Public Organization Adaptation to Extreme Events

Evidence from the Public Transportation Sector

by

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ABSTRACT

This dissertation consists of three essays, each examining distinct aspects about public organization adaptation to extreme events using evidence from public transit agencies under the influence of extreme weather in the United States (U.S.). The first essay focuses on predicting organizational adaptive behavior. Building on extant theories on adaptation and organizational learning, it develops a theoretical framework to uncover the pathways through which extreme events impact public organizations and identify the key learning mechanisms involved in adaptation. Using a structural equation model on data from a 2016 national survey, the study highlights the critical role of risk perception to translate signals from the external environment to organizational adaptive behavior.

The second essay expands on the first one to incorporate the organizational environment and model the adaptive system. Combining an agent-based model and qualitative interviews with key decision makers, the study investigates how adaptation occurs over time in multiplex contexts consisting of the natural hazards, organizations, institutions and social networks. The study ends with a series of refined propositions about the mechanisms involved in public organization adaptation. Specifically, the analysis suggests that risk perception needs to be examined relative to risk tolerance to determine organizational motivation to adapt, and underscore the criticality of coupling between the motivation and opportunities to enable adaptation. The results further show that the coupling can be enhanced through lowering organizational risk perception decay or synchronizing opportunities with extreme event occurrences to promote adaptation.

The third essay shifts the gaze from adaptation mechanisms to organizational outcomes. It uses a stochastic frontier analysis to quantify the impacts of extreme events on public organization performance and, importantly, the role of organizational adaptive capacity in moderating the impacts. The findings confirm that extreme events negatively affect organizational performance and that organizations with higher adaptive capacity are more able to mitigate those effects, thereby lending support to research efforts in the first two essays dedicated to identifying preconditions and mechanisms involved in the adaptation process. Taken together, this dissertation comprehensively advances understanding about public organization adaptation to extreme events.

DEDICATION

To my parents, Xiaoyi Zhang and Yongxian Wang, who have taught me the importance of education, perseverance and strong will, and inspired me to try my best to achieve goals. Without them, I would not have been able to attend college, to say nothing of completing this dissertation for my doctoral degree.

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CHAPTER 1

INTRODUCTION: ADAPTATION TO EXTREME EVENTS

Public organizations are confronted with an advancing list of natural and man-made extreme events, ranging from extreme weather, disease outbreaks, critical infrastructure collapse, ecological crisis to technological breakdowns (Boin & Lodge, 2016). Extreme events are major, unpredictable and abrupt occurrences with high salience and consequences for the impacted organizations. The events are of such intensity that they deviate from historic norms, exceed local, regional or national threshold and generate impacts. Traditionally regarded as low-probability occurrences, extreme events are characterized by increased frequency and intensity due to constant technological advances and ongoing changes in the Earth's biophysical and seismic systems (Folke, 2006; Turner & Pidgeon, 1997). Their occurrences have become so frequent and impacts so profound that they are becoming the "new normal" for today's public administration (Tierney, 2014).

Extreme events put tremendous pressure on public organizations and managers charged with providing security and maintaining operation continuity. Effective and expedient response requires substantial capacity to gather and assess information, acquire and deploy resources and coordinate with key stakeholders for joint actions (Comfort & Okada, 2013; Turoff et al., 2011). Significant efforts are required in the post-event period to restore to an acceptable state of normality (Berke et al., 1993; Wolensky & Wolensky, 1990). The focus on incidence response and loss mitigation after events characterize the traditional approach in public administration to extreme events. Despite the progress made in emergency and crisis management, those approaches are increasingly found wanting in meeting the extraordinary demands brought about by extreme events (Cigler, 2007; Comfort et al., 2012; McEntire, 2004). This is partially because the progress does not keep up with the escalation of challenges confronting today's public organizations (Boin & Lodge, 2016). More critically, the conceptual framework of those approaches are ill-suited for the types of actions required to manage the altered patterns of vulnerability amid intensifying extreme events (Boin & Van Eeten, 2013; McEntire, 2008).

It has become increasingly evident that solutions in response to extreme events need to be sought at the strategic rather than the operational level (Boin & Lodge, 2016; McGuire & Schneck, 2010). A common perspective is that traditional emergency and crisis management need to be complemented with planned organizational adaptation to reduce organizational vulnerability and foster resilience against a wider range of external shocks, thereby preventing full-blown crises or breakdown (Boin & Van Eeten, 2013; McEntire, 2008; McGuire & Schneck, 2010). Adaptation refers to organizational accommodations of routines, processes and structures in response to actual or anticipated shocks from the outer environment (adapted from Nelson et al., 2007). Public organizational can undertake adaptation in various ways, such as investment in human and political capital to raise the preparedness of personnel and organization networks for future shocks, alteration of organizational structure and arrangements to enable learning and capacity to improvise, or improvement in materials resources and infrastructure to boost the system resilience (Gupta et al., 2010; Kusumasari et al., 2010). As the environment presents more threats and uncertainties that repeatedly fail standards and routines, accomplishing goals is often a question of how well public organizations are adapting to the constraints and challenges from the external environment.

Despite the theoretical imperative to enhance organizational effectiveness and survival in a changed environment, adaptation is a rare practice among public organizations. Numerous studies have shown the continued predominance of reactive responses to extreme events (i.e. managing immediate consequences after the event occur) with very few organizations incorporating adaptation strategies and measures in their operations, design and planning (Hill & Engle, 2013; McEntire et al., 2010; Somers, 2009; Welch et al., 2016). What explains the scarce and slow take-up of adaptation in public organizations? More importantly, what are the driving forces behind the adapting organizations? As public organizations are increasingly caught up with the ever-growing challenges from extreme events, understanding the mechanisms through which adaptation occurs (or not) is of critical importance to inform management and policy.

This dissertation advances the literature by investigating public organization adaptation in an interrelated set of physical, social, political and institutional contexts in which the organizations operate. It seeks to uncover the pathways through which extreme events affect public organizations in order to identify necessary mechanisms for organizational adaptation. Taking an open systems perspective, the dissertation examines conditions internal and external to the organization that enable or stimulate adaptation. Furthermore, with all the academic arguments and practical imperatives to develop organizational adaptive capacity against extreme events, how do public organizations actually perform under the influence of those events? And to what extent does organizational adaptive capacity matter to moderating weather impacts? Answers to this question will help public organizations and manager achieve an objective assessment of their environmental challenges, which forms a fundamental motivational basis for change in public organizations (Behn, 2003; Meier et al., 2015; Nicholson-Crotty et al., 2017).

The Three Essay Dissertation

The dissertation consists of three essays, each focusing on different aspects of organizational adaptation to extreme events. The three essays seek to answer the following questions.

1. What conditions, experiences and perceptions lead some public organizations to adapt while not others? Can adaptation be a spontaneous reaction to recurring risks, or is there a need for cognitive processes that translate risk stimuli to adaptive responses?
2. Since public organizations operate in complex and dynamic political, institutional and social systems, how do those contexts influence their adaptation? In light of their embeddedness, how does adaptation unfold over time as organizations' experience with extreme events evolves?
3. How do extreme events affect organization performance? Moreover, with efforts to boost adaptive capacity emerging at various levels of governments, to what extent does adaptive capacity moderate the impacts of extreme events?

The first essay adopts the central concept of vulnerability and builds a theoretical framework to elucidate the ways through which exposure to extreme events impacts public organizations over time. The complex and latent nature of vulnerability necessitate the critical role of organizational perception of risks in channeling environmental stimuli to adaptive responses. Based on the framework, this paper develops several hypotheses to examine exposure to extreme events and how it influences risk perception and ultimately organizational adaptation. Using a 2016 national survey dataset on US transit agencies, the paper applies a structural equation model (SEM) to disentangle the direct and indirection relationships in organization response to extreme weather.

But the perception-mediated learning model does not tell the whole story. It implicitly assumes a cumulative and continuously evolving process that leads to change when at or beyond certain thresholds. However, previous studies show cases when high risk perception fails to lead to adaptation (Birkland, 2006; Grothmann & Reusswig, 2006; Mockrin et al., 2018). In the presence of high risk perception after repeated extreme events, how does adaptation occur or not occur? These mechanisms are less clearly specified in the model. The second essay aims to achieve a unified framework for understanding organizational adaptation. Drawing from extant theories and empirical studies, it includes risk perception, risk tolerance, opportunities to over financial constraints as well as social nearing to investigate how cognitive, institutional and social forces interact and coalesce to produce the aggregated pattern of adaptation among public organizations. Grounded in the empirical contexts of transit agency adaptation adapting to extreme weather, the essay identifies the reference pattern from empirical observations to guide the modeling and conducts qualitative interviews with transit managers to achieve an operational understanding of the adaptation process. The end product of this study is a set of refined propositions about the micro-mechanisms through which public organization adaptation takes place.

The third essay complements the previous two papers by quantifying the actual impacts of extreme events on organizational performance over time, again using the empirical setting of U.S. transit agencies under the influence of extreme weather. It systematically assesses the impacts of extreme weather on transit system performance over an extended period of time. Moreover, with more public organizations called upon to adapt to extreme weather and climate effects, the analysis examines the extent to which adaptive capacity mitigates the weather impacts and helps maintain or grow organizational performance. Specifically, it investigates the effects of three factors constitutive of organizational adaptive capacity, namely formal institutions, capital stock and contracting out. The empirical analysis uses all the fixed-route bus transit systems in the Midwest and Northeast during the winter season (November-February) from 2008 to 2017. Treating extreme weather and organizational adaptive capacity as explanatory variables for inefficiency, the analysis applies the panel data stochastic frontier model (SFA) proposed by Battese and Colelli (1995). It further incorporates the heterogeneous effects from those factors in estimating both the level and efficiency of production (Greene, 2004). The paper contributes a systematic assessment on the impacts of extreme weather on organizational performance. It also helps inform future adaptation policy and planning by generating empirical evidence on the effectiveness (or lack thereof) of adaptive capacity to mitigate the weather impacts.

The following sections of the introduction proceeds as follows. The next section describes the research settings and rationale for the choice. Following the section are explanations on how the three essays as whole contribute both theoretically and practically to understanding and dialogue on public organizational adaptation to extreme events. Contributions to both the public administration literature and adaptation literature are separately discussed.

Research Setting

The public transit sector provides a fruitful context to examine the impacts of extreme weather and adaptation mechanisms. Because transit agencies rely on exposed, dispersed and interconnected infrastructure for daily operations, they are particularly susceptible and vulnerable to weather-related changes and perturbations (Koetse & Rietveld, 2009; Meyer et al., 2012). The impacts can be immediate and disruptive, including emergency conditions experienced during hurricanes, flood or snowstorms. They also build up over time, as accumulated stress and strains from recurring extreme weather events lead to degradation of vehicles, facilities and roadways. The consequences are heightened when extreme weather triggers cascading failures throughout interdependent networked systems (Boin & McConnell, 2007; McDaniels et al., 2008). At the same time, performance of transit agencies has broader social ramifications, owing to their criticality in transporting citizens and delivering necessity goods and services under crisis circumstances. Should they respond inadequately, the impact will disproportionately fall upon transit-dependent populations, thereby giving rise to social equity concerns (Hodges, 2011). Moreover, transit systems are similar to many other systems, such as electricity, water and telecommunication, in terms of their exposure to extreme events, broad coverage, system interconnectedness and resource intensiveness. The system similarities stand to increase the generalizability of this research. Finally, the lack of top-down institutional mandate determines the discretionary nature of transit agency adaptation, making it possible to achieve theoretically meaningful and practically relevant insights.

In the meantime, the US is prone to a variety of extreme events, ranging from tornadoes, hurricanes, snowstorms, flood and heat waves. The year of 2017 registered 16 billion-dollar weather and climate disasters across the United States (NOAA, 2018). Despite its record-breaking number of extreme weather events, 2017 was not an anomaly. The NOAA time series data shows an increasing frequency of billion-dollar weather disasters, approximating a yearly growth rate of about 5 percent (Smith & Katz, 2013). There is a strong scientific consensus that weather extremes will continue to rise in frequency, duration and magnitude, due to the underlying changes in the Earth’s climatic systems attributable to both natural and anthropogenic forces (Handmer et al., 2012; IPCC, 2014; Melillo et al., 2014). Public transportation is already experiencing costly impacts from weather extremes leading to damaged roads, flooded bus stations, buckled rails and service delay or breakdowns. Those impacts are projected to increase as the trend of extreme weather escalates (FHWA, 2018). The threats of extreme weather are increasing and actions required to tackle the challenges similar, raising the potential for systematic investigation into the pattern of weather impacts and responses of the affected organizations.

Contributions

This dissertation contributes to the public administration literature with an alternative approach to extreme events by emphasizing ex-ante adaptation vis-à-vis ex-post response through emergency or crisis management practices. It does so by deemphasizing the uniqueness and exceptionality of extreme events and highlighting the non-random generation of risks and commonality across different extreme events. As such, it is able to connect the research on extreme events with the mainstream literatures such as organization theory, policy change and climate adaptation to enable a systematic investigation of how public organizations are impacted and adapt to significant discontinuous changes in their environment. Through focusing on public organizations as the adapting entities and using large-N datasets, this dissertation is one of the few theoretically informed and quantitative research on core topics about organizational adaptation and resilience (Boin & Van Eeten, 2013; Christensen et al., 2016). Its interdisciplinary approach, both theoretically and methodologically, also allows the dissertation to offer insights and unmask key mechanisms that are otherwise unachievable.

The dissertation also contributes to the adaptation literature. It highlights the discontinuous and non-linear changes brought about by extreme events, as compared to the continuous and incremental changes organizations routinely encounter. Through a focused investigation on extreme events, the dissertation provides a conceptual foundation for understanding how extreme events impact organizations and shape their adaptive behavior, as well as the key mechanisms involved in adaptation. The dissertation adds to the emerging line of organizational-level studies on adaptation to extreme changes in the natural environment, with a particular focus on public organizations. It further bridges the critical gap between adaptation studies from the public management policy development literature, with enhanced promise to inform policy making and managerial practices.

CHAPTER 2

PUBLIC ORGANIZATION ADAPTATION TO EXTREME EVENTS: MEDIATING ROLE OF RISK PERCEPTION

Introduction

Public organizations are increasingly encountering a broad class of extreme events, ranging from critical infrastructure breakdown, disease breakout, extreme weather to ecological crises. Typified by high uncertainty, unpredictability and consequentiality, those events have the potential to overwhelm organizational defenses and lead to damaging impacts (Boin & Lodge, 2016; Comfort, 2002b). Despite their seemingly uniqueness, extreme events are characterized by the non-random generation of risk in the modern society, pointing to root causes such as the ongoing changes in the Earth's biophysical and seismic system (Folke, 2006; Hegerl et al., 2007), the increasing interdependence of critical infrastructure as well as the deployment of high-risk and emerging technology (Perrow, 1984; Turner & Pidgeon, 1997).

Response to extreme events is traditionally addressed through emergency, crisis and disaster management in public administration. All too often, however, the challenges of those events are compounded by the traditional reliance on emergency or crisis management to manage immediate reactions when an extreme event strikes (Comfort et al., 2012; McEntire, 2008). Treating extreme events as unique and out-of-the-ordinary situations while ignoring the systematic generation of risk carries significant costs. Practically, confining the responsibilities to crisis management narrows the scope of the problem and diminishes the role of and potential contribution from other organizational levels and units. The scale of response is also limited: responses taken at the emergency management unit are unlikely to feed into the decision making at other units and levels, a key barrier to vertically integrate decision making and actions across the organization (Ziervogel et al., 2019). Focusing on managing post-event reactions also denies the opportunities for public organizations to build capacity and prepare for the unexpected (McEntire, 2008). Theoretically, a preoccupation with the exceptionality of extreme events contributes to disconnecting this discipline from the mainstream studies (Roux-Dufort, 2007), missing the opportunity for systematic research and cross-fertilization that could shine important light on public management under the challenges of extreme events.

