Conceptual Framework of Life-Cycle Performance Measurement: Ensuring the Resilience of Transport Infrastructure Assets

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Abstract

Having efficient and effective transport infrastructure (e.g. bridges, roads, railways, airways and tunnels) in place is essential for supporting the economic and social well-being of an economy. External disturbances that emerge as a result of climate change, for example, are impacting its performance. Delivering, managing and maintaining transport assets that are resilient and adaptive to changing environmental conditions have become a priority for many governments worldwide. Central to ensuring that transport infrastructure functions at their optimum and is resilient to external changes is performance measurement, as it enables those processes that need to be modified and improved for enhancing the asset's adaptability throughout their lifecycle to be identified. Despite the importance of performance measurement in ensuring the resilience of transport infrastructure, it has received limited attention by governments in their policy making. Therefore, this paper provides a review of the extant literature and proposes a life-cycle resilient performance measurement framework (PMF) within transport context. The developed PMF is robust in comprehensively capturing the underlying perspectives that are significant for: (1) understanding the current state of the resilient level of transport assets; and (2) enabling a higher ability of the assets to adapt to environment-related changes in the future. The implications of the proposed framework for transport policy development are also discussed in this paper.

Keywords: Climate change, performance measurement, transport infrastructure, resilience

1.0 Introduction

> "When you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever the matter may be" (Lord Kelvin, 1883)

Transport infrastructure describes the networks, assets, and services that facilitate socio-economic activity in an economy. It involves not only traditional engineering structures such as bridges, roads, railways, airways, and tunnels but also digital and information communication technology (ICT) systems. The efficient provision of transport infrastructure provides the hallmark of a well-functioning economy (Hughes and Healy, 2014). For example, the construction of transport infrastructure contributed approximately AU$32 billion to Australia's Gross Domestic Product from 2016 to 2017 (ABS, 2017). The Commonwealth Government of Australia announced in 2014 that $50 billion will be invested in the next seven years to deliver vital transport infrastructure for the 21st Century (Australian Government, 2014). The European Commission, for example, has invested a total of €700 million to develop sustainable and innovative transport infrastructure projects (European Commission, 2018). Similarly, in the United Kingdom (UK) the government has prioritized the need to ensure its infrastructure is resilient and adaptable to climate change and shifting demographics, particularly in sectors such as energy, ICT and conventional transport (Cabinet Office, 2017).

Many transport assets, however, are unable to effectively absorb and adapt to intensive disturbances, especially in countries where there exists a significant amount of aged or aging infrastructure (Sircar *et al.*, 2013). In Australia, for example, natural hazards (e.g. flooding, cyclones, and extremely hot weather) have severely impacted the operations of roads and railways over the past several decades, as a result of changing climatic conditions. In 2017, Melbourne (Victoria) experienced an unprecedented deluge (i.e. in excess of 300mm of rain over a weekend) that caused extensive flooding throughout the Central Business District, and surrounding suburbs, which adversely disrupted traffic, flights, and the tram and rail network. However, this is just an example of the many floods that occur throughout Australia on a yearly basis and severely impact commuters, business and the transportation of food, supplies, and goods. To mitigate the negative impacts of such natural hazards, it is imperative to develop a resilient and adaptable infrastructure that is able to effectively respond to the influences of climate change (Hughes and Healy, 2014).

The concept of resilience incorporates issues such as adaptability and recovery ability (Bosher and Dainty, 2011). It focuses on how infrastructure in an economy can positively withstand and absorb disturbances and respond to changing conditions (NCCARF, 2013). The enablement and enhancement of resilient infrastructure is a sophisticated and systematic process, which integrates the engineering, technical and managerial issues associated with an asset's lifecycle (Desouza, and Flanery, 2013). More specifically, performance measurement has been identified as being able to play a decisive role in determining the effectiveness and efficiency of resilient infrastructure development (e.g. Baroud *et al.*, 2014; Adjetey-Bahun *et* *al.*, 2016; Minaie and Moon, 2017). Despite this significant role, there remains a void about how to measure the performance of resilience, especially within the context of transport infrastructure. In addressing this void, we develop a performance measurement framework (PMF) that can be used to determine and enable the resilience of conventional transport (engineering) assets to climate change and suggest its implications for policy development. We commence our paper with an in-depth review of extant literature of transport infrastructure resilience. Our observations from the review is then used to develop a life-cycle transport resilience PMF. The implications of our proposed framework for policy are discussed.

2.0 Infrastructure Resilience

A detailed review of transport resilience can be found in Cox *et al*. (2011), Reggiani (2013), Reggiani *et al*. (2015), Chmutin *et al*. (2016) and Wan *et al*. (2017), but for the purposes of brevity studies directly relevant to the research presented in this paper are examined herein. However, there is a need of being cognizant that when transport networks are damaged and disrupted, then an economy's economic and social wellbeing can be adversely impacted (Hughes and Healy, 2014). Such impacts can be significantly minimized if infrastructure systems are designed, constructed, operated and maintained to accommodate shocks and changes that may be imposed upon them (Love *et al*., 2017; Zhang and Li, 2018).

