however, the technology market has become highly dysfunctional and unreliable. For an individual who has to make a living with only a hammer, all infrastructure problems become nails. The daunting task of structuring and establishing best practices for leveraging technology remains a challenge for professional organizations such as the ASCE, ASNT, and for U.S. federal agencies such as NIST, NSF, FHWA and EPA. To succeed, we not only require innovation paradigms and concepts we also require a context-based classification at a higher resolution for technology (such as those suitable for applications to bridges, pavements, traffic operations, etc.).

Table 4 presents an example specifically for major highway bridges, illustrating how we may integrate measurement (red), simulation (blue), information (magenta) and decision (black) technology tools for condition and performance assessment, risk analysis, health and performance monitoring, and lifecycle asset management of major highway bridges, shown in **purple** in the first row.

Table 4: Bridge Technology Integration Framework

Enhanced Bridge Inspection Technology	Identification of as-is Geometry and Material Properties	Evaluation of Condition and Performance	Diagnosis, Prognosis and Risk; Design Interventions	Health & Performance Monitoring Integrated w/Asset Management
Create an e-Archive for Legacy Plans-Reports-Data-Information System with 3D Flythrough **FE Model: Predict critical regions, critical elements, possible failure modes**	**Surveying and GPS: coordinates critical for documenting as-is geometry and validation of as-constructed plans** **Evaluate long-term movements, Fnd-Soil, Hydrology and Hydraulics**	**Evaluation of: 1. Operational, 2. Structural: (a) Serviceability (b) Durability (c) Safety, (d) Failure Modes (e) Lifecycle Cost 3. Organizational Performance**	**Scenario Analyses: Critical demand & capacity envelopes** **Load rating, maintenance, repair, retrofit needs, posting**	**Operational enhancement (ITS) technology such as dynamic lane allocations, variable speed limits, WIM, open-road tolling, driving condition alerts & actions such as automatic de-icing, automated security & law enforcement**
Practical local NDE: Impact-echo, Thermographic, GPRadar and Magnetic probes	**Non-contact geometry capture – close-range photogrammetry, 3D Laser scanning, Drone-based mapping**	**Systematic wide-area NDE Drone and Robot based inspection interacting with human engineer**	**Identify overloads, hazards, vulnerability, and exposure; Assess risks due to a lack of bridge performance**	**Structural health and performance monitoring to drive need-based custom inspections and need-based maintenance**
Practical vibration monitoring for global dynamic characterization	**Sampling & lab testing materials for physical, chem and mechanical characteristics, Vibes monitoring**	**Controlled Testing: Truck loads; Excitation; Impact;**	**Identify risk mitigation via demand control; Emergency prep and response needs**	**Customized maintenance tracking and documentation software linked to e-Archive**
Voice-commanded wearable tablets linked to e-archive for past photos, notes and real-time reporting	**Validate by mapping the as-is geometry of system, elements, and material properties**	**Parameter Id; FE model calibration & validation; Bounds and Uncertainty**	**Identify if technology or innovative renewal materials/engineering may help mitigate risks**	**Asset Management based on systems level lifecycle analysis: Performance expectations, preservation measures, hazards, risks, costs and financing**

CONCLUSIONS AND RECOMMENDATIONS

Infrastructures are complex systems that integrate a myriad of engineered, natural and human elements, serving as the backbones of our built environment. Civil engineers are the principal stakeholders and stewards of the constructed elements of infrastructures, such as buildings, water distribution systems, highway transportation and mass transit. This paper offers a road map for innovating the financing, engineering and management of infrastructures based on the author's research and experiences over the past four decades.

It is interesting that the strategic importance of infrastructures for the well-being of our society was not recognized until the 1990's (NSF, 1993). Civil engineering mainly focused on "new construction" until the fall of the Berlin Wall in 1989. In fact, the reunion of both Germany's brought civil engineers an awareness of the challenges in bringing the infrastructure of East Germany up to a similar state of condition and performance of the infrastructure of the West. Following the NSF's Civil Infrastructure Systems initiative (1993), and focusing on events such as the 9/11/2001 attacks, the 2005 Katrina flood, the 2007 I-35 Bridge collapse and the 2011 Tohoku earthquake and Tsunami, amongst others precipitated by infrastructure failures, the aging and degrading of our roads, bridges, levees, dams and in fact our entire built environment has now become obvious.

Further, the cost of repairing, rehabilitating, retrofitting or renewing the infrastructures in the U.S. to bring them up to contemporary standards of condition and performance that we see in some of the European or the Far Eastern urban centers has become untenable, evidenced by the multiple trillions estimated by ASCE to maintain the current minimum levels of infrastructure performance. The opportunity cost of not innovating infrastructures by first reforming the civil engineering education and research are also going to increase, as civil engineers remain as essential ***architects*** of the urban built environment.