This study contributes to the literature by taking an organizational approach to study public organization response to extreme events. It integrates the adaptation, organizational effectiveness and organizational learning literature to unmask the ways through which extreme events influence public organizations. The central argument is that recurring exposure to and impacts from extreme events requires planned and deliberate adaptation to increase organizational capability to withstand disruption while reorganizing to maintain continuity under extreme events. The observed variations in public organization adaptation and importantly the driving forces behind the variations lead to this research.

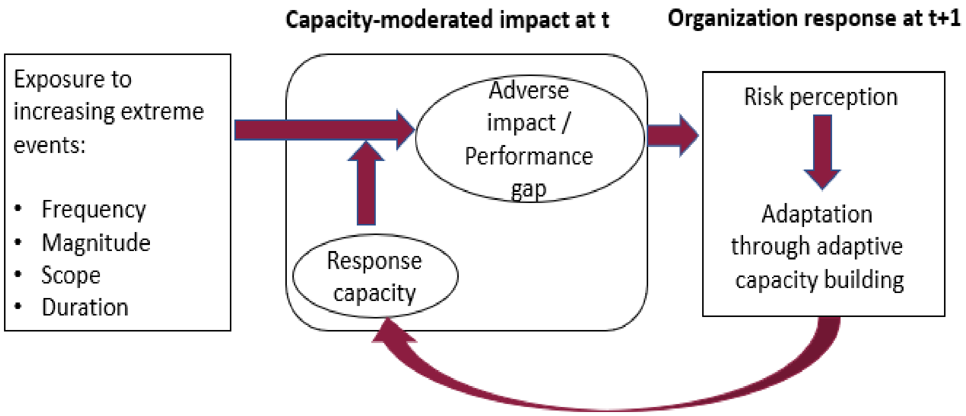
This paper begins with a framework to explicate the necessity of organizational adaptation in light of the growing vulnerability of public organizations to extreme events. Based on the framework, the paper develops several hypotheses linking extreme events, organizational vulnerability, risk perception and adaptive capacity. It examines the interface between the organization's environment and the learning mechanisms that enable adaptation. Specifically, it investigates how exposure to extreme events impacts public organizations, and how the occurrence and impact of extreme events are related to organizational perceptions of risk and their adaptive responses. Is organizational adaptation a spontaneous response to recurring risks or is it mediated by cognitive mechanisms that enable organization-wide sensemaking of emerging developments? Based on a unique dataset from a 2016 national survey of 892 managers in 273 U.S. largest public transit agencies that cover 82% of the entire FTA population of transit agencies with an annual fare revenue of 1 million, the findings underscore the essential role of risk perception in channeling environmental signals to adaptive responses. The article concludes by discussing its theoretical contribution and implications for management.

Organizational Adaption to Reduce Vulnerability

A key premise of this research is that organizations can learn from their prior experience and adjust to their changing environment (Lawrence & Lorsch, 1967; Thompson, 1967), thereby reducing vulnerability from repeated perturbations and disruptions from extreme events. Vulnerability, which is the degree to which an organization is likely to experience harm due to its exposure to hazardous events (Turner et al., 2003), is recognized as an outcome of the interaction between an organization's exposure to environmental stresses and its ability to prepare for and react to them effectively (Berkes, 2007; McEntire, 2008). Because organizations have limited control over the frequency, magnitude, and scope of extreme events, effective vulnerability management is a primary means by which they are able to alter the consequences of such events (Dutton & Jackson, 1987; McEntire et al., 2002).

Figure 1 presents the framework depicting the key determinants of vulnerability in public organizations and the organizational mechanisms through which vulnerability can be managed. From left to right, an organization is exposed to the frequency, magnitude and scope of extreme event, but the level of harm an organization experiences is contingent on the capacity it has at time t=0 to respond to the event (Cigler, 2007; McEntire, 2005). Organizations having greater capability experience less harm and manifest fewer gaps in performance (i.e. impacts) during events. Perceptible gaps in performance are called revealed vulnerability. Risk perception results from an organization's assessment and understanding of the risk inherent in its environment (Comfort, 2007; Sitkin & Pablo, 1992). Depending on its experience and perceived risk, the organization builds adaptive capacity at t=1 after the event occurs. The response of the organization at t=1 further influences its vulnerability and response to future extreme events. The cycle from adverse impact to organization adaptive response occurs over a period of time, the length of which depends upon the size of the gap, initial organization capacity and other factors. I discuss the theoretical rationale for this framework in the following paragraphs and in the hypothesis section.

Figure 1. Organization Vulnerability and Response to Extreme Events



Extreme events and organizational performance

Several factors constrain public organizations' ability to effectively deal with extreme events. Public organizations are characterized by their search for structural (i.e. lack of organizational duplication) and fiscal (i.e. frugality) efficiency with a focus on their core competencies and routines (Perrow, 1984; Stark, 2014). This "lean and mean" strategy (Staber & Sydow, 2002), which reduces system redundancy, resilience and slack, can increase vulnerability to extreme events and complicate efforts to manage their consequences (Boin et al., 2016; Schulman, 1993). As Stark (2014, p. 696) notes, "the pursuit of efficiency without consideration of the benefits of auxiliary resources will create systems that cannot adapt to the emergence of potentially disastrous failures." Additionally, interconnectedness and interdependence of critical infrastructure increases organizational vulnerability and complicates adaptation. High complexity increases the potential for a single localized performance failure to cause a cascade of disruptions that result in system-wide failure (Little, 2002; Perrow, 1999). Crichton and colleagues (2009) aptly exemplify how failure in one electricity feeder cable during a heat wave propagated faults in another two feeders and escalated into a profound 10-week disruption in electricity supply in New Zealand. Moreover, repeated exposure to extreme events can reduce an organization's performance well below the desired level of achievement (Comfort, 2005). The compromised integrity of system components and linkages, while not necessarily precipitating catastrophe during a particular event, can increase vulnerability and widen the performance gap during future extreme events (La Porte, 1996; Perrow, 1994).

Adaptive capacity

Strengthening adaptive capacity is a key mechanism by which public organizations can reduce vulnerability to repeated stress or perturbations (Berkes, 2007; McEntire, 2008; Staber & Sydow, 2002). Adaptive capacity is defined not only in terms of an organization's capability to bounce back to a state of normalcy after an extreme event, but also of its ability to absorb disruptions and reorganize while undergoing changes so as to retain the essential functions and structures (Berkes, 2007; Boin & Van Eeten, 2013).

Increasing adaptive capacity entails deliberate efforts to make longer-term and anticipatory adjustments to fill the possible performance gaps for a wider range of observed or anticipated extreme events. It reflects an organization's stock of resources and enables it to exploit its resources in a more productive manner (Kusumasari et al., 2010). Common measures to build adaptive capacity include improvement in material resource inputs, information and technology, infrastructure and equipment, human capital and inter-agency coordination arrangements (Comfort & Okada, 2013; Kusumasari et al., 2010; McEntire, 2005). As an example, Arizona mobilized adaptive responses to severe droughts in 2008-2011 by developing an integrated water conservation system and fostering collective planning and response among water suppliers and users (Hill & Engle, 2013).

Development of adaptive capacity is distinguished from emergency management, which focuses predominantly on responding to the immediate impacts of extreme events (Cigler, 2007; McEntire, 2008; Somers & Svara, 2009). Crisis management planning and preparation for extreme events establish risk-based intentions but do not constitute adaptive capacity (Christianson et al., 2009; Clarke, 1999). As Perrow (1999, p. 152) notes, "Even 'worst case' scenarios usually refer only to the worst state of the *environment"*, giving little attention to an organization's overall vulnerability, maintenance of infrastructure, the process of event escalation, the availability of backup resources or potential for maximum failure of the organizational management (Fischbacher-Smith, 2010; McEntire, 2008; Roux-Dufort, 2007).

Risk perception

Nevertheless, reducing vulnerability and enhancing adaptive capacity in the face of extreme events are complicated by multiple intervening factors. Vulnerability is often not obvious in the absence of significant triggers or events (Rijpma, 1997; Sarewitz et al., 2003) and the evidence of capacity surfaces only after extraordinarily complex problems are solved (Kusumasari et al., 2010; Levinthal, 2000). As a result, decision makers face high ambiguity, complexity and uncertain payoffs from investment and change. These challenges to building adaptive capacity, coupled with the evidence that disasters motivate adaptive planning in some organizations but not in others (Ebert et al., 2009; Haigh & Griffiths, 2011; Hoffmann & Rotter, 2012), suggest a cognitive mechanism that governs how organizations respond to these external stimuli.

Scholarship across disciplines has identified risk perception as a crucial factor for explaining why disasters motivate adaptation planning in organizations (Berkhout, 2012; Comfort, 2007; Dutton & Jackson, 1987; Hoffmann et al., 2009; Somers & Svara, 2009). Risk perception comprises the perceived probability of being exposed to negative impacts and the appraisal of how harmful those impacts would be on the organization (Grothmann & Patt, 2005).

Uncertainty and complexity associated with extreme events limit the applicability and usefulness of analytic techniques and tools (Garrett, 2004; Moynihan, 2008; Simon, 1979), as well as the ability of existing data to capture event complexity (Fischbacher-Smith, 2010). As a result, organizations rely on a messy process of sensemaking, attribution, and judgment for decision making and strategy selection (Daft & Weick, 1984; Kiesler & Sproull, 1982; Sitkin & Pablo, 1992). Adaption is less likely to occur when the affected organizations fail to notice and attach meaning and significance to variations in their environment that pose risks (Comfort, 2007; McEntire, 2004; Sitkin & Pablo, 1992). In contrast, perceived risk can stimulate organizations to undertake non-routine and non-incremental action that aims to increase adaptive capacity (Comfort, 2007).

The theoretical framework presented in Figure 1 provides a starting point for further development of theory-based hypotheses linking exposure to extreme events, impact, risk perception and adaptation. Following the framework, I hypothesize that organization adaptation to extreme events is affected by its vulnerability to extreme events which is manifested in the impacts it realizes during the events. I also expect that exposure and impact lead to adaptation through perception of the risk associated with extreme events.

Theory and Hypotheses

Exposure, impact and adaptation

Organizational systems are typically designed to cope with a certain range of external perturbation and disruption, the levels and scopes of which are largely determined by their historical norms and experiences. However, extreme events are invariably outliers against which the existing operating system does not provide sufficient defense (Fischbacher-Smith, 2010). Repeated exposure to extreme events inevitably leads to accumulation of severe weaknesses and deficiencies until the system reaches the tipping point and loses viability and robustness (Roux-Dufort, 2007). As Comfort (2002, p. 102) puts it, “governmental systems designed to provide security at one level of exposure may fail when they are exposed to cumulative threats of different types at different levels of operations”. The situation rapidly escalates as a result of a series of interdependent cascading failure in which failure in a single component triggers failures throughout a complex and tightly coupled system (Perrow, 1984; Turner & Pidgeon, 1997). Recurring extreme events are more likely to overwhelm the control and management system and lead to disastrous impacts on the affected organization.

H1: Organizations that experience greater exposure to extreme events are more likely to experience greater impacts (i.e. performance gap).

It is often the case that structural, political and capacity constraints limit the ability of public organizations to pursue adaptive solutions in the face of extreme events (McGuire & Schneck, 2010; Smith et al., 2009; Wise, 2006). Extreme events that cause significant property damage, economic loss, human casualties, aggressive media coverage and political pressure act as powerful catalysts for reexamining standard approaches and practices (Boin & Hart, 2003; Stehr, 2006).

Meanwhile, the increasing inapplicability and ineffectiveness of existing routines and procedures force organizations to make greater investments in exploration and implementation of more fitting solutions (Cyert & March, 1963; March, 1991). Facing low control in high-risk environments, organizations can best respond by adjusting their internal processes and building adaptive capacity (Dutton & Jackson, 1987; Staber & Sydow, 2002). Prior work demonstrates that significant adjustments of organizational strategy and practices usually do not occur until an organization has unequivocally suffered disastrous consequences associated with extreme events (Comfort, 2007; Dutton & Jackson, 1987; Linnenluecke et al., 2012; McEntire, 2004).

Importantly, impactful extreme events open “windows of opportunity” (Kingdon, 1984) for reform-minded organizations to exploit the significant damage and build support for non-incremental changes by directing attention to the flaws and deficiencies in the existing systems (Boin & Hart, 2003). Such opportunities are scarce and fleeting, and organizations have to act expeditiously before the public attention and impetus for reform fade away (Birkland, 2009; Dekker & Hansén, 2004; Gallagher, 2014; Parker et al., 2009). This suggests that organizational mobilization of support and for adaptive capacity development must be carried out within a relatively short time span. Delay or slow response can miss the opportunity. The higher the consequences of the extreme event, the more leverage an agency can apply to facilitate non-incremental changes (Birkland, 1997). I thus hypothesize that higher impacts of extreme events are more likely to provide the momentum as well as the leverage for organizations to increase adaptive capacity.

H2: Organizations that experience greater impacts (i.e. performance gap) from extreme events are more likely to undertake adaptive capacity building.

At the same time, greater exposure to extreme events increases problem familiarity essential for organizational learning (Levitt & March, 1988; Sitkin & Pablo, 1992). Recurring extreme events inform organization decision makers about the rapid escalation of harm and the significant scale of failure that escalation can generate, both of which work to invalidate their assumptions about control (Fischbacher-Smith, 2010). The lessons learned are reflected in their exploration and adoption of adaptive responses to the threats, independent of the outcomes from the past exposure (Sitkin & Pablo, 1992). The increased exposure also allows for trail-and-error experimentation to acquire and test knowledge on how to best adapt (Berkes & Folke, 2002; Levitt & March, 1988). Given this discussion, it is expected that greater exposure to extreme events will be positively associated with adaptive capacity development.

H3: Organizations that experience greater exposure to extreme events will be more likely to undertake adaptive capacity building.

Risk perception and adaptation

Organizations typically must experience a continuous stream of events to grasp trends and attempt to make sense of them (Daft & Weick, 1984; Thomas & McDaniel, 1990). Given bounded cognitions of decision makers (Simon, 1979) and the magnitude of complexity and uncertainty of extreme events, the associated risks are often not easily recognized. Instead, organizations only selectively attend to emerging developments (Dutton and Jackson 1987; Weick 1977). As selectivity is governed by knowledge or ideology filters (Boin & Van Eeten, 2013; Thomas & McDaniel, 1990), organizations tend to resist perceptions and conclusions that challenge their prevailing routine and frames of reference (Sitkin & Pablo, 1992; Staw et al., 1981). To the extent that extreme events challenge fundamental assumptions about risks and control (Boin & Lodge, 2016; Fischbacher-Smith, 2010; ’t Hart, 2013), they are likely to be excluded from consideration for organizational decision making.

Selective filtering of stimuli is particularly strong in public organizations which are highly constrained by organizational inertia and cultures of risk denial (Cigler, 2007; Ford & King, 2015a; Perrow, 1999). Boin and Eeten (2013) aptly exemplify how the entrenched safety process and culture of high reliability in the National Aeronautics and Space Administration (NASA) prevented “an accurate assessment of the impending threats to the safety of the doomed shuttle” (442) and caused the well-known *Challenger* accident. There are many reasons for this, but at base the failure to recognize risk and act has been explained by scarcity of evidence, blindness to evidence and uncertainty in assessing the relevance of evidence (Levitt & March, 1988).