2.1 Defining Resilience

The epistemology of resilience is underpinned by four fundamental questions: (1) resilience *of* what? (2) resilience *to* what? (3) resilience *for* whom? and (4) *how* to be resilient (Vale, 2014; Chmutin *et al.,* 2016). Tables 1 and 2 provide a summary of the key studies that have attempted to provide a definition of 'resilience'. These studies not only define resilience but also specify their *purpose* (Wan *et al*., 2017). While there exists no universally accepted definition of resilience, particularly in relation to infrastructure, four core elements contribute to its ability to: (1) predict and resist impacts; (2) absorb and accommodate stress and remain functional; (3) be 'self-organised'; and (4) learn, change and adapt (Davoudi, 2012; Thayaparan *et al.,* 2016).

A recurring theme of resilience, spurred by calls to respond to global warming, has been the ability to adapt to environmental changes (e.g. Bruneau *et al.*, 2003; Bosher and Dainty, 2011; Emmanuel and Krüger, 2012; Sircar *et al*. 2013; Balsas, 2014; Spaans and Waterhout, 2017).

Research addressing this issue has attempted to identify how communities respond to natural impacts through the implementation and adoption of innovative planning for infrastructure development (Ingirige, 2016).

Table 1. Defining resilience for an entire infrastructure system

Authors	Ability (of an asset/system/community)	Impacts (from)	Outcomes
Solomon *et al.* (2007)	Absorb, self-organise, adapt	Disturbance, stress and change	To retain the same basic structure and ways of functioning
McDaniels *et al.* (2008)	Maintain, alternate, mobilize, return	Stress and emergencies	Robustness, redundancy, resourcefulness and rapidity
McBain *et al.* (2010)	Continue, recover, return	Unusual event and threat	To provide essential services and maintain normal operations
Hallet (2013)	Prevent, withstand, recover and learn	Extreme weather hazards	No specified
Environmental Protection Agency (2015)	Anticipate, prepare for, respond to, recover	Hazards	Minimum damage to social wellbeing, economy and environment

Table 2. Defining resilience for a transportation system

Authors	**Ability (of an asset/system/community)**	**Impacts (from)**	**Outcomes**	**Observed Targets**
Berche *et al.* (2009)	Withstand, recover	Major disruption	An acceptable degradation and recovery to in time and cost	Public transport systems
Mansouri *et al.* (2010)	Adapt, recover	Potential disruption	Recovery in an efficient timeframe after a disruption	Ports
Adams *et al.* (2012)	Resist, recover	Weather events	No specified	Roadways
Omer *et al.* (2012)	Absorb, recover	Natural disruption	Well absorb to shocks and efficient recovery to an acceptable level	Maritime transport
Reggiani (2013)	Absorb	External shocks	Without catastrophic changes in its basic functional organisation	Transportation networks
Becker *et al.* (2015)	Absorb, retain	Natural hazards	To be remaining basic function and structure	Seaports

Transport systems resilience (e.g. underground rail and buses) to terrorism has been a subject of great interest worldwide as a result of the London bombings in 2005 (Cox *et al.*, 2011; Bruyelle *et al.*, 2014). Emerging from Cox *et al.* (2011) research, for example, were a series of operational metrics that sought to determine a passenger transportation system's resilience to terrorism based on their vulnerability, flexibility and resource availability to cope with a terrorist attack or natural disaster. Continuing with the theme of underground rail and buses, Jin *et al.* (2014) focused on the development of an integrated multi-modal transport network to improve a system's ability to adapt to increasing population and urban density. In stark contrast, Venkittaraman and Banerjee (2013) examined the resilience of existing bridges to natural hazards (e.g. seismic activity) by taking an *ex-post* perspective. As a result, Venkittaraman and Banerjee (2013) identified that there was a need for bridges to be retrofitted to accommodate the likelihood of earthquakes. Similarly, Becker and Caldwell (2015) adopted an *ex-ante* approach to resilience by soliciting the views of stakeholders to design and develop strategies to ensure the resilience of a seaport.

2.2 Performance Measurement

While *ex-ante* and *ex-post* evaluations can be used to determine infrastructure resilience, a further systematic perspective (e.g. performance measurement) is needed to identify 'what' needs to be improved so as to provide a direction about 'how' to safeguard the progress that is attained (e.g. Baroud *et al.*, 2014; Adjetey-Bahun *et al.*, 2016; Minaie and Moon, 2017).

Fundamentally, performance measurement aims to (Gunasekaran and Kobu, 2007; Franco-Santos *et al.*, 2012): (1) identify an organisations' success, customer satisfaction, and where problems exist and improvements can be made; (2) understand an organisations' processes and determine what they do and do not know; (3) ensure effective decision-making and improve organisational performance; and (4) determine if stakeholders' expected outcomes have been met so that satisfaction can be improved in the future. Theories of performance measurement abound the extant literature with the most popular being Kaplan and Norton's (1992) *Balanced Score Card* and Neely *et al*.'s (2001) *Performance Prism*. Such theories fundamentally aim to identify: (1) measures for 'what' and 'whom'; (2) 'how' to measure and (3) 'how' to enable or ensure better performance. Performance measurement has been aligned with the epistemology of resilience, as it attempts to identify the issues related to its 'what', 'whom' and 'how' (i.e., the resilience of/for what, resilience for whom and how to be resilient). As a result, there are a number of studies that have focused on measuring the resilience of transport assets/systems being undertaken (e.g., Cox *et al.* 2011; Ip and Wang, 2011; Adams *et al.* 2012; Omer *et al.*, 2012; Baroud *et al.*, 2014; Adjetey-Bahun *et al.*, 2016; Minaie and Moon, 2017). Francis and Bekera (2014) elaborated that the performance measurement of infrastructure resilience is an assessment for not only asset's capacities, but also stakeholder engagement and vulnerability.