The author's research greatly benefited from integrative, coordinated multi-domain and multi-discipline problem-focused fundamental research on living infrastructure field laboratories, exploring how we may transform the current practice of engineering and management of infrastructures. Our societal concerns with the engineering and management of infrastructures demand civil engineers to lead a challenging new field of intellectual inquiry and coordinated, collaborative research in real-life infrastructure field laboratories with researchers from other domains and disciplines of arts, science and engineering. The opportunity for embracing such a new field of inquiry is great since they may plant the seeds for a renaissance in the engineering and management of infrastructures while immediately impacting the quality of life in their urban area.

The challenges in the structuring of societal infrastructure concerns so that we may seek innovative solutions are numerous and daunting, a first-cut preliminary classification of these issues is presented in this paper. The complexity of infrastructures will defy simple, reductionist solutions to infrastructure concerns. We have to start by recognizing the need for the adoption of transformative paradigms such as performance-based civil engineering, lifecycle asset management and systems-identification, performance and health monitoring as the enabling foundations for lifecycle asset management. Leveraging these paradigms requires societal, institutional and organizational reform in addition to technology integration for new knowledge and best-practices demonstrations.

For example, as we seek to leverage private financing for infrastructures through various PPP arrangements, it is critical to incorporate technology for a birth-certificate that will document properties such as as-built dimensions, flexibility and intrinsic forces due construction in accepting the delivery of a constructed system such as a bridge. Subsequently, as a constructed system is under the purview of a concessionaire as its temporary steward, it becomes even more important to maintain a quantitative and comprehensive record of changes in condition and performance, and how preventive and corrective maintenance has impacted the system. This type of quantitative documentation requires technology integration, as discussed in relation to Table 4 in the paper.

In the past, mission agencies have focused more on technology tools than their integrated application scenarios and demonstrations. We now recognize that technology is not a silver bullet and its leveraging for innovation requires a more sophisticated approach to policy for integrative field research – and not just field testing. It follows that all mission agencies should come together and help develop academe-government-industry partnerships including infrastructure owners-stewards, and establish the minimum requirements of creating living infrastructure laboratories in the field and performing problem-focused research as well as demonstrations at these laboratories. This cannot happen without champions from critical mission agencies of government at federal, state and local levels.

ASCE's leadership recognizes the importance of the championing infrastructure innovation, and the necessity of civil engineers to lead and coordinate this innovation. A new multi-institute and multi-agency ASCE Committee is being formed to create a road-map for demonstrating innovation by leveraging paradigms and associated technology integration. The writer gratefully acknowledges his many distinguished collaborators from academe, government and industry for championing and joining such an effort.

The principal recommendation of the paper is the difficulty of bringing innovation to civil engineering by reductionist thinking as it has been the tradition in the 20th Century. We need to see the entire system-of-systems with its human, natural and engineering elements, together with the intersections and interdependencies between these elements and systems. Innovating infrastructure financing, engineering and management have to be approached in a holistic manner, by leveraging paradigms, concepts and technology tools in an integrated manner. A road map has been briefly described in the paper.

ACKNOWLEDGEMENTS

The author gratefully acknowledges his mentors (Professors Ersoy, Sozen, Bertero, Popov and Yao) and collaborators (Brown, Helmicki, Meystel, Comfort and McNeil), post-doctorate associates and students, practicing engineers (Arzoumanides, Lowdermilk, Khazem), as well as the funding agencies and program managers who have shaped his worldview and encouraged him during the field research he initiated in 1984 for structural identification of real constructed systems. The champions at LADOT, ODOT, PennDOT, NJDOT, DRPA, BCBC, NY City DOT, NY City MTA as well as NSF and FHWA who have supported, encouraged and guided his research are deeply and gratefully acknowledged. Finally, significant contributions by his associate Dr. Moon to the research in the last decade, and excellent support provided by Mr. Andrew Katz of Intelligent Infrastructure Systems (IIS) are deeply appreciated.

REFERENCES

Aktan, A. E., Frangopol, D. M., Ghasemi, H. M., Shinozuka, M., Madanat, S., and Shenton, H. W. (2004). "A problem-focused agenda for highway transportation infrastructure: a holistic systems identification and integration approach using field test sites." *Final Rep. No. NSF CMS 0338817*.

Aktan, A.E. and Roësset, J.M., "The Need for a Renaissance in Civil Engineering to Effectively Address our Societal Concerns Related to Infrastructures." Presented at the CEE EDU Reform Workshop supported by NSF-EU-Japan at Istanbul, 4-7 October 2006.

Aktan, A. E., Ellingwood, B. R., and Kehoe, B. (2007). "Performance-Based Engineering of Constructed Systems" *J.Struct.Eng.*, 133(3), 311-323.