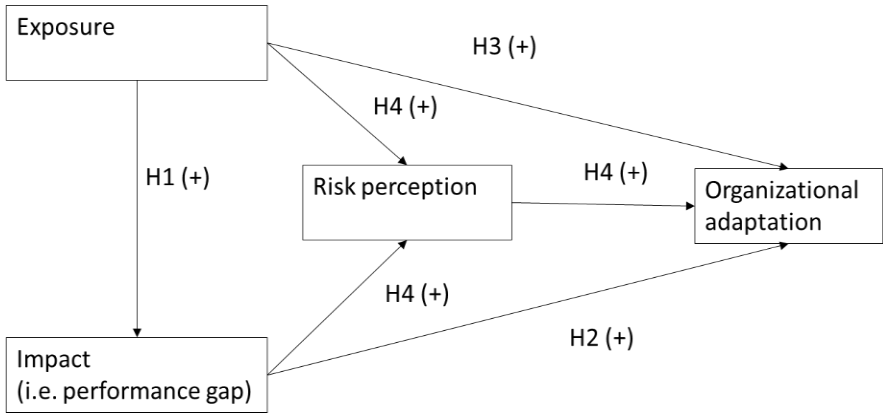
Therefore, before organizations engage in problem-solving behavior, they must first recognize the problem and then implement change (Daft & Weick, 1984; Sitkin & Pablo, 1992). To paraphrase Repetto (2009), just because organizations can adapt does not mean they will. The joint capacity to detect the out-of-ordinary developments and to recognize the inherent risk they pose creates a trigger that enables an organization to initiate an adaptation process (Comfort, 2007; Duncan, 1972; Dutton & Jackson, 1987). Given this, it is relevant to ask why some organizations are capable of perceiving the risks while others not. As a first step, emerging events or trends influence perceptions because of their potential to interfere with an organization's salient objectives (Daft & Weick, 1984; Schwenk, 1984). Extreme weather signals "uncontrollable" and "negative" threats (Dutton & Jackson, 1987; Kahneman & Tversky, 1979) to which some organizations are more sensitive than others. For example, organizations in the transportation, energy, water, and utility sectors may be particularly attuned to extreme weather signals because their operations hinge on the sound functioning of an exposed, interconnected and dispersed lifeline infrastructure (Boin & McConnell, 2007; Little, 2002; McDaniels et al., 2008). The threats intensify as an organization's experience with extreme weather events rises. As Berkhout (2012, p. 95) states: "…the more frequent, unambiguous and salient evidence from experience is, the greater the likelihood it will be recognized and interpreted as significant (by organizations)".

An organization's perception of risk is therefore a function of its experience with extreme events, in terms of both exposure and impact. Referring back to the discussion about the cognitive significance of risk perception, this suggests a process that links environmental stimuli to organization action through risk perception. It therefore stands to reason that risk perception positively mediates the effect of signals from extreme events on organizational adaptive responses. Based on this discussion I hypothesize

H4: An organization's risk perception positively mediates the effect of its experience with extreme events (i.e. exposure and impact) on its adaptive capacity building.

Figure 2 presents the conceptual model of the theorized relationships. I hypothesize that an organization will experience greater adverse impacts from increased exposure to extreme events. Exposure to extreme events can directly affect an organization's adaptive capacity building through a learning mechanism. The direct experience with extreme events (i.e. exposure and impacts) is also expected to trigger the organization's perception of risks concerning ongoing environmental change and ultimately lead to a higher level of organization adaptation.

Figure 2. Theoretical Model: Mediating Role of Risk Perception



Research Contexts

Extreme weather events pose a serious challenge to public agencies (Hodges, 2011; Meyer et al., 2012). Not only do they disrupt operations, impair service quality, and cause additional safety threats, but they also damage infrastructure and impose strain and stress on the state of good repair. As demonstrated by Hurricane Sandy and other recent weather-related disasters, weather can have significant ramifications for regional mobility and functioning of economic systems. How to effectively manage the risks of extreme weather is a question that often concerns public organizations and managers. This issue has become increasingly urgent with the likely increase in the frequency and intensity of extreme weather events (Folke, 2006; Hegerl et al., 2007; Parmesan & Yohe, 2003), such as floods, heat waves, and severe storms. While many agencies have long experience coping with weather disruptions, they are increasingly confronted with the challenge of identifying and developing appropriate longer-term adaptation strategies to address greater risk and uncertainty associated with extreme weather (Hodges, 2011; Meyer et al., 2013).

Selection of transit agencies offers several advantages for the study of extreme weather and adaptation. First, because transit agencies rely on an interdependent and interconnected network of exposed and dispersed capital assets for service delivery, they are particularly sensitive and susceptible to extreme weather. In addition to the impacts on infrastructure, extreme weather also diminishes the quality and reliability of transit services in the form of increased assess time, prolonged trip duration, declined service frequency and forced vehicle rerouting (Singhal et al., 2014). Given the interconnectivity and lack of redundancy in most current transit systems (Meyer et al., 2012), extreme weather results in substantial costs to network efficiency and mobility (Koetse & Rietveld, 2009). Moreover, weather-related disruptions disproportionately affect transit-dependent populations, such as the elderly, the poor and people with disabilities (Hodges, 2011). That weather impacts on the public transportation sector have received scant attention in the literature (Koetse & Rietveld, 2009) contributes further to the importance of this study.

Data

This study matches survey data collected from U.S. transit agencies 2016 with agency profile data obtained from the Federal Transit Administration’s National Transit Database (NTD) and demographic data taken from the U.S. Census Bureau. The full data set is used in a structural equation model (SEM) to test the hypotheses.

The NTD is the primary source for information and statistics on the U.S. transit system. I used the entire list of agencies in NTD to identify target agencies for this study. The target population included all major U.S. metropolitan fixed-route public transit agencies operating bus and/or rail transit services with an annual fare revenue of at least one million dollars in 2013. Agencies having a small vehicle fleet (i.e. 30 or fewer vehicles according to FTA's definition of small systems) or those run by universities were excluded from the study because of their limited capacity to undertake adaptation. Private companies (less than 30 in number) were not included because most manage transit systems in multiple cities and states. The resulting target population included 312 public transit agencies that satisfy the selection criteria.

Because different key decision makers within agencies likely have different perspectives on extreme weather events, vulnerability and risk depending upon professional background, experience and position in the agency, the study identified the leader manager in five different departments for inclusion: maintenance, operations, engineering, service planning and strategic planning. Names and contact information were collected using a protocol that included three methods: searching of online sources such as NTD, telephone calls to agencies and Freedom of Information requests. Because some agencies did not respond, refused to provide information or were non-reachable after repeated attempts, I had to drop 39 agencies resulting in a final agency-level sampling frame of 273 agencies (88% of the target population). As not every agency has all five departments or functions, the final individual-level sampling frame included 892 respondents (equivalent to an average of 3.3 people per organization).

The survey asked respondents about organizational experience with extreme weather events, perceptions about future weather risks, strategies employed to address extreme weather, and other questions concerning operation and management. Most questions were set within a two-year time frame to reduce recall bias. Survey instrument development was informed by a small set of interviews of transit managers in four agencies in different regions of the United States. The instrument was coded in Sawtooth Software® and administered online first as a pretest to 20 individuals from the sample and then to the entire sample. Administration of the full survey extended from April 28th to June 11th, 2016. An initial hard-copy notification letter, sent to each of the respondents informing them about the survey and requesting their participation, was followed 10 days later by an electronic invitation with web link to the live survey, username and password.

The survey was administered to an adjusted sample of 862 respondents after ineligible, retired, and non-contactable individuals were dropped. A total of 306 individuals completed the survey, yielding a survey response rate of approximately 35.5%. Of the 273 agencies surveyed, 199 provided at least one response (72.9%). Nonresponse bias analysis showed no difference by size or region ($\alpha < 0.05$) between responding agencies and either the sampling frame (n=273) or the target population (n=312). I merged the survey response data with other organizational data taken from NTD and 2010-2014 U.S. Census survey, including items such as organizational size and population density of the transit service area.

Measurement

Variables of primary interest: Organizational adaptation

An organization's adaptation strategy comprises a combination of adaptation measures and the distinct strategic goals they aim to accomplish (Hoffmann et al., 2009). For conceptual focuses, this paper examines two critical adaptation strategies relevant for addressing the potential threats posed by extreme weather to resource-intensive public service organizations: *vulnerability assessment* and *infrastructure enhancement*.

Vulnerability assessment. Public organizations must decide where to make improvements and how to apply scarce resources to address extreme weather (Henstra, 2010). Vulnerability assessment generates specific information necessary for making strategic decisions (Cairney et al., 2016; Somers & Svara, 2009). The information is particularly useful for organizations operating in tightly coupled and complex systems prone to cascading disruptions and failures (Little, 2002). Because people tend to underestimate the likelihood that natural hazards will have negative impacts on them (March & Shapira, 1987; Sitkin & Weingart, 1995), knowledge about system vulnerability can serve to raise vigilance and generate support for strategic changes to avert possible damage.

Vulnerability Assessment uses a composite of discrete response questionnaire items asking the respondent if his/her organization: 1) assessed the agency's vulnerability to extreme weather; 2) estimated the costs of responding to an extreme weather event; and 3) conducted or contracted research on the risks of extreme weather events (1=yes, 0=no). *Infrastructure enhancement* comprises four discrete items: 1) invested in weathersmart equipment and technologies, such as sensors that detect changes in pressure and temperature in materials; 2) invested in information and communication technologies; 3) invested in back-up power supplies and equipment; and 4) invested in weather-proof infrastructure improvement or retrofitting projects (e.g. strengthening parts of a building, improving stations or tracks). The two outcome variables—vulnerability assessment and infrastructure enhancement—are constructed as two latent factors underlying the corresponding binary indicators.

Infrastructure Enhancement. Resource-intensive public organizations often find their material resources and infrastructure insufficiently designed for and severely damaged by dramatic variability in weather conditions. In the case of transit agencies, for example, excessive rainfall can flood tracks, bus ways, tunnels and stations, and hurricanes often cause power disruption, vehicle crashes and signal damage (Hodges, 2011; Meyer et al., 2013). How far those effects propagate and how serious they become depend partly on whether or not countermeasures such as redundancy are in place (Little, 2002; McDaniels et al., 2008). Aged, under-designed and weather-sensitive critical infrastructure needs to be reinforce, upgrade or replaced such that it is resistant to extreme events (Fankhauser et al., 1999; Hodges, 2011).

The variable *Exposure* is a composite index of a set of questionnaire items about the organization's experience with extreme weather by event type, where extreme weather was defined in the survey as "unusually severe storms, floods, heat waves or other weather incidents that lie outside of historical norms or experience". Respondents were asked: "During the last two years, about how many times have the following extreme weather events occurred in your transit service area?” The list of extreme weather events includes: extreme cold temperatures, extreme heat waves, floods, hurricanes/tropical storms, severe rainstorms/thunderstorms, tides/storm surges, extreme high winds, tornadoes, and extreme snow storms (Scale: 0=never, 1=once, 2=two to three times, 3=more than three times). Although the data are limited, the frequency of extreme events as defined in the survey provides a reasonable measure of exposure that is sufficient to trigger responses.

For each type of event experienced, respondents were subsequently asked to rate the adverse *Impact* on their organization. The question asked: “Considering the extreme weather events that have happened in your area in the previous two years, has the level of adverse impact been catastrophic, major, moderate, minor, or no impact?” (Scale: 0=no impact, 1=minor, 2=moderate, 3=major, 4=catastrophic). The variable *Impact* is measured as the mean response across all events.

The two-year time span was designed in the survey to reduce recall bias and as a stable proxy measure of the longer-term location-based pattern of extreme weather the agencies experienced. Weather patterns are fundamentally localized and relatively consistent over the short term. NOAA extreme weather data confirm that while extreme weather trends are gradually increasing over the long term, they are relatively stable within a short segment of time such as two to five years (NOAA, 2016; Smith, 2017). Therefore, the two-year snapshot provides a strong location-based measure of extreme events. Organizational adaptation -- non-incremental changes from existing routines -- needs to happen relatively rapidly enough so that agencies are able to leverage windows of opportunity opened by major extreme weather events and their impacts. Kimrey's (2016) extensive literature review demonstrates that the political issue-attention for extreme events usually lasts only two to three years. The required timeliness of adaptive responses strengthens the confidence about using the two-year time frame for exposure and impact to test the hypotheses.

Risk perception was measured as an index of three survey questions asking about the level of agreement with the statements: 1) "Most people in my agency recognize that extreme weather events are becoming more frequent."; 2) "My agency is increasingly concerned about the impact of extreme weather events on our transit infrastructure."; and 3) "My agency is increasingly concerned about the impact of extreme weather events on our transit operations." (Scale: 1=strongly disagree, 2=disagree, 3=neither disagree nor agree, 4=agree, 5=strongly agree). Risk perception is constructed as a latent factor underlying the three ordinal response variables. The measure is based on responses of upper-level managers reporting about their organizations. The top managers surveyed serve in departments that are most affected by extreme events. I adopted an upper echelon perspective for conceptualizing the organizational risk perception measure because top management cognitions can causally determine organizational strategic choices and outcomes (Hambrick, 2007; Hambrick & Mason, 1984). In their classic work on organizational interpretation, Daft and Weick (1984) specifically stress the role of top management in synthesizing information from nested sub-systems and formulating the interpretation for the organizational system as a whole. They note (1984, p. 285): "when one speaks of organizational interpretation one really means interpretation by a relatively small group at the top of the organizational hierarchy”.

Control Variables

Given the variation in complexity of transit systems, the estimations included control variables about the agency and its service area resepectively. About the agency, *Bus Only* is coded as 1 if the agency operates bus services but not heavy or light rail. *Infrastructure-based capacity* is an index of responses to one multi-item question asking respondents to assess the quality of the transit-relevant infrastructure in their service area. Items included: bus transit services, bus station structures and shelters, commuter rail transit services, rail control systems, rail bridges, structures and tunnels, rail track, switches and track work, rail station structures and platforms, streets, roads and highways, roadway bridges, structures and tunnels, transit facility ventilation systems, transit maintenance equipment, electrification/power system, communication systems, drainage systems, and revenue/fare collection systems. Items were automatically populated in the survey depending upon the type of transit services (e.g. bus only system respondents did not receive the rail-specific questions) and respondents were given definitions of the five quality categories (Scale: 1=poor, 2=marginal, 3=adequate, 4=good, 5=excellent; see Appendix A for definitions). To account for the political control the agency is under, Director is coded 1 if the agency has a politically appointed and 0 otherwise.

Additional data to capture agency characteristics were collected from the National Transit Dataset (NTD) and the 2010-2014 U.S. Census, matched by county code.

Authority is coded 1 if the agency is an independent transit authority and 0 if the agency is affiliated to a city or state government. Organizational Size, used as a proxy of an organization's comprehensive capacity for adaptation, is measured by the natural log of an agency's annual total funding in 2013, including funding from directly generated revenue as well as funding from local, state and federal governments.

With regard to the agency's service area, Density is the natural log of service population normalized by service area. Commute Time serves as an indicator of the demand for transit services and uses the mean travel time to work in minutes. Median Household Income is the natural log of median household income in the county the agency is located. Finally, a set of the dummy variables (1=Yes, 0=No) were used to indicate the Census region the agency is located in: Northeast, Midwest, South and West respectively.

Descriptive statistics for all variables except risk perception are displayed in Table 1. Since the mean and variance of ordinal variables have no meaning (Jöreskog, 1994), I report the number of respondents and the univariate proportion for each category of the 3 indicators in Appendix B.