Despite the merits of resilience measurement research within the transport sector, it has tended to be limited to developing mathematical measures (e.g. Ip and Wang, 2011; Adams *et al.* 2012; Miller-Hooks *et al.* 2012; Omer *et al*., 2012; Adjetey-Bahun *et al.*, 2016; Dobie and Schneider, 2017; Johansen *et al.*, 2017). For example, Cox *et al.* (2011) and Minaie and Moon (2017) developed a series of operational metrics to determine the resilience of passenger transportation systems and bridges. Similarly, Baroud *et al.* (2014) devised metrics to measure the resilience of inland waterway networks. Notably, there has been an absence of a systematic performance management framework putted forward to measure transport infrastructure resilience. This has resulted in there being an inability to determine how effective transport systems are in accommodating and responding to environmental changes (Faturechi and Miller-Hooks, 2014; Wan *et al.*, 2017).

In recognition of this shortcoming, Hughes and Healy (2014) developed a measurement framework for transport infrastructure that comprised of two perspectives: (1) technical; and (2) organisational. The developed measurement framework was designed within a systematic context but eschewed to provide a life-cycle process perspective, which is a critical component of resilience theory.

3.0 Design of a PMF for Transport Resilience

A PMF acts as an audit and learning system that can be used to challenge the status quo and provide a basis for amending existing performance measures that are in place (Bourne, 1999). The design of a PMF typically incorporates three stages: (1) reviewing and interpreting extant measurement approaches or current practice in performance measurement; (2) deriving core measurement perspectives; and (3) developing relevant key performance indicators (KPIs) according to the derived perspectives (Bourne *et al*., 2000). Essentially, a PMF needs to capture the inherent complexities of the object (i.e. resilience in this case) to be measured (Neely *et al.*, 2001; Liu *et al.*, 2015). Markedly, resilience encompasses not only the fundamental theoretical issues identified by Vale (2014) (e.g. resilience of *what*, resilience for *what* and resilience for *whom*), but also a practical nature about 'how to be resilient'. Considering aforementioned perspectives in terms of new PMF development (e.g. review of extant approaches, deriving performance measurement perspectives and developing the KPIs relevant to the identified perspectives) and the key components of resilience theory, the process to design a new PMF for measuring transport infrastructure resilience is proposed as Figure 1.

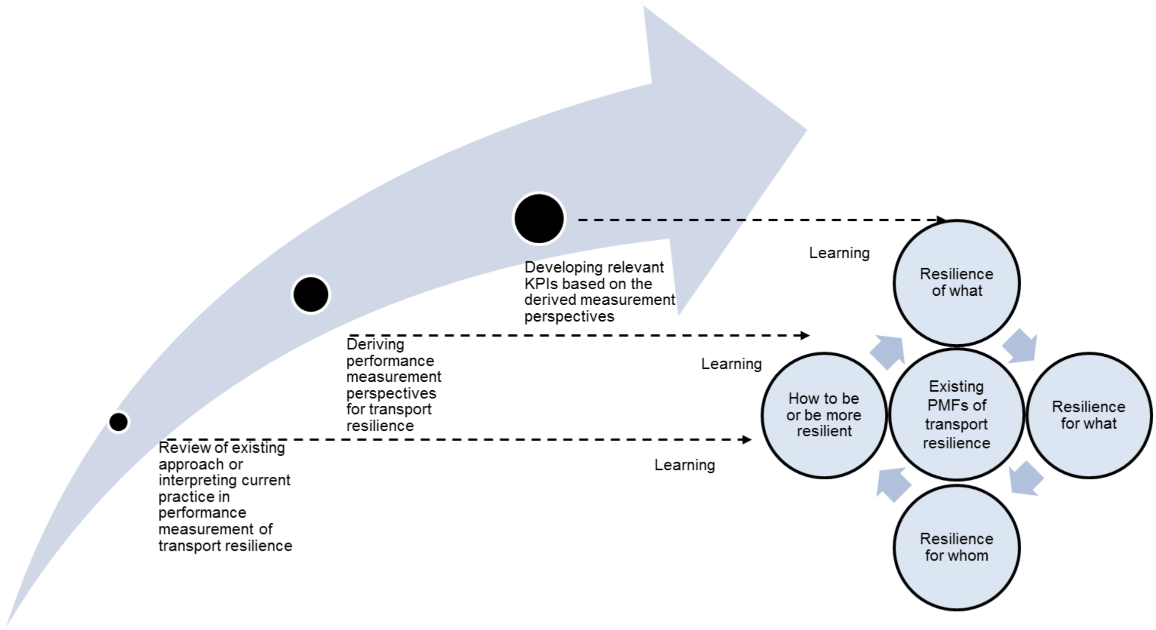

Figure 1. Design of a resilience PMF for transport systems

Building on prevailing theory and the overarching principles identified in Figure 1, the conceptual life-cycle resilience PMF is presented in Figure 2. Conventionally, the measurement of infrastructure resilient performance is focused on examining the assets' abilities to adapt to environmental changes (Hughes and Healy, 2014). Moreover, a performance measurement system needs to be developed with key stakeholders' perspectives (Neely *et al.*, 2001; Liu *et al.*, 2015; 2018a). Therefore, the developed PMF emphasises the 'conventional' aspects of performance measurement such as "Asset's Technical Ability" and stakeholders' expectations and capabilities (e.g. "End-user and Local Resident Expectations" and "Government's and Contractor's Capabilities"). Notably, infrastructure resilience can be determined by the 'processes' leading to asset's technical abilities and their future improvements (Chmutina *et al.*, 2016). Thus, a series of new perspectives has also been proposed in the developed PMF (i.e. Figure 1), including: (1) balanced measurement addressing life-cycle process view; (2) improvement for vulnerability; (3) measurement for specific object(s); and (4) public policies.