Aktan, E., Moon, F., Gurian, P., and Montalto, F. (2008). "Workshop on Performance-Based Infrastructure Asset Management (PBIAM)" *Final Rep. No. NSF CMMI 082873*.

Aktan, E., Moon, F., (2012) "The Learning Bridge," *Project Report No. NSF EEC 0855023*

ASCE. (2013). "Report Card for America's Infrastructure." ASCE (American Society of Civil Engineers)

Altman, J. (2010). *Best Practice in Infrastructure Asset Management - Creating and Maintaining Value for All Stakeholders.* PEI Media Ltd, London.

Approaches, Methods and Technologies for Effective Practice of St-Id (2012), A State-of-the-Art Report by ASCE SEI Committee on Structural Identification of Constructed Systems, Edited by Catbas, Correa and Aktan.

Arnott, R., and Small, K. (1994). "The Economics of Traffic Congestion." *Am.Sci.*, 446-455.

AWWA. (2001). "Reinvesting in Drinking Water Infrastructure. Dawn of the Replacement Era," AWWA (American Water Works Association), USA.

Bordogna, J. (1995). "Civil Infrastructure Systems: Ensuring Their Civility." *J Infrastruct Syst*, 1(1), 3-5.

Chase, S., and Ghasemi, H. (2003). "A Vision for Highway Bridges for the 21st Century." *Proceedings of the 4th International Workshop on Structural Health Monitoring*, 205-213.

Christensen, P. N., Sparks, G. A., and Kostuk, K. J. (2005). "A Method-Based Survey of Life Cycle Costing Literature Pertinent to Infrastructure Design and Renewal." *Canadian Journal of Civil Engineering*, 32(1), 250-259.

Comfort, L. K. (1994). "Self-Organization in Complex Systems." *Journal of Public Administration Research and Theory: J-PART*, 4(3), 393-410.

Dalton, P.A., 2008. Physical infrastructure: challenges and investment options for the nation's infrastructure. Washington, DC: USGA Office, Editor 2008, 30.

Deming, W. Edwards (1986). "*Out of the Crisis*." MIT Press.

De Neufville, R. (1990). "Applied Systems Analysis: Engineering Planning and Technology management."

EPA and FWHA. (2009). "Multisector Asset Management Case Studies." U.S. Environmental Protection Agency.

Establishing a Public-Private Partnership Program: A Primer. (2012). FHWA, Innovative Program Delivery.

Flintsch, G. (2002). "Infrastructure Management Research and Education Workshop", Final Report. http://128.173.204.63/IMRE_Workshop/IMRE%20Final%20Report.pdf

Geiger, D.,et al (2005-11). "Transportation Asset Management in Australia, Canada, England, and New Zealand." *TRB*, FHWA-PL-05-019 160.

Grigoriu. (2006)."System Performance under Multi-Hazards", Presentation at MCEER 2006 Annual Meeting.

Guidelines for Successful Public – Private Partnerships (2003). European Commission, http://europa.eu.int/comm/regional_policy/sources/docgener/guides/PPPguide.htm

Gurian, P. L., Aktan, A. E., Montalto, F., and Moon, F. (2010). "Research Priorities for Infrastructure Asset Management." *Speaker's Journal on Pennsylvania*, 43-54.

Little, R. G., (2007). "A Clinical Approach to Infrastructure Management." ASCE Special Publication, Infrastructure Reporting and Asset Management: Best Practices and Opportunities, Editors: Adjo, Amekudzi and Sue McNeil.

Madanat, S. (1993). "Optimal Infrastructure Management Decisions under Uncertainty." Transportation Research Part C, Vol. 1, Issue 1, pp. 77 – 88.

Moon, F., A.E. Aktan, F. Jalinoos, S. Jin. (2009). "Leveraging Technology for Performance Based Bridge Engineering," *Materials Evaluation, Journal of ASNT*, Sep.

NSF (1993), Civil Infrastructure Systems Research: Strategic Issues, A Report of the Civil Engineering Systems Task Group, NSF 93-5

Office of the Press Secretary, 2010. Remarks by the president on rebuilding America's infrastructure [online]. Available from: http://www.whitehouse.gov/the-press-office/2010/10/11/remarks-president-rebuilding-americas-infrastructure

Spatari, S., and Aktan, A. E. (2013). "Asset Management in Civil Engineering." *Structure and Infrastructure Engineering*, 9(4), 295-296.

Sussman, J. M., et al, 2005. "New Approach to Transportation Planning for the 21st Century: Regional Strategic Transportation Planning as a Complex Large-Scale Integrated Open System." Transportation Research Record: Journal of the Transportation Research Board, 1931(-1) 89-98;

Sussmann, Course materials for Frameworks and Models in Engineering Systems, MIT OpenCourseWare, 2007.

Use of Transportation Asset Management Principles in State Highway Agencies (2013). NCHRP synthesis 439