An overwhelming majority of organizations, over 95%, have experienced at least one extreme weather event and suffered the impacts during the past two years. Overall, organizations are relatively neutral about their perception of risks associated with extreme weather events. Approximately 25% agencies provide rail services and 64% agencies are independent transit authority organizations.

Table 1. Descriptive Statistics

Variable	Mean	SD	Min	Max	Size
Vulnerability Assessment					
Vulnerability Assessment 1	0.55	0.50	0	1	299
Vulnerability Assessment 2	0.25	0.43	0	1	300
Vulnerability Assessment 3	0.09	0.28	0	1	303
Infrastructure enhancement					
Infrastructure enhancement 1	0.11	0.31	0	1	299
Infrastructure enhancement 2	0.62	0.49	0	1	302
Infrastructure enhancement 3	0.72	0.45	0	1	301
Infrastructure enhancement 4	0.28	0.45	0	1	301
Exposure	9.94	4.94	0	24	304
Impacts	1.29	0.66	0	3	295
Bus Only	0.74	0.44	0	1	304
Infrastructure-based capacity	3.20	0.60	1	5	304
Authority	0.64	0.48	0	1	304
Organization size	17.33	1.49	15	23	304
Density	7.50	1.29	-0.68[1]	12	304
Director	0.17	0.38	0	1	287
Median household income (log)	10.89	0.21	10	12	304
Commute time	24.40	4.71	15	42	304
Northeast	0.13	0.33	0	1	304
Midwest	0.22	0.42	0	1	304
South	0.33	0.47	0	1	304
West	0.32	0.47	0	1	304

Analysis and Results

Structural equation modeling

Because the model assumes multiple relationships and mixes latent and observed variables, structural equation modeling (SEM) is a suitable analytic method for this study (MacKinnon, 2008). SEM is preferred over regression analysis because of its capacity to estimate constructs by separating the unique variance of observed items from shared items (Kline, 2015). It also has the advantage of incorporating indirect effects when

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[1] The negative log value of density comes from three observation within the same agency, with a density of about 0.50. However, the organization has normal values in other organizational attributes, so we kept the three observation in the analysis. For robustness check purposes, the model was also run without the three observations and the results did not qualitatively change.

mediating variables are included. Because the three adaptation measures and risk perception were constructed using categorical variables, the relationships between the manifest variables and the latent factor are considered nonlinear. A common practice to account for the non-linearity is to replace the observed categorical variables with their underlying latent and continuous factors (Hoyle, 2012). Therefore, I analyzed the model using the weighted least square means and variance adjusted (WLSMV) estimator in Mplus 7.4 (Muthén, 1993). The WLSMV estimator uses a probit function to link the underlying continuous latent variable to the observed categorical indicators, allowing analysis of relationships between the underlying latent variables. Compared to the commonly used maximum likelihood (ML) estimation, WLSMV estimation has more accurate factor loading and model fit when the number of categories is small (e.g. 2 or 3 categories) (Beauducel & Herzberg, 2006).

Additionally, because the transit agency is the unit of analysis and there is more than one response from some responding agencies, clustered standard errors by agency were used to account for the nested data structure (Wooldridge, 2003). I included all control variables in all paths to estimate the relationships of primary interest. I also weighted the observations to ensure equal representation of each agency in the analysis.

Measurement Model

A confirmatory factor analysis (CFA) on the categorical indicators shows good model fit (RMESA= 0.050 with 90% CI [0.028, 0.071], CFI=0.984, TLI=0.978, WRMR= 0.811). The fit indices satisfy the general cutoff points for measurement models with WLSMV estimation: RMSEA ≤ 0.05, CFI ≥ 0.96, TLI ≥ 0.95, and WRMR ≤ 1.0 (Yu, 2002). The chi-square test statistic ($\chi2$=56.672, df=32, p-value=0.0046) indicates unsatisfactory fit, but can be attributed to its sensitivity to sample size and is usually not considered sufficient evidence to reject the model when contrary to other fit indices (West et al., 2012).

Table 2 shows the standardized factor loadings for each scale. The R-square values indicate how much variance in the indicator is explained by the underlying latent factor. The standardized factor loadings are relatively large, ranging from 0.65 to 0.96. The Wald tests for each pair of the latent factors are all highly significant with p-value < 0.000. Therefore, both convergent and discriminant validity are achieved for the latent constructs.

Table 2. Measurement Model

Factor and indicators	Estimate	S.E.	P-value	R-Square
Vulnerability Assessment				
Vulnerability Assessment 1	0.681	0.075	0.000	0.464
Vulnerability Assessment 2	0.783	0.066	0.000	0.613
Vulnerability Assessment 3	0.846	0.095	0.000	0.716
Infrastructure enhancement				
Infrastructure enhancement 1	0.649	0.096	0.000	0.421
Infrastructure enhancement 2	0.698	0.072	0.000	0.487
Infrastructure enhancement 3	0.800	0.068	0.000	0.640
Infrastructure enhancement 4	0.771	0.069	0.000	0.594
Risk perception				
Risk perception 1	0.822	0.028	0.000	0.676
Risk perception 2	0.704	0.036	0.000	0.496
Risk perception 3	0.964	0.026	0.000	0.929

Structural model

There are 306 responses (35.5% total response rate) from 199 transit agencies (72.9% of all agencies have at least one response) in the dataset. The missing values in two cases resulted in a final set of 304 observations from 199 transit agencies, which I used in the entire SEM model. The structural model achieved good model fit ($\chi 2$=151.263, df=116, p-value=0.0155, RMESA= 0.032 with 90% CI [0.015, 0.045], CFI=0.966, TLI=0.950, WRMR= 0.795). Those indices satisfy the general cutoff points for structural models using WLSMV estimation: Chi-P $\geq$ 0.01, RMSEA $\leq$ 0.06, CFI $\geq$ 0.96, TLI $\geq$ 0.95, and WRMR $\leq$ 1.0 (Yu, 2002).

Table 3 reports the SEM results. The parameter estimates are followed by the standard errors in the parentheses. Northeast was used as the baseline for the effects of the region dummies. It is important to note that Impact is positively associated with an organization's exposure to extreme weather, yet negatively associated with its infrastructure quality. This is consistent with the theoretical framework which expects greater capacity to buffer the negative impacts of extreme events on the affected organization.

Meanwhile, among the control variables only organizational size had a statistically significant effect on *Risk Perception* such that risk perceptions are higher in larger organizations. Among the control variables, *Organization Size* is positively associated with vulnerability assessment but not associated with capital assessment. Results also show that independent organizations (transit authority agencies) are less likely to conduct vulnerability assessment compared to agencies affiliated with a city or state government, and that agencies with higher *commute time* are more likely to undertake infrastructure enhancement.

Table 3. SEM Results

Effects on Impact	**Impact**	
Exposure	**0.265 (0.068)*** **	
Bus Only	**-0.22 (0.06)*** **	
Infrastructure Quality	**-0.155 (0.065)***	
Authority	0.053 (0.069)	
Organization Size (log)	-0.057 (0.073)	
Director	0.109 (0.065)	
Density (log)	-0.057 (0.073)	
Median Household Income (log)	0.095 (0.082)	
Commute Time	0.017 (0.094)	
Midwest	-0.113 (0.099)	
South	-0.156 (0.11)	
West	-0.223 (0.118)	
Effects on Risk Perception	**Risk Perception**	
Exposure	**0.212 (0.083)**	
Impact	**0.155 (0.067)**	
Bus Only	0.028 (0.098)	
Infrastructure Quality	-0.128 (0.076)	
Authority	0.021 (0.068)	
Organization Size (log)	0.023 (0.100)	
Director	0.044 (0.075)	
Density (log)	0.028 (0.039)	
Median Household Income (log)	0.047 (0.082)	
Commute Time	0.142 (0.095)	
Midwest	-0.043 (0.124)	
South	0.036 (0.132)	
West	-0.141 (0.139)	
Direct Effects on Organizational Adaptation	**Vulnerability Assessment**	**Capital Investment**
Exposure	0.120 (0.104)	**0.269 (0.097)**
Impacts	-0.045 (0.071)	0.040 (0.074)
Risk Perception	**0.341 (0.074)*** **	**0.244 (0.094)** **
Bus Only	-0.039 (0.084)	0.017 (0.094)
Infrastructure Quality	0.002 (0.088)	0.028 (0.078)
Authority	**-0.198 (0.091)***	0.039 (0.095)
Organization Size (log)	**0.339 (0.097)*** **	**0.270 (0.107)**
Director	0.016 (0.081)	0.036 (0.088)
Density (log)	0.037 (0.082)	**-0.192 (0.077)***
Median Household Income (log)	0.033 (0.089)	-0.08 (0.105)
Commute Time	0.003 (0.104)	0.132 (0.112)
Midwest	0.07 (0.105)	-0.058 (0.116)
South	0.052 (0.129)	-0.029 (0.134)
West	0.033 (0.127)	0.114 (0.135)

$^{\#}$p<0.10, *p<0.05, **p<0.01, ***p<0.001; Unstandardized coefficients are reported
304 observations from 199 agencies; Reference category: Northeast

Testing hypotheses

The relationships among variables of primary interest are presented in Figure 3. Standardized coefficients are reported to facilitate comparison of the relative effect of each predictor.

Hypothesis 1 postulates a positive relationship between an organization’s exposure to extreme events on the impacts it experienced. The analysis supports this hypothesis, with a significant and positive effect of exposure to extreme weather on impacts. Hypothesis 2 posits that as an organization suffers greater impacts from extreme events, it is more likely to build adaptive capacity in preparation for future shocks. The results show non-significant effects of impacts on the two adaptive strategies, therefore suggesting no support for Hypothesis 2.

These findings indicate that an organization’s increased exposure to extreme events leads to greater negative impacts, but the impacts do not directly lead to organizational adaptive responses. I interpret this finding by separating the impacts organizations suffer from their exposure to extreme events and their learning and shift in decision making derived from the experience. Longer-term initiatives that are adaptive may require organizations to perceive a substantially different environmental context in which the harm associated with maintaining the status quo is greater than the harm associated with adaptive change. As exposure increases and causes more significant impacts, only those organizations that cognitively process a different level of risk will adapt.

There can be an alternative explanation for this finding: it is possible that impact can both motivate and undermine an organization's capacity to adapt. This may be especially true when organizations focus on immediate survival and on maintaining the status quo without embracing a longer-term vision to build adaptive capacity. The "hold-the-line" practice has been widely observed as diminishing capital resources for longer-term and hampering an organization's learning and adaptation from recurring major perturbations (Adger et al., 2011; Linnenluecke et al., 2012; Winn et al., 2011).

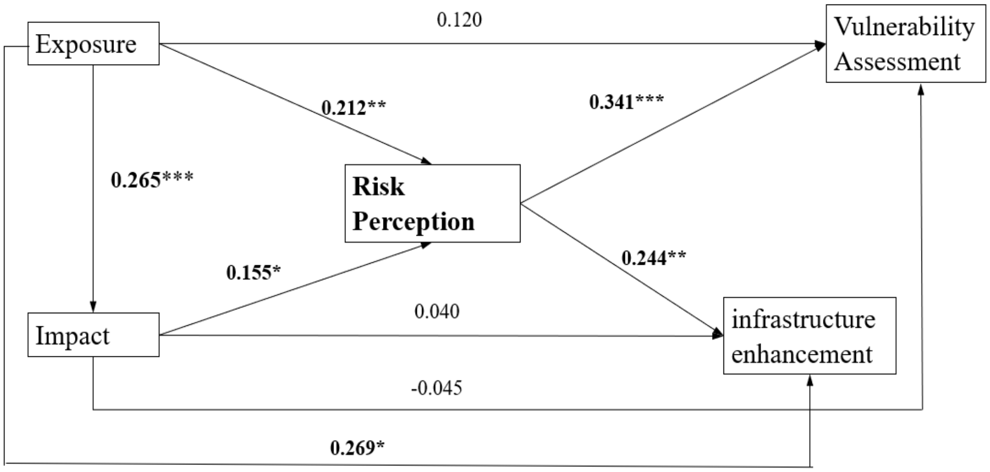
Hypothesis 3 expects that exposure to extreme events will directly affect an organization's adaptive capacity building due to the learning mechanisms. Exposure turns out to be a positive predictor of an organization's infrastructure enhancement and a nonsignificant predictor for vulnerability assessment. Thus, Hypothesis 3 is partially supported.

Hypothesis 4 focuses on how risk perception mediates the effect of an organization's exposure to and impact from extreme events on its adaptive responses. The path coefficients from exposure and impacts to risk perception are significant and positive, so are the effects of risk perception on an organization's implementation of vulnerability assessment and infrastructure enhancement.

In light of the asymmetry of the distribution of the product of multiple path coefficients, I applied bootstrapping to derive the confidence interval of the mediated effects through risk perception (MacKinnon, 2008). There are two paths through which exposure affects adaption via risk perception: one path from exposure to risk perception and then adaptation, and one path from exposure to impact and then risk perception and adaptation. The results indicate that an organization’s risk perception effectively mediates the effect of exposure on vulnerability assessment (standardized β=0.089, 95% CI= [0.022, 0.173]) and infrastructure enhancement (standardized β=0.061, 95% CI= [0.003, 0.139]). It also shows that risk perception significantly mediates the effect of impact on vulnerability assessment (standardized β=0. 054, 95% CI= [0.003, 0.113]) and infrastructure enhancement (standardized β=0.037, 95% CI= [0.002, 0.187]). Therefore, the model shows consistent support for Hypothesis 4.

The results for the hypothesis testing, particularly with regard to Hypothesis 4, points to the significant effects of risk perception in converting the signals from an organization’s environment to its adaptation responses.

Figure 3. SEM Analysis Result: Mediating Role of Risk Perception



*p<0.05, **p<0.01, ***p<0.001
Standardized coefficients are reported

Robustness Check

One major limitation of the current analysis is the reliance of survey data measured at one point of time for the key variables, making it difficult to disentangle the temporal sequence and relationships among the factors. For instance, it is unclear whether the agencies' experience with extreme events preceded their risk perception or adaptation responses so as to cause behavioral changes. Absent further information, it could be possible that the agencies adopted the adaptation practices at the beginning of the two years examined in the survey, followed by their exposure to and impact from extreme weather events that occurred at the end of the two years examined.

In order to provide more temporal clarity and validate the mediation effects of risk perception, I conducted an alternative model using data on the weather-related declarations of major disasters and emergencies at the Federal Emergency Management Agency (FEMA). Following McGuire and Silvia (2010), the analysis uses the total number of weather-related disasters in the past five years from 2012 to beginning of April in 2016. Using this metrics, *exposure* ranges from 0 to 5, at a mean of 1.03 and standard deviation of 1.15. This alternative measure has a narrower scope and smaller mean compared to the measure acquired from the survey, as extreme weather events have to be of a sufficiently high scope, magnitude and impact to qualify for declarations. Lacking corresponding data on the impacts of the major weather disasters or emergencies on the survey transit agencies, the analysis proceeded without including the variable *impact* in the theoretical model. It examined the relationships among exposure to extreme events, risk perception and adaptation. Similar to the approach in the original model, the SEM estimation includes all the control variables in each of the separate paths to ensure consistency.