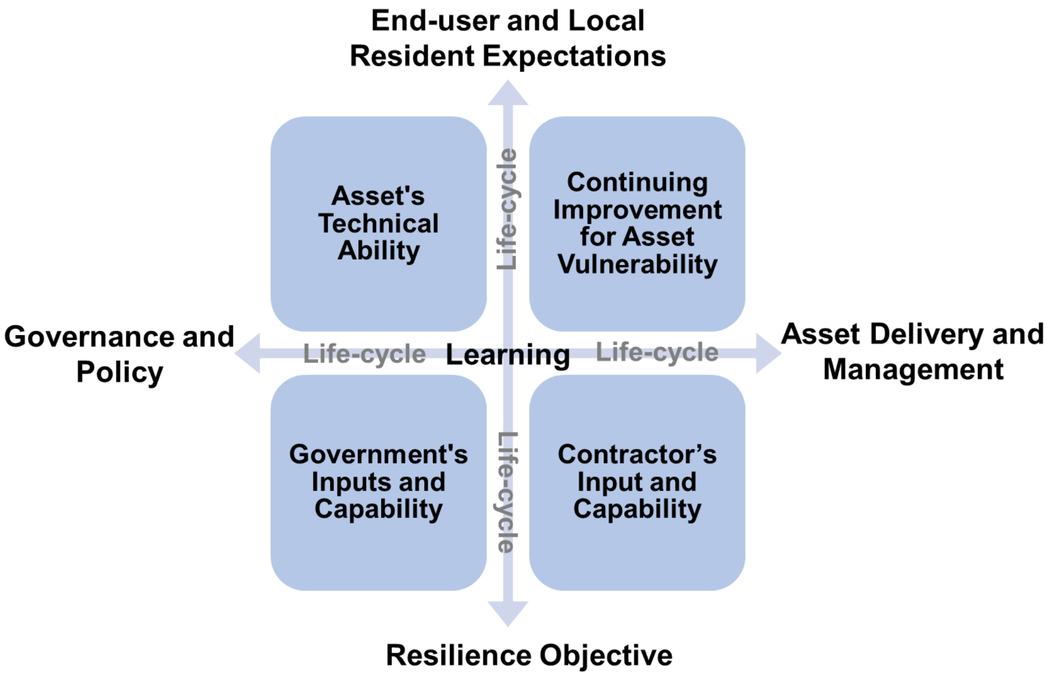

Figure 2. Conceptual life-cycle resilience PMF of transport assets

The 'life cycle' addressed in Figure 2 covers the stages cascading from the project's feasibility study and land-use planning to the operation/maintenance/replenishment of the asset. It is noted that performance measures (i.e. KPIs) underpin the measurement perspectives of a PMF (Liu *et al.*, 2015). Bearing these in mind, the resilience PMF (i.e. Figure 2) can be further developed to Figure 3, in which learning mechanisms have been embedded to ensure that lessons from the KPIs of each stage of the project (e.g. Initiation & Planning, Design & Construction, and Operation & Maintenance) can be effectively and efficiently absorbed and learned to improve asset's life-cycle resilience. Noteworthy, Figure 3 illustrates the interconnections between the developed PMF's measurement perspectives (e.g. Asset Technical Ability, Continuing Improvement for Asset Vulnerability, and Government's/Contractor's Inputs and Capabilities) and their relevant KPIs (e.g. adaptability, absorbability, restorability, appropriateness of vulnerability analysis, skilled workforce for business case and asset management/maintenance, robustness of technologically predictive capability, effectiveness of governance and knowledge management and innovation) within the context of an asset's lifecycle.