Table 4. SEM Results for the Alternative Model

Effects on Risk Perception	Risk Perception	
Exposure	0.170 (0.081)*	
Effects on Adaptation	**Vulnerability assessment**	**Infrastructure enhancement**
Exposure	-0.159 (0.104)	-0.028 (0.087)
Risk Perception	0.377 (0.075)***	0. 315(0.090)**

Table 4 shows the results on the key variables in the model while abbreviating the findings on the control variables for presentation purposes. The model shows that exposure has a positive effect on risk perception, which in turns positively predicts organizational adaptation through both vulnerability assessment and infrastructure enhancement. The bootstrap method confirms the mediation effects of risk perception on vulnerability assessment (standardized β= 0.064, 95% CI= [0.009, 0.118]) and infrastructure enhancement (standardized β=0.053, *****, 95% CI= [0.003, 0.184).

Discussion

This study sets out to examine public organizations' experience with extreme events and to explain the variations in their adaptive responses. The conceptual framework (Figure 1) integrates organizational adaptation and learning literature to establish an initial organizational response model that captures the essence of longer-term adaptation to reduce vulnerability to recurring extreme events. The theoretical model (Figure 2) addresses key interrelated questions surrounding the reasons why some public organizations adapt to extreme events and others do not, or do so more slowly. The model posits that exposure leads to capacity-moderated impacts (i.e. performance gap), but subsequent adaptation through capacity development is mediated by organization risk perception.

The analysis estimated two empirical models, one drawing all key variables from a 2016 national survey on US transit agencies and another using FEMA disaster declarations to measure agencies' exposure to extreme events in order to validate insights from the previous model. Combining insights from both models, the findings can be summarized as follows. An organization's increased exposure to extreme events can lead to increased impacts. Increased impacts from those events do not directly lead to organization adaptation. Both exposure to and impact from extreme events, however, can motivate adaptive behavior through raising organizational risk perception. This means that even if organizations have experienced increased extreme events and suffered more impacts, as long as they do not recognize the systematic pattern of risk and its continuance in the future, they are unlikely to commit resources and efforts to undertake adaptation and build capacity against future shocks. The uncertainty about the future foresight of risks, upfront costs required of adaptation as well as the undervaluation of benefits to be derived from those efforts makes risk perception a cognitive precondition for paradigm shift toward adaptation in a changing environment.

Conclusion

The study contributes to the broader literature in several ways. It captures the common patterns across extreme events and takes an organizational approach to address the challenges associated with adaptation to reduce vulnerability in public organizations.

This responds to the recent literature by connecting the study on extreme events with organizational theory to enable a more systematic and generic understanding and treatment of extreme events (Boin & Van Eeten, 2013; Christensen et al., 2016; Fischbacher-Smith, 2010; Roux-Dufort, 2007). As such, this research provides one of the few theoretically informed, quantitative studies on core topics concerning extreme events and organizational resilience (Boin & Van Eeten, 2013; Christensen et al., 2016).

The findings, in conjunction with the broader conceptual model, can be interpreted as evidence for perception-mediated learning in which adaptation requires not simply exposure to a phenomenon, but also the cognitive understanding that longer-term performance of an organization depends on some form of purposive adaptation. Both exposure and the effects of exposure on performance create opportunities for organizations to raise questions about their ability to perform. When severe events increase in frequency, and when emergency responses become more frequent, ineffective and costly, organizations begin to make sense of the pattern of the challenges and realize that longer-term investment in capacity is necessary for sustainable operation.

The study may point to a cognition-based stepwise learning model in which organization commitment to change is incremental and depends on the recognition that exogenous shocks are systematic, solvable and require new modes of response. A baseline exists when an organization responds to extreme events using routinized or programmed emergency response actions. A higher frequency of exogenous shocks may increase familiarity with performance gaps, demonstrate fundamental limitations in capacity and stimulate learning manifested as increased perceptions of risk. Increased perception of risk may facilitate organizational commitment to undertake some form of adaptive behavior to reduce vulnerability.

Practically, the study reveals the pitfalls in assuming that organizational adaptation to extreme events will occur spontaneously with growth in impacts from extreme events. Instead, the effect of extreme events on adaptation behavior is most likely channeled through a cognitive process wherein the risks are perceived and appropriately interpreted by the affected organization. The significant role of risk perception gives important room for management intervention. Since people are more sensitive to threats than opportunities in undertaking larger-scale internal responses (Dutton & Jackson, 1987), managers can affect organization-wide risk perceptions by actively recognizing and framing threats, seeking to systematically collect and interpret new information and establishing it as part of the organizational memory. Managers can prime organizational members to better identify extreme events, recognize patterns and develop solutions that reduce threats (Weick, 1977). Managers may adopt a participatory approach to promote shared understanding and interpretation of extreme events, and pave the way for potentially adaptive solutions. The participatory efforts can be more successfully implemented by highly trusted individuals in the organization (Dutton & Jackson, 1987).

A few limitations of this study are acknowledged. The empirical analysis focuses on transit agencies, which may reduce generalizability of the findings of this study to other organizations. However, to some extent, the national-level approach in which agencies are surveyed across a wide range of weather conditions and extreme events and the similarity of transit agencies with many other resource intensive public agencies (i.e. utility, power, waste management) reduces this concern. Reliance on survey data for the construction of key variables in the estimation may raise concerns about common source bias. The use of survey data is valid for two reasons. First, other sources of data on organizational experience with extreme weather events, especially impacts, are difficult to collect. Additionally, because risk is fundamentally a perceptual construct, it may be best to rely on perceptual measures collected in surveys. Previous studies have suggested that self-reported data can provide valid indicators of organizational properties (Lincoln and Zeitz 1980; Moynihan and Pandey 2005; Pandey and Wright 2006). That many coefficients in the empirical model are low and not significant can also help alleviate the common method bias concern (George & Pandey, 2017). Results from the alternative modeling using FEMA’s disaster declaration data also provides additional defense.

Another limitation has to do with the use of cross-sectional data to test the mediation effect. The data availability prohibits a three-wave longitudinal data to effectively test mediation effects as suggested by the literature (Cole and Maxwell 2003). However, given the scarcity of data on how public organizations adapt to extreme events, a growing and salient challenge to public organizations worldwide, the survey and analysis still shine light on this important topic. Moreover, a major concern with longitudinal data relates to the difficulty of correctly specifying the time lag between the data collection points such that the data actually captures meaningful variation in the variable of interest, instead of stochastic changes due to time lapse (Cole & Maxwell, 2003; Ployhart & Vandenberg, 2010). In studies of adaptation, the time lag between extreme weather exposure, impact and risk perception is difficult to pinpoint (Berkhout, 2012; Christianson et al., 2009; Weick, 1993). This makes specification of the exact duration of the time lag challenging such that longitudinal data and methods may not be necessarily superior. To the extent that the time interval is small, the use of cross-sectional data instead might be a viable representation of reality in this case (Wong and Law 1999).

This study raises several new questions for further work. Are public organizations actually learning from increasingly frequent and severe events in ways that fundamentally alter investment patterns over time? This study is suggestive, but not conclusive. What other adaptation strategies are organizations undertaking besides those examined in this study? In large complex organizations, at what point do occasional shocks become recurrent; at what point do frequency, magnitude and scope force organizational attention? Is there a stepwise learning process in which commitment is contingent on risk perception and adaptive actions are nested? Given the rise in ‘extreme events’ that cause significant disruption (Boin & Lodge, 2016; Comfort et al., 2012; Tierney, 2014) future research should begin to address these issues.

Next Steps

A key feature of the perception-mediated learning is the accumulative effects of learning: repeated exposure to extreme events calls into question the fundamental assumptions organizations hold about the nature of risk; aggravated impacts from those encounters expose underlying vulnerability and challenge organizational beliefs about controls and their performance under extreme circumstances. This model articulates how risk perception occurs or grows. It is less explicative, however, on the causal mechanisms through which risk perception leads to adaptation. For example, it does not explain why adaptation does not occur when perceptions of risk are high (Birkland, 2006; Mockrin et al., 2018). Set against complex socio-political and institutional contexts, the model's expectation that public organizations have sufficient capacity to implement change when desired deserves reconsideration. After all, adaptation is as much about decision making as the power to implement those decisions (Nelson et al., 2007). The examination of only direct experience with extreme events further sets organizations separate from their embedded contexts. This theorizing deviates from the abundant evidence of indirect learning in which organizations accumulate information and knowledge from other organizations and apply them to their decision contexts (Berry, 1994; Nathan & Kovoor-Misra, 2002). The second essay seeks to address the limitations by incorporating the behavioral and contextual factors in the examination.

CHAPTER 3

WHAT EXPLAINS THE EMERGING YET LIMITED ADAPTATION TO EXTREME EVENTS IN PUBLIC ORGANIZATIONS: A MIXED-METHOD APPROACH

Introduction

The increasing susceptibility and vulnerability of public organizations to extreme events is well established in theory and practice (Comfort, 2002; McEntire, 2008; Tierney, 2014). Extensive studies in various disciplines have pointed out the pitfalls in managing immediate reactions during and after extreme events and relying on contingency plans to deal with future shocks (Adger et al., 2011; Linnenluecke et al., 2012; Smit & Wandel, 2006; Winn et al., 2011). The “quick fixes” and worst-case scenario planning fly in the face of the organization’s growing vulnerability as extreme events intensify. Things that do not go wrong during a particular event can hide substantial vulnerability (Comfort, 2002; Perrow, 1999). Threats to safety and reliability continue to build up without notice until being activated by some trivial triggers, with sobering consequences for the affected organization and beyond (Cedergren et al., 2019; McDaniels et al., 2008).

Public organization efforts have long concentrated on managing the ex-post actions, giving little consideration to reducing vulnerability in advance (Birkland, 2006; McEntire, 2008). As vulnerability continues to build through recurring strains from extreme events, the organizations often find themselves surprised by and unprepared for escalating demands in extreme events (Comfort et al., 2012; Farazmand, 2007). More recently, we see evidence of early adapters undertaking proactive adaptation to address challenges associated with extreme events. This is exemplified by their incorporation of those concerns in long-range plans, infrastructure design and construction, asset management and interorganizational coordination (Boin & Van Eeten, 2013; Hill & Engle, 2013; McDaniels et al., 2008; Miao et al., 2018a). In a world characterized by inertia and cultures of risk denial (Cigler, 2007; Ford & King, 2015a; Perrow, 1999), what drives adaptation among the early adopters? And what explains the slow take-up of adaptation in most public organizations?

Previous studies have addressed different aspects of the preconditions for adaptations. Some emphasize a conducive sociopolitical and institutional environment (Crow et al., 2018; Miao et al., 2018b; Mockrin et al., 2018), others focus on the behavioral and cognitive determinants for adaptation such as risk perception and perceived capacity (Grothmann & Patt, 2005; Zhang et al., 2018), and still others highlight the influence of other organizations and social learning (Hovik et al., 2015; Nathan & Kovoor-Misra, 2002; Orsato et al., 2018). Absent from the literature is an integrated approach to explore how behavioral, institutional and social forces interact and coalesce to produce adaptive responses among public organizations. The integration is expected to shed important light on central puzzles in the adaptation literature. For example, while it is a broad consensus that the experience with extreme events is a powerful drive for adaptation, the mechanisms by which this occurs is less clear. A prevailing explanation is that extreme events and the resulting damage heighten organizations' perception of risks and recognition of the need for adaptation (Berkhout, 2012; Demski et al., 2017; Linnenluecke et al., 2012; Miao et al., 2018b). Nevertheless, if risk perception is key, why would high risk perception sometimes fail to produce adaptation (Birkland, 2006; Grothmann & Reusswig, 2006; Mockrin et al., 2018)? Under high risk perception, how does adaptation occur? Some scholarship underscores the role of disasters as focusing events to drive change (Aamodt & Stensdal, 2017; Birkland, 2006; Birkmann et al., 2010; Kingdon, 1984; Michaels et al., 2006), but why is adaptation still limited after repeated disasters and some catastrophic consequences?

Public organization adaptation to extreme events unfolds in a complex, dynamic and interdependent system consisting of the environmental hazards, organizations, policies and networks (Adger et al., 2005; Birkland, 2006; Johnson et al., 2005). Explicating how organizations respond to threats from their environment given the barriers and facilitators they face is crucial to understanding the limited emergence of adaptation among public organizations. This study combines agent-based modeling and qualitative interviews to advance theory development that articulates the micro-level processes behind organizational adaptation to extreme events. Building on extant theories and empirical studies, it incorporates risk perception, risk tolerance, opportunities to overcome financial constraints and social learning to examine the interplay between cognitive and non-cognitive factors involved in adaptation. To ensure the empirical relevance of this study, the theories and constructs are applied to public transit agencies' adaptation to extreme weather events.

The end product contributes a series of refined propositions about the microlevel processes that lead to adaptation to extreme events in public organizations. In particular, the analysis suggests that risk perception needs to be examined relative to risk tolerance to determine organizational motivation for adaptation, and highlight the criticality of the coupling between risk-directed motivation to act and opportunities to enable adaptation. Moreover, the refined propositions and the subsequent experiments help inform public management and policy by uncovering micro-mechanisms as leverage points to promote the field-level diffusion of adaptation.

Research Approach

My research approach consists of three broad steps. First, it surveys and synthesizes the existing literature to identify factors and theoretical propositions about the microlevel mechanisms that lead to adaptation in public organizations. The literature review will also extract the system features that can serve as the building blocks for the theory development. In doing so, this study follows Colyvas and Maroulis (2015) to identify two types of insights that can be drawn from an extensive examination of the existing literature. One is a system feature which they define as the "a characteristic of the underlying social system that can be used to guide modeling decisions" (p.604). The other type of insights is proposition, a theoretical statement relating one factor in the system to the outcome of interest.

Second, to ensure its empirical relevance, the theory development is grounded in a particular context: transit agencies' adaptation to extreme weather through resilience-enhancing infrastructure enhancement. Importantly this includes semi-structured interviews with transit agency managers to inform an operational understanding of the adaptation process and refine the model's causal mechanisms.

Third, the model development combines insights from both the extant literature and the interviews to link the micro-level behavior to the aggregated pattern of adaptation through the use of computational modeling. The process of organizational adaptation in the interrelated and overlapping systems is difficult to disentangle in the real world. Traditional analytical and statistical approaches are limited in their ability to investigate multiplex, interdependent and simultaneous processes. Computational simulation has therefore gained traction as an attractive alternative to study the complexity and simultaneity of organizational behavior (Burton & Obel, 2011; Harrison et al., 2007).

With the aim of theory development in mind, this essay consequently adopts a pattern-oriented approach to render a "simplified representation" of the real systems using only key structures and elements to reproduce the fundamental properties of the underlying context (Railsback & Grimm, 2011). The model will include the key lower-order characteristics and behavioral rules and seek to qualitatively match them with the higher-order outcome of interest (Gilbert, 2008). I describe the particular class of computation modeling -- agent-based modeling (ABM) (Wilensky & Rand, 2015) – in more detail below.

Agent-Based Modeling

An agent-based model consists three central building blocks: 1) the agents, including individuals and collective entities such as organizations and groups , 2) the environment in which the agents operate, 3) the interaction among the agents. The agents are represented as autonomous individuals capable of receiving and responding to inputs from their local environment as well as other agents. The program endows the agents with selected attributes and a set of rules to guide their behavior. The model starts with an initial configuration of the agents' attributes, where the parameter values are derived from empirical observations or theoretical rationale (Wilensky & Rand, 2015). ABM simulates the studied process in discrete equidistance time steps (Gilbert, 2008). At each time step, agents cycle through all the applicable behavioral rules in a predetermined sequence. Those actions lead to an end state for the current period which becomes the initial condition for the next period. The process repeats and leads to a certain outcome after a researcher-defined number of iterations.

In agent-based models, the agent-to-agent and agent-to-environment interactions induce effect on the aggregate pattern at the system level that cannot be attributed to the individual behavior of the agents (Gilbert, 2008). Researchers can modify agents' behavioral rules or alter the initial condition to reveal effects of micro-level changes on the system-level. As such, agent-based models are often developed to discover plausible explanations for emergent phenomena or explore the boundary conditions of empirical observations (Epstein & Axtell, 1996). Generating emergent collective behavior from the bottom up, ABM allows exploration of non-linear dynamics that can be characterized by threshold or if-then statements. It is also bears the potential to investigate social processes where agents are heterogenous, interact in complex, different and nonlinear ways, or exhibit temporal correlations in their behavior such as learning and adaptation (Bonabeau, 2002).

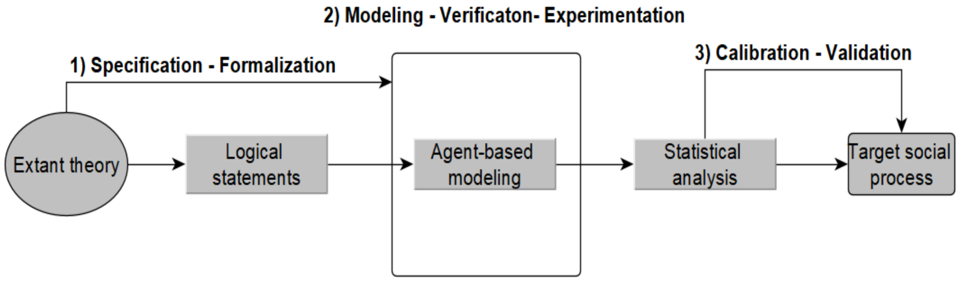
Given the novelty of ABM in public administration research, a few limitations of ABM as a research tool and its application to social sciences are acknowledged. Because simulation models produce results through numerical derivation (Chang & Harrington, 2006), one common skepticism is that researchers can always manipulate the inputs to get any desired outputs. However, ABM explicitly incorporate stochasticity by sampling values from distributions for the probabilistic components so that the behavior of the model depends on chance to some extent (Harrison et al., 2007). Additionally, the heterogeneity in agents and complexity in agents' interaction make it very difficult to anticipate the characteristic patterns of the emergent behavior. Some of the emergence can be even surprising or counterintuitive. In fact, it takes decomposition of the sub-processes and extensive experimentation to identify micro-level mechanisms that can bring about shifts in the system-level outcome. Second, an agent-based model does not include everything we know about the target system. Because the goodness-of-fit can always improve by adding more explanatory factors, researchers need to make tradeoffs between goodness-of-fit and simplicity and interpretability of the results. To achieve this, this study adopts the pattern-oriented modeling to only include aspects of the system necessary (i.e. agents, attributes, rules and processes) to reproduce the reference pattern of interest.

Moreover, ABM applied in social sciences usually involve agents with internal cognitive structures, subjective choices and bounded rationality that are difficult to measure, quantify or even justify (Bonabeau, 2002). The lack of empirical data hinders model validation, especially when it comes to model longitudinal phenomena, transient dynamics or systems with multi-level structures (Klügl, 2008; Wall, 2016). Finally, there are also practical issues with the modeling. ABM takes a bottom up approach to study emergence at the system level. The model stochasticity also requires repeating the simulation run many times and taking average to observe the representative outcome for the model. Simulating the individual behavior of all the constitutive units of the system for repeated times can be extremely computationally intensive and thus time consuming, especially when large systems are involved.

Despite its limitations, ABM remains an advantageous tool to investigate how micro-level process interact and proceed concurrently in a complex system to bring about the macro social phenomenon. In an attempt to overcome some of the limitations, the study adopts a pattern-oriented approach to capture the key elements and property of the system. It also applies the “categorical calibration” to qualitative reproduce the pattern of adaptation to extreme events among public organizations (Railsback & Grimm, 2011, p. 259).

Building an agent-based model follows a more or less standardized research process. Salgado and Gilbert (2013) summarizes the main stages and steps in Figure 4: 1) Specification and formalization; 2) Modeling, verification and experimentation; 3) Calibration and validation. The sequence starts with extant theories and finishes with the target social process the model aims to simulate. The first stage involves articulating the research question and identifying plausible and testable causal mechanisms underlying the social phenomenon. In the second stage, the researcher encodes and verifies the formal model to represent the causal mechanism in a computer program. The third step includes calibration and validation to ensure the credibility and usefulness of the model. In practice, the steps can proceed in parallel and the whole modeling process is performed iteratively as knowledge and ideas about the causal mechanisms are refined or further developed. A more detailed description of the three stages can be found in Appendix C.

Figure 4. Main Stages and Steps for Agent-based Modeling



Adapted from Salgado and Gilbert (2013)

In developing an explanatory agent-based model, the initial explanations extracted from the existing literature provide a template for the model development. The study complements the theoretical insights with the semi-structured interviews to validate the initial explanations and mechanisms as well as generate details necessary to specify the process or clarify possible ambiguities.

Public Organization Adaptation to Extreme Events

This research identifies three key system features from a critical synthesis of the literature: 1) Organizational risk perception; 2) Financial constraints; 3) Social learning.

Organizational risk perception

Extreme events are inevitably outliers. Consequential damages notwithstanding, their relatively low probability and considerable uncertainties often lead organizations to distrust the possibilities of the hazard being realized and dismiss the necessity to mitigate risks in advance (Camerer & Kunreuther, 1989). The denial is partly a function of the lack of a priori evidence available for decision making and partly a function of the cultural inertia that characterizes many public organizations (Cigler, 2007; Fischbacher-Smith, 2010; Ford & King, 2015a). Complicating the matter further, the traditional way of predicting and managing extreme events through contingency plans and incident responses in public organizations often fosters a false sense of security and control (Roux-Dufort, 2007; Taleb et al., 2009).

In recognition of the range of institutional, cultural and informational barriers to adaptation, the behavioral strand of research highlights the central role of risk perception to translate signals from the external stimuli to adaptive behavior (Grothmann & Patt, 2005; Zhang et al., 2018). Risk perception involves a sensemaking process through which organizations monitor the streams of events in their environment, detect patterns and trends, and construct or alter interpretive frames of risk to guide decision making (Daft & Weick, 1984; Sitkin & Pablo, 1992). In light of the considerable uncertainties and ambiguities associated with extreme events, a comprehensive conception of weather hazards and risks is critical for organizations to transcend emergency management framework and start addressing the linkages between adaptation and their day-to-day operations (Solecki & Michaels, 1994).

In the context of extreme events, perceptions of risk requires exposure to frequent, unequivocal and salient stimuli which make it difficult to ignore or trivialize the hazard (Berkhout, 2012; Hertwig et al., 2004). Besides, materialized extreme events need to cause existing defenses and controls to fail and results in tangible impacts on the organization to precipitate behavioral change. The effects combine to help unravel the non-random generation of risk and escalation of vulnerability, calling into question the sustainability of the prevailing palliative strategies. The recognition of increased risk and their vulnerability therefore serve as strong motivational bases for organizational adaptation. Therefore,

System Feature A. A model of adaptation in public organizations to extreme events needs to capture the organizational perception of extreme weather risks.

Financial constraints

Adaptation is an expensive undertaking with no immediate payoffs. Risk perception and motivation to adapt can be insufficient to produce adaptive response. Non-cognitive factors also play a role, among which limited financial resources is identified as a persistent barrier (Biesbroek et al., 2015; Eisenack et al., 2014; Miao et al., 2018a; Moser et al., 2019). Financial constraint is widely conceptualized as encompassing inadequate funding from higher-level government, limited access to financial resources, lack of capacity to mobilize financial resources as well as absence of institutions to facilitate adaptation financing (Biesbroek et al., 2013). For public organizations, being able to adapt requires a supportive environment that grants them the necessary autonomy, authority and particularly resources to execute change (Fankhauser et al., 1999; Moser et al., 2019).

However, the domain of extreme events in public administration is long characterized as a “policy without publics” (May, 1991). The risk and danger of extreme events usually go unnoticed or absorbed in crisis management routines, and the importance of tackling related challenges is swamped by many other priorities (Birkland, 2009; Boin & Hart, 2003). Unlike areas such as gun control, criminal justice or healthcare, issues related to extreme natural or manmade hazards additionally suffer from a lack of organized group mobilization to make sustained demands for government intervention (Corfee-Morlot et al., 2011; Lorenzoni & Pidgeon, 2006). The decentralized management of many extreme events at the local levels further reduce the likelihood of persistent and influential group efforts to press for adaptation in public organizations (Rodríguez et al., 2007).

But opportunities exist for reform-minded organizations to adapt, usually taking the form of disasters with dramatic salience and consequences for the impacted organization and its locality (Kingdon, 1984; Pelling & Dill, 2010). Given the preponderance of funding-based challenges to climate adaptation, this paper adopts a narrow view of opportunities as *sporadic finite periods that expand or facilitate organizations' access to financial resources to implement adaptation practices that are otherwise unachievable or unimaginable in organizations' everyday routine.*

The role of disasters to drive adaptive behavior is widely present in a range of hazards and risk management scenarios, including technological breakdowns (Nohrstedt, 2005; Onuma et al., 2017), wildfires (Crow et al., 2018), hurricanes (Cigler, 2007; McGuire & Schneck, 2010), floods (Johnson et al., 2005; Smith & Schwartz, 2019) and droughts (Dolan, 2019; Wolf et al., 2010). Disasters are a small subset of extreme events of sufficient magnitude and scale to cause massive discontinuous changes in organizational environments. As such, disasters can increase the salience of risks, exposure failures or limitation in the existing response system, compel reflection and precipitate revised interpretation of the problem. Not only do their consequences and future recurrence add urgency to the issue of adaptation, disasters also offer significant fodder for political discourse in support of adaptation (Birkland, 1997; Busenberg, 2001; Ford & King, 2015b). In the aftermath of a disaster, we usually see resource allocation or reallocation as public organizations attempt to ramp up fiscal capacity through various mechanisms such as applying for reimbursement for disaster-related damage, seeking new grants or loans and levying taxes (Muñoz & Tate, 2016; Tate et al., 2016).

This leads to system feature B.

System feature B. A model of adaptation in public organizations to extreme events requires capturing the opportunities that help overcome the financial constraints on adaptation.

System A and B both relate to organizations' experience with extreme events as an impetus for adaptation, though the mechanisms vary. Summarizing the discussion above, it is expected that:

Proposition 1. The experience with frequency and impactful extreme events can drive adaptation through two mechanisms: 1) direct exposure increases risk perception; 2) disasters provide opportunities to overcome the financial constraints on adaptation.

Social learning

Experience with extreme events does not have to be direct for organizations to learn about risks in their environment and develop solutions. Instead, organizations can capture and respond to information and choices of other organizations, the influence of their choices and apply them to their own decision contexts (May, 1992; Nathan & Kovoor-Misra, 2002). The vicarious learning primarily takes two forms. On the one hand, learning about others' experience with disasters triggers or enhances an agency's perception of similar risks and threats in its own environment. The consequences of a disaster go well beyond the immediate physical harm to the directly affected organizations to include cognitive effect on others (Kasperson & Kasperson, 1996). The massive quantity of information generated by a disaster and its distribution via myriad communication channels amplify others' risk perception (Kasperson et al., 1988). On the other hand, strategies and measures practiced in other organizations constitute important sources of information available to the borrowing organization (Davis & Luthans, 1980). The uncertainty and complexity associated with extreme weather are powerful forces for organizations to scan others' experience to 1) achieve a better understanding and interpretation of risks in their own environment or 2) identify ideas for alternative problem solving (DiMaggio & Powell, 1983; Milliken, 1987).

It is important to distinguish the conditions under which the two types of learning occur. An enhanced appreciation of threats from disaster is more likely among organizations with similar hazard profiles, which is particularly relevant when it comes to natural extreme events (Birkland, 2006). Since natural extreme events are geographically distributed, the learning organization and the directly impacted organization need to be geographically congruent for the former to imagine and anticipate similar weather hazards, thereby increasing its risk perception (Tilcsik & Marquis, 2013; Wejnert, 2002). For instance, organizations in Florida and North Carolina can be sensitized to each other’s exposure to and damage from hurricanes; those in New York will learn how their peers in Massachusetts experience snowstorms. In contrast, extreme heat and droughts in Arizona and Nevada will likely tell little about the weather hazards in coastal areas where flooding, tsunami and storm surges are of primary concern; and vice versa.

On the other hand, learning about adaptation tools and strategies is less restrictive on the similarity of risk profiles, especially given that adaptation can enhance performance in a wide range of extreme conditions (Adger et al., 2005; Carpenter et al., 2012). For organizations with no familiar alternatives to emerging challenges, other organizations experimenting with new strategies and instruments are obvious examples to follow (Anguelovski & Carmin, 2011; Berry, 1994). Adaptation activities in other agencies afford the focal agency an important entry point to learn about the adoption, the implementation details and possibly the performance of those changes. For instance, despite the distinct natural hazard profiles in Arizona and the Washington DC, the differences did not prevent the Arizona Department of Transportation from applying the Federal Highway Administration’s Infrastructure Voluntary Evaluation Sustainability Tool to evaluate its own sustainability practices (Hansen et al., 2016). Similarly, the Colorado Department of Transportation followed the RAMCAP Plus framework from the DC-based American Society of Civil Engineers to conduct an all-hazard risk and resilience assessment of the I-70 corridor (Flannery et al., 2018). Organizations can discover and imitate adaptation practices through contacts with other organization or movement of personnel across organizations (DiMaggio & Powell, 1983). They may also consciously capture the practices through consultation, encoded scripts as well as promulgation by government agencies or professional associations (Decker, 1986; Scott, 2008). Therefore,

System Feature C. A model of adaptation in public organizations to extreme events requires incorporation of social learning from other organizations.

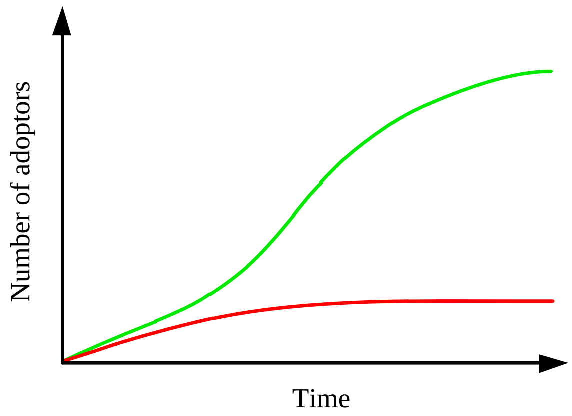
Empirical Context: US Transit Agencies

This study situates the examination in the U.S. metropolitan transit agencies and investigates the diffusion of one specific adaptive practice in response to extreme weather events: *infrastructure enhancement* geared toward raising the organizational resilience against extreme weather risks. Infrastructure enhancement is a type of "hard" adaptation based on techno-engineering interventions to reduce potential climate impact (Jones et al., 2012). The measures are typically capital investment and designed to respond to specific weather risk. Specific to the transit sector, examples include installing heating coils in the station platforms to prevent ice formation, elevating passenger stations, upsizing the stormwater drainage system as well as deploying a combination of installed and portable generators to ensure continuity of power supply.