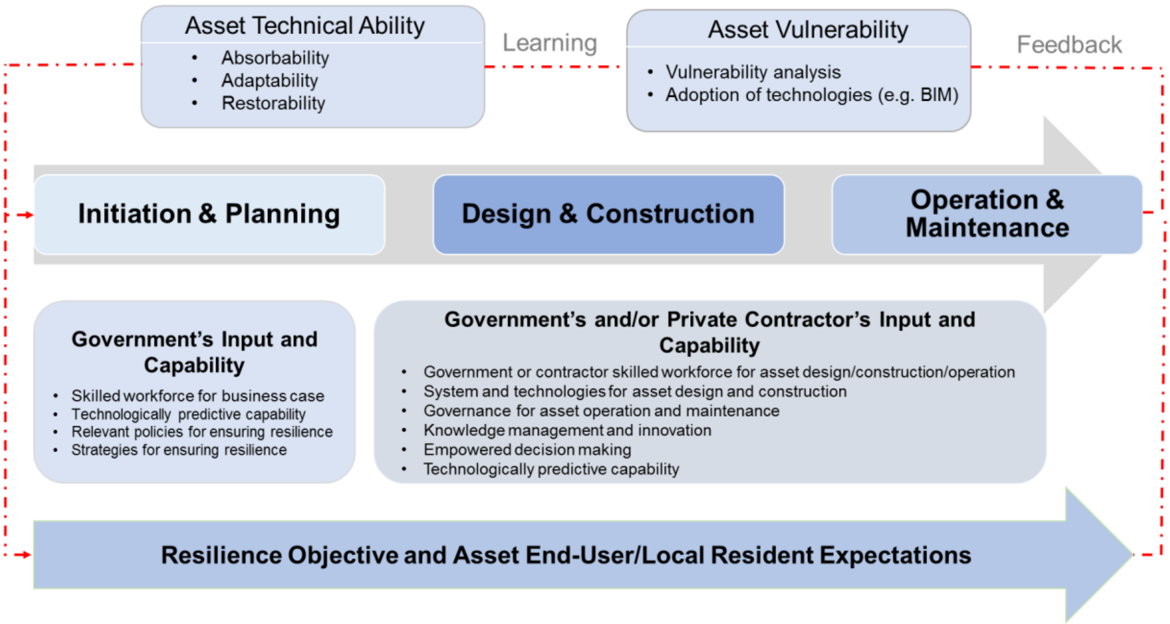

Figure 3. Developed PMF integrated with a project life-cycle perspective and relevant KPIs

3.1 Asset Technical Ability

The theory of resilience, as identified above, incorporates two perspectives in terms of '*resilience of what*' (Kaplan, 1999; Chmutina *et al.*, 2016): (1) the *product-oriented* view focusing on the output quality of a final product (i.e. asset's abilities to be resilient to impacts; and (2) *process-based* view, which focuses on the engineering, technical and managerial aspects. As noted in Figure 2, both resilience concepts need to work in concert to ameliorate an asset's performance (Madni and Jackson, 2009; Dobie and Schneider, 2017; Faturechi and Miller-Hooks, 2017). However, the prevailing measurement frameworks of infrastructure resilience tend to only take a product-oriented perspective where an emphasis is placed on the asset's absorbability, adaptability (i.e. abilities to absorb/adapt of impacts) and restorability (i.e. ability to be repaired easily and efficiently), which are known as asset's technical ability or capacity to accommodate impacts (Francis and Bekera, 2014).

Within the context of transport infrastructure, an asset's technical abilities of resilience mentioned above can be broken down to: (1) Tolerance; (2) Redundancy; (3) Safe-to-Fail; (4) Connectivity; and (5) Accessibility (Hughes and Healy, 2014; Reggiani *et al.*, 2015). Tolerance refers to an asset's ability to withstand a given level of stress without a substantial loss of its function (Bruneau *et al.*, 2003). Redundancy and safe-to-fail relate to the capacity in: (1) satisfying functional requirements and (2) the planned or controllable failure in an event of a disruption (Park *et al.*, 2013). Hence, the design of performance measures (i.e. KPIs) under the measurement perspective of an 'Asset's Technical Ability' in the developed PMF need to be associated with the three main abilities (e.g. adaptability, absorbability and restorability) identified above (Figure 3). The KPIs of a 'process' measurement perspective is developed to evaluate the robustness and effectiveness of the business process used to enable a transport asset's resilient abilities.

Resilience also needs to be incorporated into the business case of a transport infrastructure development proposal by considering how innovative technologies and management techniques can be used to ensure value for money throughout the asset's lifecycle (Li and Herbert, 2012; Suryanto *et al.*, 2015). For example, building information modelling (BIM) and associated technologies have a pivotal role in ensuring the correct information is available at the right time and place during operations and maintenance (Love *et al*., 2017; 2018).

3.2 Resilience Objective

The '*resilience to what*' is a key question that must be addressed when designing a PMF (Hughes and Healy, 2014). Thus, "determining what needs to be measured and designing the metrics to be implemented are key objectives of a PMF" (Bourne *et al.*, 2000, p.758). In this regard, it is necessary to identify the types of external disturbances that could potentially impact an asset so that they can be incorporated as relevant measures into the PMF (Francis and Bekera, 2014; Hughes and Healy, 2014). If, however, the PMF is not aligned with a specific 'object', it will be difficult to identify appropriate and effective performance measures (Park *et al.*, 2013).

The ultimate goal of transport infrastructure is to provide a mechanism to enable and ensure the movement of humans, animals, and goods from one location to another. The ability to achieve this goal can be severely hampered by adverse environmental impacts. Therefore, the KPIs that are embedded into the measurement perspective entitled '*Resilience Objective*" within the developed PMF should be specific to natural hazards that may severely bring disruptions to transport systems (Figures 2 and 3).

3.3 End-user and Local Resident Expectations

'*Resilience for whom*' is akin to stakeholder engagement (Francis and Bekera, 2014; Sauders and Becker, 2015). In essence, stakeholder satisfaction is a central tenet of performance measurement (Gunasekaran and Kobu, 2007). Indeed, stakeholder demand provides the basis for the design and development of strategies and internal business process of an organisation (Neely *et al.*, 2001). Therefore, measuring stakeholder satisfaction (e.g. businesses, passengers and local residents) can provide governments with an improved understanding about the functioning of their transport services and assets (Queensland Department of Transport and Main Roads, 2018). For example, light rail transit (LRT) systems are often implemented to offset climate change impacts as they can be used to (City of Ottawa, 2012; Love *et al*., 2017): (1) reduce traffic congestion and greenhouse gas emissions; and (2) stimulate economic development (e.g. positive impact on the property market).