Incorporating weather-related considerations in infrastructure design and construction represents an important measure of adaptation to weather risks in transit agencies. For years, the design and construction of transit systems have strived to achieve efficiencies by reducing costs and speeding up the organizational processes. This has led to the development of ever more complex and interdependent technologies and infrastructure, necessarily removing much of the slack available in the system (Hodges, 2011). Further complicating matters are the organizational routines to restore things back to the pre-event state after the event, replicating the very vulnerability that made the damage so bad in the first place. The repeatedly fumbled system responses to extreme weather points to the imperative of managing vulnerability instead of merely managing the after-event impacts (Hodges, 2011; Meyer et al., 2012). Deliberate investment and efforts are needed to upgrade, reinforce, replace and enrich critical infrastructure to enhance the agencies' weather-related resilience (FHWA, 2018). On the other hand, however, infrastructure enhancement requires substantial adjustments to the transit system, incurring more barriers to overcome than planning and implementing immediate measures to cope with extreme weather impacts (Moser & Ekstrom, 2010). Finally, the absence of top-down institutional mandate leaves the process of adaptation dependent on the organizational uptakes of adaptation technologies and practices, making it theoretically meaningful and practical relevant to investigate their adaptive behavior.

In this paper, organizational adaptation at the collective level is characterized as a higher-order outcome in the spread of adaptation practices among transit agencies. Figure 5 depicts the reference pattern (Sterman, 2000) for this study. The green line portrays a typical innovation diffusion model where a new practice or policy spreads through organizations and reaches full or very high levels of adoption in the system. The red line represents the current distribution of resilience-enhancing infrastructure enhancement among transit agencies. The emerging albeit limited spread of this adaptation practice is the central focus of this study. Through the analysis, the study aims to generate insights on micro-mechanisms driving adaptation among the organizations, such that the red curve can shift toward the green curve to achieve higher levels of diffusion.

Figure 5. Transit Agency Adaptation to Extreme Events



Interview Insights

The interviewees were identified partly through the author's personal network and partly from the list of respondents to 2016 national survey on transit agencies (see details about this survey in Essay 1). The study used a purposive sample to ensure representation from various geographical areas and work responsibilities. After obtaining the approval from the Institutional Research Board (IRB) as an add-on project to the 2016 national survey (see details from essay 1), the author sent personal invitation emails to selected managers, both from her personal network and a random selection of managers to improve the representativeness of the sample.

A total of 19 managers from 11 agencies participated in the interviews. The participants are lead managers in functional roles of key importance to adaptation in the transit sector, ranging from strategic planning, executive management, emergency management, operations, finance, risk management, asset management to engineering. Participants are spread across the four Census regions with varying weather risk profiles and heterogeneity in organizational response. Appendix D displays the sample distribution by region, city size and position, where a cutoff point of 500,000 is used to distinguish big- from medium- sized cities. The initial interviews were conducted over the phone for about one hour in length with extensive notes taken to record the key points. Drawing on the theoretical insights from the literature, the interviews included open-ended questions to gain an in-depth understanding of the agency's experience with extreme weather, adaptation practices if any, motivation for the adaptation and ways to identify the adaptation strategies. The managers were also asked about the barriers to adaptation and particularly how they addressed the barriers. Appendix E includes the protocol for the initial interview with the managers.

The data collection from the interviewees proceeded in parallel with model development, where more details were iteratively added to specify or refine the causal mechanisms via follow-up inquiries with the managers typically through email communications. Given the iterative nature of the data collection, the interview process spanned a few months, starting in March 2019 and continuing through August 2019. The data from the interviews and follow-up inquiries were compiled in a word document for qualitative coding. The constructs and theories from the literature form a list of key themes for initial coding to identify the chunks of texts that exemplify the codes in the list (Ritchie & Lewis, 2003). At the same time, I also amended the list of codes during the analysis when new ideas or codes emerged (Kuckartz, 2014).

The interviews generated a few key insights to inform the model design and development. The insights will be discussed in three categories based on subsequent changes to the model: 1) enhancing an operational understanding of the mechanisms; 2) altering the behavioral rules; 3) adding new system features. The direct quotes in the discussion below are drawn from the follow-up email communication, where the basic information for each interviewee can be found in Appendix D.

1) Enhancing an operational understanding of the mechanisms

Findings in his category are congruent with the mechanisms identified from the literature, but they help improve the operational details in the model development. First of all, perception of weather risks is a dynamic process, responding most sensitively to an organization's recent experience with extreme weather. A number of managers referred to their recent experience with extreme weather events when talking about how they understand the risks associated with extreme weather. For example, a manager ascribed the trigger of their agency's risk perception to a recent snowstorm. "We had a big snowstorm in 2017, which was the largest one we had in the past decade since 2008. The ice sat on the road for one week and our agency was not prepared for the inundation…The 2017 snowstorm makes people more conscious and they try to take more control… Even though some extreme weather events are not catastrophic, they are above the average storms and are debilitating in the long term" (Interviewee 4). However, organizations do not hold fast to the same view of risk in face of new information from their environment. In particular, perception of risks fades over time and organizations tend to develop complacency after experiencing an extended period of non-occurrences. This is aptly captured by a manager's concern about the danger associated with hurricanes. "The worst that can happen is there is no (hurricane) hit in five years. People get complacent and lose attention. Then finally another Hurricane hits. We have to stay alert in case things happen… (Interviewee 6)”.

Second, besides the social network with their peers, transit agencies are also connected to a regional information and coordination hub served by the FTA regional office or transportation research centers in the region. The hubs garner ideas and knowledge about adaptation, develops guidelines and recommendations, and communicates and promotes those approaches to agencies in the region. When possible, the hubs provide training, certification and educational materials to promote resilience practices. Transit agencies can also approach those hubs for guidelines and assistance in the process of identifying solutions.

2) Altering behavioral rules

Insights in this category show some inconsistency with the theoretically derived mechanisms, leading to changes in specification of the behavioral rules in the model.

To begin with, echoing previous studies, there is a strong consensus among the managers about the financial constraints on adaptation. Once a solution is identified, instead of being able to implement it right away, organizations typically have to explore or wait for opportunities that either bring in new funding, enhance their access to financial responses or facilitate financing adaptation.

However, various forms of opportunities emerged from the interviews, among which weather disasters is not prominent. Managers broadly agreed on the limitations of weather disasters in enabling resources for adaptation, citing the narrow eligibility criteria for FEMA funding and restrictions on funding allocation. “The FEMA grants have very restrictive criteria… Unless it is catastrophic such as Hurricane Sandy to the New Jersey subway systems, agencies will not receive funding for the weather disaster" (Interviewee 7). Multiple managers explained that FEMA only compensates for the costs of repair and recovery after a disaster and does not reimburse resilience or betterment projects that goes beyond the basic code requirement. Instead, it is evident that the agencies rely on a series of intentional adjustments to its operations or changes in its local contexts to create opportunities. Some were able to bundle resilience projects in their new grant application and approval, others waited until a new budget cycle or synchronized the projects with a pre-scheduled maintenance, upgrade, purchase or construction, and still others benefited from new streams of revenue from public-private partnership or new transit tax. Those opportunities are referred to as *non-disaster-induced opportunities* thereafter.

For instance, one manager acknowledged the budgetary constraints and recounted the agency's workaround strategies. "If the agency does not have the capacity to implement an identified solution, it will depend on what the capacity issue is. If it is a funding issue, then typically the solution waits until there are funds. We may try to prioritize it over other activities based on the necessity and if it affects operations… It is normal business to 'bundle' improvements when other construction is being completed" (Interviewee 3). Another manager remarked how the agency, with limited access to federal resources, has to rely a lot more on other organizations that are focused on resilience and security. "We may work with partners who have an interest in some of these items being implemented or considered to see if they would be interested in funding it. An example might be a real estate developer wanting a particular element or pathway that improve their access to BRT (i.e. bus rapid transit) facility…(Interviewee 2) ”. The same manager detailed how a recently passed transit tax expanded their revenue base making it possible to implement “betterments – those items that are outside the work necessary to construct or operate a project or facility— (that) would not be reimbursed as part of an FTA project” (Interviewee 1). The role of new stream of revenue to facilitate adaptation implementation was similarly noted by managers from another agency which doubled its budget from a voter-approved sale tax measures dedicated to sustaining and expanding bus and rail services. It is interesting to note that none of the managers including those from disaster-prone areas identify weather disasters as an opportunity to acquire necessary capabilities and resources to invest in resilience-enhancing projects. The limitations of the disasters to facilitate fiscal capacity for adaptation are similarly noted in other studies (Barrett, 2013; Moser et al., 2019; Webber, 2013)

Additionally, although the literature suggests the possibility of social learning and social amplification of risk perception, the managers widely suggest that knowing their regional neighbors experiencing extreme weather or disasters generally has limited influence on their view of risks. Reasons include the agencies’ preoccupation with their own everyday operations, the nuanced differences in landscape attributes and hazard profiles as well as uncertainties about future climatic conditions. When asked whether the recent 2019 Iowa flooding can help them rethink about the potential of having similar floods in their service area, a transit manager from the Midwest answered: “I think in some cases, the issues in Iowa and Nebraska will cause more concerns among those cities that are similarly situated on major rivers, especially since the floods were a confluence of rain events and melting snow at the headwaters (in as much as I'm aware) and thorny questions about what to do with the dams on the river. I think the floods in our area are still more likely to be of the 'flash flood' variety because the headwaters of the White River just aren't as vast as those on the Missouri and we have fewer upriver dams… When events like the flooding in Iowa/Nebraska occur, we are likely to recognize dissimilarities that wouldn't necessarily prompt us to action" (Interviewee 2). Another manager attributes to the underlying unpredictability in future weather conditions. "Again, I do not think that most Transit Staff change their 'thought process' due to what others are experiencing. This is an assumption though. I would think that you would actually have to ask that specific question throughout different levels of the organization to determine this is true. Also, there is so much 'unpredictability' in weather I think the basis that it is unpredictable plays into the reason why more people do not prepare. For example, this winter, NOAA predicted Portland was going to be hit with a severe weather snow event that could affect all local traffic for potentially days. However, the way the microclimate is in Portland, the city proper was spared and just 15-20 miles away was significant snowfall. Another example would be tornados – you can have houses stand with no damage, with complete decimation across the street. Transit Operators may plan on how to store their assets, how to shut down and resume service, but I do not think 'watching' other events across the nation influences the behavior or prepares the agency better" (Interviewee 3).

3) Adding new system features

Unlike the two previous categories of insights which can find some correspondence in the literature, insights in this category are largely missing from the extant theories and hence treated as an emerging system feature in the model.

It is clear across the managers that organizations are not motivated towards change with every increase in their risk perception. Instead they can tolerate a certain level of risks associated with extreme weather and stay satisfied with their existing practices. The organizations’ risk tolerance varies both within and across geographical regions. Data from the 2016 national transit survey shows adapting agencies are distributed across all the four Census regions, where the proportion of adapters ranges from 0.22 in the Midwest to 0.32 in the South. The managers also implied different levels of risk tolerance across regions when they commented on the costs and benefits involved in organizational decisions to handle weather risks. A manager from a hurricane-prone area stated that their agency went beyond the legal mandate to build the system up to withstand the highest risk from wind, because “hurricanes and tornados can happen all the time” (Interviewee 19).In the Midwest where threats from weather disasters are less salient, a manager explained how their agency had to carefully balance the costs and benefits to determine the optimal level of risk to plan for. “If you have limited resources and you can only offset the risks of a weather disaster that has a 10% chance of occurring at any given year versus the one that has a 0.01% chance in any given year, unless the cost of the latter is more than 1,000x greater than the 10%, the rational choice is to offset the 10%. It may well be that the cost of the 0.01% does exceed that … Further, given the uncertainty associated with negating the impact and the low probability of occurrence, it is more difficult to marshal resources to offset those impacts relative to the more probable" (Interviewee 2). Meanwhile, risk tolerance also varies within a geographical region. This is illustrated by observations on three transit agencies all located in the West. While Agency 10 continued its reliance on emergency management approach by revising its snow/ice removal plan and strengthening public communication under storms and service disruptions, Agency 3 started questioning the costs and sustainability of relying on incident responses to meet demand in future shocks, and Agency 7 took a step further to prepare for the sea level rise despite its slow onset and more distant impacts. Since agencies in the same region are subject to similar weather hazards which shape their risk perception, the within-region variation in adaptive behavior needs to be sought at the dissimilar levels of risk tolerance among the agencies, other things being equal.

To incorporate this emerging system feature, the study defines risk tolerance as the upper limit of perceived risk beyond which changes will be worth pursuing for their anticipated benefits as compared with the status quo (Saravanamuthu, 2018). The varying levels of risk tolerance among agencies results from a set of tradeoffs involved in dealing with extreme weather risks. This insight leads to System Feature D.

System Feature D: A model of adaptation in public organizations to extreme weather events needs to capture organizations' tolerance about extreme weather risks.

Modeling Transit Agency Adaptation

Integrating the interview insights with the initial explanatory mechanisms involved in the process of organizational adaptation, Appendix F synthesizes the system features, the constructs and assumptions involved and their computational representations. Note that although the extant theories suggest that others' experience with extreme events can interact with social and cognitive processes to heighten risk perception of the focal organization, this mechanism is not confirmed by the interviews and is therefore not included in the model.

The agent-based model simulates the emergence of transit agency adaptation where a small number of agencies switch from reactive coping toward proactive adaptation to deal with risks associated with extreme weather. Specifically, the model characterizes the process through which transit agencies perceive the risks, activate problemistic search to identify solutions and implement the target solution.

Simulating risk perception

Risk perception is operationalized as the product of the expected impact from extreme weather and the probability of its occurrence. Consistent with the extensive decision theory literature on risk and uncertainty, the model assumes bias in agencies' probabilistic judgment about the extreme weather risk. According the psychological literature, individuals' perception of risk follows a standard Bayesian learning process, where they continually update their probability risk assessment based on hazard occurrences in a way unaffected by the true level of risk (Rogers, 1997; Viscusi, 1985). Organizations tend to underestimate or ignore low probability risks, until aroused by some peak events when the risks materialize in significant magnitude and over a short time horizon (Camerer & Kunreuther, 1989; Hertwig et al., 2004; Yohe & Tol, 2002). Experience with dramatic weather events heightens the reality, memorability and imaginability of the hazard, raising the probability estimate for future risks (Hertwig et al., 2004; Tversky & Kahneman, 1973). But the perception of risk gradually fades away until some new extreme weather events or disasters reorient the organization’s attention to weather risks (Konisky et al., 2016). As individuals learn and incorporate new information to update their assessment, they also tend to misconstrue a consecutive series of non-occurrences and assign unwarrantedly low probabilities to future extreme weather events (Haasnoot et al., 2015; Viscusi, 1985). Taking as a whole, the organizations show low risk perception, punctuated by a brief interval of heightened perception of future weather risks.

Moreover, instead of assuming organizations are prompted to act by every single update in their risk perception, the simulation includes each organization’s risk tolerance to represent the discontinuity in organizational behavior. When extreme weather risk is perceived to be higher than what the organization can tolerate, it serves as the starting point of doubt and sets the stage for subsequent behavioral change (March & Simon, 1958; Schneider, 1992). In contrast, an agency shows no behavioral change as long as its perceived risk stays within the tolerable range (i.e. the threshold).

Simulating problemistic search

When their perception of risk exceeds risk tolerance, the agencies initiate problemistic search aiming to reduce the level of expected impacts (Cyert & March, 1963). This aligns with the thrust from much of the literature on organizational learning and adaptation that organizations will initiate focused search when 1) minimum level of threats or concern are perceived and 2) some heuristic assessment of the risk probability, cost and benefits associated with the current solution suggests a search-justifying threshold has been reached or exceeded (Grothmann & Reusswig, 2006; Huber, 1991; Mintzberg et al., 1976).