By incorporating resilience into a government's transport strategy, future needs and expectations of key stakeholders, in addition to their satisfaction, can be considered (Becker and Caldwell, 2015; Mott MacDonald, 2017). Drawing on the *Expectation Confirmation Theory* of psychology, the expectation is a latent factor of satisfaction but relates directly to the perceived performance. Thus, measuring expectations can provide a more robust assessment of stakeholders' satisfaction. In this instance, the KPIs would focus on the expectations of direct asset users and the residents of the local communities that are being served.

3.4 Continuing Improvement for Asset Vulnerability

Despite every effort to enable and ensure assets are resilient, severe disruptions to transport systems and networks can still materialize (Park *et al.*, 2013). As part of a risk management process, it is important that potential vulnerabilities are identifiable (Love *et al*., 2018). Hence, having in place an initiative that aims to improve and manage asset's vulnerability to prevent an unexpected crisis is an innate feature of infrastructure resilience corresponding to the theory of '*how to be resilient*' (Omer *et al.*, 2012; Thayaparan *et al.*, 2016). Francis and Bekera (2014) also argue that vulnerability analysis plays a vital role in ensuring transport asset's resilient ability, as it contributes to reducing the possibility of being impacted.

The proposed PMF incorporates a measurement construct, '*Continuing Improvement for Asset Vulnerability*'. The concept of infrastructure vulnerability places an emphasis on identifying and managing aspects of the system that will be of risk to environmental disturbances (Hellström, 2007). In addressing vulnerability, there is a need to focus on reducing an asset's weaknesses in terms of its absorbability, adaptability and restorability/restorative capacity, through material and technology-focused actions (Biringer *et al.*, 2013; Francis and Bekera, 2014; Love *et al*., 2018). This view is supported by Seppänen *et al.* (2018), who have suggested that to mitigate a system's vulnerability it requires: (1) the identification of the asset's weaknesses that may lead to system failure during an external impact; (2) an assessment for the potential effects that may materialise from the identified weaknesses; and (3) the use of appropriate technologies to reduce the likelihood to the occurrence and its effects. With this in mind, specific KPIs for improving asset vulnerability include the: (1) appropriateness of weakness identification and relevant effect assessment; and (2) effectiveness of the advanced technologies applied to reduce the system's vulnerability and ensure to its adaptability and restorative capacity (Figure 3).

3.5 Government and Contractor Inputs and Capabilities

The inputs and capabilities of government and contractors have been identified as determinants of infrastructure resilience in terms of '*how to be resilient*' (Bruneau *et al.*, 2003). While inputs are designed to measure the resources to be used to enable/enhance resilience, an organisational capability is created to measure whether the basic building blocks of competitiveness are robust enough to ensure satisfactory performance (Neely *et al*., 2001; Cabinet Office, 2016).

In the developed resilience PMF for transport assets, the KPIs for '*Government's Inputs and Capabilities*' and '*Contractor's Inputs and Capabilities*' thus relate to: (1) skilled workforce (i.e. designed to measure if the workforce of the government contractor is experienced or knowledgeable in planning/designing/constructing /managing resilient assets); (2) empowered decision making (i.e. designed to measure the level of authority provided to skilled staff to respond to the disruption); (3) knowledge management and innovation (i.e. implemented to measure the effectiveness and efficiency of organisational mechanisms, for example, training and learning systems, in government or contractor to manage the knowledge of and facilitate the innovation of knowledge of transport resilience); and (4) effectiveness of the strategies (e.g. of future investment into an enhancement of transport resilience) (Figure 3). In this instance, initiatives to be considered are an asset's resilient abilities (e.g. absorbability and adaptability) to accommodate foreseeable and unforeseeable impacts by improving its design or restoration (process).

In addition, the robustness of a transport asset's technological ability to resilience can be determined by the predictive capability of the organisations engaging with their design and management (i.e. government) (Bruneau *et al.*, 2003; Orsato *et al.*, 2017). The predictive capability is referred to as the key-stakeholder organisations' technological capability to anticipate an event and its impacts (Park *et al.*, 2013). This capability refers to the government's or relevant organisation's systems, technologies, database and/or techniques useful for supporting the identification of future potential impacts. Hence, a KPI, which relates to the technology-focused ability in predicting potential events of disruption, is developed to measure the effectiveness and efficiency of the systems and technologies to forewarn of potential disruptive threats from climate change.

The KPIs under the measurement perspectives of government's and contractor's inputs and capabilities are the measures for examining the effectiveness and efficiency of the works and resources required to enable resilience over an asset's development process. Hence, they are interconnected with each other on the basis of the resilience objective and key stakeholders' expectations. For example, the knowledge and experience of skilled workforce in government or private contractor can determine the robustness of the organisation's predictive capability or governance, which may affect the effectiveness of the policies/strategies/technologies and decision-making system implemented and adopted to plan, construct, operate and maintain the infrastructure. This in turn underpins improving asset's vulnerability and then enhancing its technical ability to absorb and adapt to the impacts of environmental changes (Figure 3).

3.6 Governance and Policy

Infrastructure development is influenced by public policies (e.g. land, planning, and procurement) with varying political dimensions being pivotal to facilitate and enhance asset resilience (Nierop, 2014; Giezen *et al.*, 2015; Sage *et al.*, 2015). Thus, 'policy' is a key determinant of '*how to be resilient*'. The design of a PMF for the public sector must, therefore, consider the influence of relevant policies on their ability to manage an asset throughout its lifecycle (Bacci *et al.*, 2017). However, it has been noted that policy-related issues have been largely ignored by prevailing measurement frameworks of transport resilience. Relevant KPIs need to be concerned with the effectiveness of the policies (e.g. environmental) that can affect the resilience of transport assets (HM Government, 2011).

3.7 Asset Delivery and Management

Due to the influence of procurement policy on the resilience of transport assets (Love *et al*., 2017), '*Asset Delivery and Management*' has been included in the conceptual framework presented in Figure 2 as it is associated with '*Contractor's Input and Capability*' and '*Continuing Improvement for Asset Vulnerability*'. Accordingly, the KPIs that are relevant to 'Asset Delivery and Management' in the developed resilience PMF are aligned with the procurement method that is selected and used to deliver and manage the asset.

The selection of the most appropriate procurement option is dependent on the public sector's requirements and needs (Love *et al*., 1998). Though, there has been a subtle shift by Australian state governments to use Public-Private Partnerships (PPPs) or variants thereof to procure major roads and rail assets (Regan *et al.*, 2017). For example, PPPs have been used to deliver LRT systems in cities such as Canberra, Gold Coast and Sydney (Love *et al*., 2017). Specific performance measures (i.e. KPIs) for the 'Asset Delivery and Management' perspective of the developed PMF, particularly in the case of PPPs, will need to focus on the effectiveness and efficiency of monitoring of construction, operations and maintenance phases being managed by the private sector. In addition, it has been identified that technology-enhanced asset management is able to support replenishing transport assets and continually improve their vulnerability by providing digital access to appropriate and reliable information (Love *et al.*, 2018). Hence, the KPIs with regard to asset management within the developed PMF should be specific for the appropriateness and effectiveness of the technologies used to monitor the assets (Figure 3), for example, real-time sensors and BIM, which are useful for collecting asset performance data essential for decision making.

4.0 Implications for Policy Development to Enable Transport Resilience

Having developed a life-cycle resilience PMF for transport infrastructure, its implications for policy development are examined and discussed. In particular, an emphasis is placed on developing: (1) an organisational culture that is attuned to resilience; (2) information policy to facilitate learning; and (3) governance of service recovery and risk prevention.

4.1 Policies for Developing Organisational Resilience Culture

The development of an organisational culture of resilience within the public sector is a necessity for ensuring assets are future-proofed (Everley, 2011; Love *et al*., 2017). Culture plays an integral part in cultivating and shaping a resilience strategy to be enacted by employees (Scholz, 1987; Bititci *et al.*, 2006; White, 2013; Hughes and Healy, 2014). It has been widely acknowledged that organisational culture can support the development and improvement of organisational capability (e.g. Hock, 2016; Chang *et al.*, 2017; Cropley, 2017).

A public transport authority that possesses a resilience culture, for example, needs to (Martins and Terblanche, 2003; Everly, 2011): (1) make an investment based on its stakeholders requirements; (2) contribute to improve organisational innovation by managing the adversities that can affect the services of its' transport assets (i.e. enhance assets' abilities to withstand natural hazards); and (3) provide investment in training and education to develop employees' knowledge to deal with short-to-long-term environmental impacts on the assets. The aforementioned initiatives can enhance government employees' skills and knowledge in identifying and innovatively managing external impacts on the functions of transport systems (Copper *et al.*, 2014). As a result, the public sector's organisational capability to respond to foreseeable or unforeseeable events from environmental disturbances (i.e. climate change) will be significantly improved.

An organisational culture of resilience can be established by putting in place appropriate strategic human resource (HR) policies, which should focus on the: (1) recruitment of employees who have appropriate knowledge and skills in developing resilient transport assets; (2) enhancement of public investment in human capital (i.e. training and continued development of workforce ability in improving transport resilience); and (3) empowerment (i.e. to facilitate decision making during a disruptive event) (Lengnick-Hall *et al.*, 2011).

4.2 Information Policy to Facilitate Learning

Learning is a central tenet of the PMF that has been developed (Figures 2 and 3). It can be enhanced through supportive organisational mechanisms (e.g. technology, system and policy) (Robey *et al.*, 2000). Thus, governments need to develop and implement policies that engender effective reciprocal learning between public authorities and private-sector contractors involved with the delivery, maintenance and operation of transport systems and networks.
Information is integral to effective learning. The *learning cycle* encompasses the generation of information, its integration into the organisational context, collective interpretation and responsive action on the interpreted meaning (Dixon, 1999). Furthermore, "information is a

vital resource as when it ceases to flow an organisation's ability to function halts" (Westrum, 2014, p.60). The Cabinet Office of the UK (2011) also identified that enabling resilience is a process, incorporating: (1) resilience measurement; (2) risk identification; (3) risk assessment; and (4) building resilience, in which information processing (e.g. information gathering, retrieving and communication) is a 'hub' (Figure 4). In this regard, information policy is useful to develop resilient transport assets (Cabinet Office, 2017), as it is the set of public laws and regulations encouraging and regulating the creation, use, storage, access, and communication and dissemination of information.

Figure 4. The process of enabling resilience [Adapted from Cabinet Office (2011)]

Information policy for transport resilience would need to regulate the use and communication of the information, regarding the: (1) services that the assets will provide; (2) physical and service status of the assets; (3) likelihood and impacts of potential risks that can cause disruption on the services of the assets; and (4) emergency assistance and management (Cabinet Office, 2011). In addition, policy needs to support the development of a system that encourages *Information Sharing and Learning* between public and private sectors to enable knowledge exchange and therefore stimulate learning and process improvement. An initiative that has been established to begin to address this issue is the *Trusted Information Sharing Network* (TISN) which has been launched across sectors in Australia to enhance infrastructure resilience (Australia Government, 2017). But, the TISN falls short as it does not provide a platform for learning to take place and a process of benchmarking, which are needed to enact a process of future-proofing to be initiated.

A significant interrelationship between information flow and organisational culture prevails (Curry *et al.*, 2011). Information is, therefore, an indicator of organisational culture, which can reflect the quality of cooperation and decision-making within the organisation (Westrum, 2014). Therefore, an information policy that aims to boost information sharing can enable the culture of a government to shift from being 'bureaucratic' to 'generative', where information exchange across their internal boundaries is valued (Westrum, 2009). A 'generative" culture thus provides the foundation to underpin effective and efficient information communication among public authorities, which has been identified above as being pivotal for an enablement of transport resilience. Yet, the culture of governments tends to be 'bureaucratic', as they "maintain their 'turf', and insist on their own rules and generally do things by the book – their book" (Westrum, 2014, p.59). The corollary being intra and inter departmental (i.e. within public sector) and cross-sector (i.e. between public and private sectors) sharing of knowledge can be stymied owing to issues of commercial sensitivity, self-protection and/or unclear clarification about what information is needed to be shared (Cabinet Office, 2017).

4.3 Policies for the Governance of Service Recovery and Risk Prevention

Governance has been embedded into the developed resilience PMF (Figures 2 and 3), as it can affect the implementations of short-to-long-term plans for infrastructure development (Taylor, 2016). However, it has been widely observed that ineffectual governance is a constraint that inhibits equitable resilience and adaptation planning (Fraser and Kirbyshire, 2017). While many governments have implemented governance policies to enable and enhance the resistance/robustness of their transport infrastructure (i.e. physical ability to withstand natural impacts), limited attention has been given to 'how' to regulate, re-route and/or recover the assets' services that have been disrupted by hazards (Department of Transport, 2014; Highways England, 2016). 'Recovery' from an adverse occurrence that causes destruction/failure is a critical ability to transport assets in terms of resilience (USDHS, 2009; Wilkinson, 2013). Thus, policies that aim to govern 'how' to effectively and efficiently back-up or substitute disrupted service are needed.

The ‘Continuing Improvement for Asset Vulnerability’, which aims to reduce vulnerability and prevent impacts from climate-related hazards/risks, has been identified as a key measurement perspective of the developed PMF. Accordingly, risk or hazard prevention needs to be addressed in future policy development relating to resilience governance. In practice, risk management is a process comprised of risk identification, assessment and control (i.e. plan to prevent risks) (Safe Work Australia, 2011). Thus, it follows that the robustness of the risk and hazard prevention for transport infrastructure depends on the effectiveness of risk identification and assessment (Department of Transport, 2014). Despite the importance of risk management, there are limited policies being implemented in practice that up-date risk assessment on a regular basis (Highlands England, 2016). For example, in the UK “transport operators are not obliged to produce an update of their Risk Assessments” and this has weakened the resilience of the assets (Department of Transport, 2014, p.45).

5.0 Conclusions

Having efficient and resilient transport systems in place is a priority for the governments in many developed economies. The corollary has been a plethora of studies examining the nature of resilience. Nevertheless, the enablement of resilience is a sophisticated process relating to asset's planning, design, engineering, construction, operations and maintenance. Performance measurement is a key facilitator to effective and efficient process management. There have been limited studies of the resilience measurement of transport assets in the literature, and therefore, the research presented in this paper aimed to develop a robust PMF to effectively manage the resilience of transport assets throughout their lifecycle.

Based on a review of the extant literature of resilience, a life-cycle resilience PMF that has been developed. The framework incorporates a series of measurement perspectives: (1) asset technical ability; (2) continuing improvement for asset vulnerability; (3) government and contractor inputs and capabilities; (4) specific objectives; (5) end-user and local resident expectations; (5) governance and policy; and (6) asset delivery and management. With these features, the developed PMF for transport assets can capture and reflect not only the robustness of transport asset’s technical abilities to adapt to the disturbances as a result of environmental change, but also the process and policies leading to such abilities. Practical implications have been identified for future policy development to enable and/or improve resilience. These include the development of: (1) organisational resilience culture activated by government's strategic HR policies; (2) information policy; and (3) policies for the governance of service recovery and risk prevention.

The study presented in this paper is significant, as it contributes to the literature of resilience measurement that has been acknowledged as being a prerequisite of building resilient transport infrastructure. Hence, it provides governments with a novel insight into ensuing and improving their asset's resilience to accommodate environmental changes and then enabling safer communities for local residents. Our paper is conceptual in nature, and thus empirical research is required to valid our proposed PMF. To this end, future research is needed to empirically examine the feasibility of the developed PMF using a series of case studies so that it can be used a frame of reference to guide policy development.

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