The model distinguishes two types of solutions dealing with weather impacts: coping and adaptation. Compared with adaptation with a long-term and proactive orientation, coping solutions are short-term tactical strategies to manage immediate reaction and quick recovery in the wake of an extreme event (Chhetri et al., 2019; Smit et al., 2000). This approach aptly maps to the emergency management based responses to extreme weather in the transit sector, ranging from temporary service rescheduling or rerouting, rider evacuation, emergency public information and communication, debris management, personnel training, mutual assistance from other agencies. Although the coping solutions are typically cheaper and easier to implement, they also are more limited in their efficacy and scope to mitigate impacts from future exposure.

For the searching agencies, their first go-to direction is to enhance the efficacy of their coping strategies. Only when the coping solutions are deemed insufficient will the organizations overcome the structural inertia, activating focused search for and forming general commit to higher-order alternatives—adaptation in this case (Adger et al., 2011; Fankhauser et al., 1999; Linnenluecke & Griffiths, 2010; Smit & Wandel, 2006). In their search for adaptation solutions, an agency can devise solution on their own, access the adaptations solutions practiced by other agencies they are connected to or those promoted or shared upon request by their regional information and coordination hub.

Simulating implementation of adaptation

Having identified a target adaptation solution, agencies assess their capacity to carry out the adaptation. In case of insufficient capacity, the agencies hold on to the solution and wait for opportunities that can boost their capacity for adaptation.

As an opportunity opens, a window emerges for adaptation if: 1) The agency's perceived risk exceeds its risk tolerance; 2) It has a solution to readily attach to the opportunity; and 3) With the additional capacity facilitated, the agency has adequate resources to cover the cost required to implement the target adaptation measures. The adaptation is successfully implemented when the three conditions are simultaneously met – hence a window, echoing the observation that organizational change is jointly determined by motivation to change, opportunity to change and capability to change (Miller & Chen, 1994).

Computational Implementation

Each time step in the model represents half a month allowing a maximum of two occurrences of extreme weather events in a given month. The time scale is determined to accommodate the fact the extreme weather events can happen more than once in an average month.

The primary elements of the model are 1) transit agencies; 2) natural environment, 3) solutions; 4) network. The basic idea is that transit agencies are geographically distributed with varying weather hazard profiles. All agencies are initialized to apply coping solutions to manage the immediate impacts of extreme weather, forming their starting point for expected impact from severe weather events. The expected impacts are reduced when they switch to more effective solutions to address weather risks. Agency endowment of capacity determines the extent to which they are able to cover the costs and implement the adaptation solution when desired.

The model contains a set of rules that govern their risk perception, problemistic search and adaptation implementation. By encapsulating all the elements in the system, the model is able to simulate the interactive dynamics among the agencies, their natural environment and networks that lead to the emergence yet limited diffusion of adaptation practices among transit agencies. Appendix G below displays the primary elements, their attributes when applicable and initial values.

A few notes on the parameterization are in order. The model uses three source of information to determine parameter values: 1) empirical data, 2) existing literature and 3) educated guesswork (Railsback & Grimm, 2011). Data from the national dataset and the 2016 national survey were used to parameterize each agency's capacity and probability of encountering extreme weather. In the survey, the agencies were asked to report how many times their agency experienced extreme weather events during the past two years. Since two years span 24 time steps in the model, the answer to this survey question is divided by 24 to derive the probability of having an extreme weather event in a given time step. This operationalization is admittedly a rough approximation to the real probability of having an event, because in reality the probability of encountering extreme weather events is not evenly distributed across different seasons of the year. The probability of weather disasters draws from FEMA's archival of weather disasters from

2000 to 2018 on the county level. The model aggregates the number of weather disasters that occurred to the county in which each agency resides during the time period and then determines the average probability of weather disasters in a time step based on the time scales, again applying a uniform distribution. Because not all agencies in the same county have the same number of weather disasters, the model slightly varies the agency-level probability of disasters to add some heterogeneity. Note that only a subset of weather disasters can receive the presidential disaster declaration (PDD) with associated fund. The model therefore refers to the state-level PDD success rate found in Schmidtlein et al (2008) to set the probability at which an agency can receive PDD funding for weather disasters. Minor randomness is added to map the state-level success rate to each agency in the state.

Other parameters cannot be determined through empirical observations or previous studies. A few rules were applied to determine the value for those parameters: 1) The parameter needs to be on the same scale with other parameters it interacts with; 2) There are upper and lower bounds for the parameter’s value, beyond which the model outcome would be unreasonable; 3) Consider the qualitative nature of the parameter to decide whether the process being modelled should move faster or slower, occur more frequently or rarely, exert a stronger or moderate effect, etc. 4) Calibrate the model to choose the parameter value that reproduces the reference pattern in the system; and finally 5) Conduct sensitivity analysis for parameters that can strongly alter the model results (Railsback & Grimm, 2011). The parameter values need to be interpreted at the qualitative rather than the quantitative level. For example, the efficacy of coping and adaptation is set between 0.05 to 1 and 1.5 to 3 respectively. Numeric values from 0.05 to 1 make little sense until being compared with those from 1.5 to 3, suggesting that coping solutions have a lower efficacy than adaptation in reducing extreme weather impacts. The same rational applies to the cost parameters for the two types of solutions.

Transit agencies

The primary attributes of the agencies are their risk perception, tolerance, capacity and opportunities. Drawing on a 2016 national survey on transit agencies (Miao et al., 2018a; Zhang et al., 2018), 197 agencies are randomly distributed in the four quadrants of the model space corresponding to the Census region they are located in.

Risk perception. The agencies' risk perception is operationalized as the product of their expected impacts and perceived probability of extreme weather (Grothmann & Patt, 2005). For agency i , its perceived risk is defined as:

$$\text{risk perception}_\text{i} = (\text{worst weather intensity}_\text{i} - \text{solution efficacy}_\text{i}) * \text{ p}(\text{worst weather intensity}_\text{i})$$

Where p denotes probability.

Since organizations cannot plan for every single worst scenario for climatic conditions, $worst\ weather\ intensity$ represents the highest level of weather intensity an organization typically plans for (Kunreuther et al., 2013). When an extreme weather occurs, an organization raises its expected probability for the worst weather event by 0.05 to 0.10. In the case of a weather disaster, the organization's expected probability grows by 0.25 to 0.30 to represent the discernible impacts of weather disasters on risk perception (Haasnoot et al., 2015). In contrast, in the absence of an extreme weather event, the agency’s expected probability of worst severe weather diminishes by a random percentage ranging from one to three, leading to dissipation of risk perception through time. At the same time, because the expected probability of extreme weather cannot go indefinitely high or low, the model bounds the expected probability of extreme weather between 0.01 and 0.25. All the rates of change as aforementioned are determined from uniform distributions. The different rates of change in the expected probability of extreme weather are theoretically derived to reflect the extensive empirical evidence that organizations’ perception of weather risks notably increases in the immediate aftermath of an extreme weather event, particularly in cases of weather disasters, but tends to fade over time (Egan & Mullin, 2017; Howe et al., 2014; Konisky et al., 2016). Short of any alteration to their solution, the agencies update their risk perception through adjusting their expected probability of extreme weather as their experience with extreme weather events evolves.

On the other hand, the agencies reevaluate their risk perception through adjusting the expected impacts when switching solutions to deal with weather impacts. For a simplified representation, the model only considers switching to solutions with higher efficacy, although in reality malpractice or maladaptation can also occur.

Risk Tolerance. Recognizing the tolerance of weather risks is partially a function of an agency’s weather hazard profile, agencies in the same region are initiated with a common mean for their risk tolerance. To reflect the varying degrees of exposure to extreme weather across regions, the common mean for risk tolerance is lower in the South and Northeast which are most exposed to extreme weather and higher in the West and Midwest. The regional mean for the South, Northeast, Midwest and West is set from 0.3 to 0.6, with 0.1 increment respectively. An agency's risk tolerance is generated through a normal distribution with the predefined mean and a standard deviation of 0.1 to reflect the within-region variation of risk tolerance.

Financial capacity. The agencies' capacities are initiated using an adjusted z-score of their total fund received from various sources drawn from the National Transit Database, ranging from 0.016 to 4.184. Given the high correlation between the agencies' slack and total revenue (r = 0.956), this variable also indicates the amount of an agency's discretionary resources to implement adaptation. In the model, each agency is designed to have a constant level of financial capacity, unless there is an opportunity that generates additional funding or expanding the organization's capacity for adaptation financing.

Opportunities. Integrating insights from the literature and the qualitative interviews, the model includes two types of opportunities: 1) opportunities induced by weather disasters that received the presidential disaster declaration.; 2) non-disaster-induced opportunities that become available due to factors more endogenous to the agencies. Those have to do with the agencies' routine and resource base, their contingency arrangement, collaboration with other organizations as well as their socio-political environment that makes additional funding more or less likely. As discussed above, the first type of opportunities is generated when an agency encounters a weather disaster and receives the presidential disaster declaration. To further represent the FEMA's restriction on funding usage, a declared disaster has a probability of 0.3 to facilitate additional funding for adaptation projects. Opportunities of the second type are created and randomly distributed across the model in the model setup, with a variable maximum number of opportunities ranging from one to ten. Sensitive analysis is conducted to examine the influence of the maximum number of opportunities on the model outcome.

Natural environment

The model distinguishes two types of weather events: 1) extreme weather events; 2) weather disasters. While all weather disasters are extreme weather, not all extreme weather result in weather disasters. That is, weather disasters are the subset of extreme weather events that are of sufficient magnitude and scope to cause catastrophic consequences.

To simulate the weather intensity and determine the occurrence of extreme weather or weather disasters, the model applies a log-normal distribution to generate the value for weather intensity at each time step, with a mean of 5 and standard deviation that equals the probability at which an extreme weather can occur to a given agency. In order to provide a threshold beyond which the weather intensity becomes extreme or even disastrous, the model simulates the weather intensity for each time step for 200 years. The generated values are stored in a vector sorted from high to low. The minimum intensity level of an extreme weather event can be located in the vector based on the agency's probability for encountering extreme weather. For example, with an extreme weather probability at 10%, the vector will contain values ranging from 4.36 to 5.59, sorted from high to low. The agency will take the number at the 10th percentile at a value of 5.27 as the minimum level of weather intensity. The model applies the same algorithm to determine the minimum level of intensity for a weather disaster.

Solutions

There model includes two types of solutions: 1) coping and 2) adaptation. The solutions differ in their cost and efficacy for mitigating weather risks. The costs and efficacy for each agency follow a uniform distribution. Coping solutions cost less than adaptation solutions, but are also less effective. In the model initiation, the coping solutions have an efficacy level ranging from 0.05 to 1 and their cost is intentionally set as lower than the organizational capacity to remove the cost constraint in improving the efficacy of coping. This reflects the empirical observations that transit agencies are usually capable of making incremental improvement to their emergency management practices (Miao et al., 2018a). The efficacy of adaptation solutions ranges from 1.5 to 3 and their cost from 2 and 6. The costs are determined relative to the organization's financial capacity, such that not all the agencies will have sufficient capacity to implement the adaptation solutions upon discovery.

Each of the coping solutions is attached to an agency in the model initialization. The model recognizes the agency's ability to devise adaptation solutions on its own, by randomly distributing adaptation solutions in the model space waiting for the agencies to notice, pick up and embed into their organizational practices.

Networks

The model includes three ways for an agency to form network connections : 1) with agencies in the same region; 2) with agencies located in difficult regions; 3) with its regional information and coordination hub. In initiating an agency's network with organizations within and across regions, the model applies the preferential attachment model from the Netlogo library (Wilensky, 1999) to reflect the fact that bigger agencies are usually more connected within and outside their region. An agency has at least one regional neighbor and one connection with agencies in other regions respectively. There are ten regional hubs connected to all the agencies in the same region.

The network links do not have attributes and are only accessed when agencies search for adaptation solution. Specifically, when looking out for alternative approaches, an agency can access solutions through their regional network or through network ties outside their region. The regional hub also garners information about adaptation practices in the region, which they either distribute to member transit agencies on a regular basis or share with agencies upon requests. The current model does not distinguish the various mechanisms and the speed thereof through which an agency can access information and choices among their three networks.

Dynamic process of transit agency adaptation

At each time step of the model, the agencies take actions described below in Figure 6:

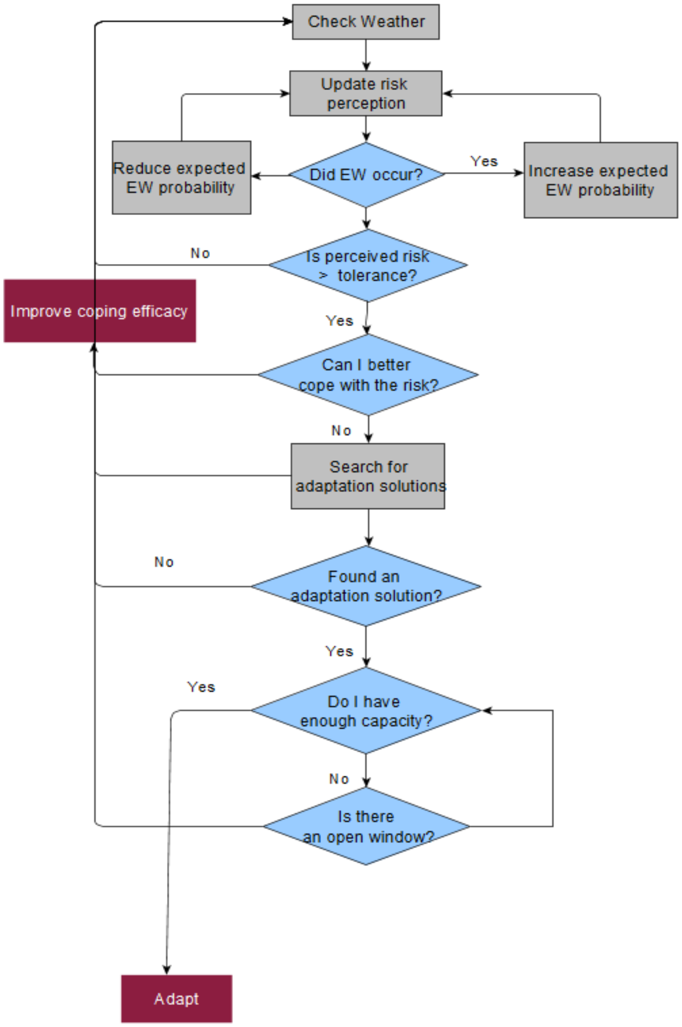
1. *Agencies check weather conditions.* Each agency experiences a certain weather condition, the intensity of which is determined on a log-normal distribution as aforementioned. If the weather intensity goes beyond the predefined threshold intensity for extreme weather, the weather is modelled as extreme weather. If it further transcends the threshold intensity for disasters, it is additionally modeled as weather disasters.

2. *Agencies update risk perception*. Each agency updates it perceived risk based on the weather conditions and their efficacy in mitigating the weather impacts.
3. *Agencies determine motivation to adapt*. An agency evaluates its risk perception relative to risk tolerance. When the perception of risk exceeds the risk tolerance, the agency embarks on problemistic searches for alternatives to alleviate the expected impacts. If an agency is able to increase coping efficacy within the upper limit, it sticks to the coping approach by improving its efficacy; otherwise it has to explore adaptation solutions. When an agency's risk perception is lower than its tolerance, the simulation skips to the next time step without executing steps 4-7 below.
4. *Agencies search for adaptation solutions.* An agency is able to either devise an adaptation solution on its own or discover it through the three types of networks. When an agency detects a solution with a higher efficacy than that of its current solution, it attaches this solution as a target. Otherwise, it repeats the search in the next time step as long as its risk perception stays above its risk tolerance.
5. *Agencies Assess capacity to adapt.* For a selected target solution, the agency then assesses its financial capacity to determine whether it is sufficient to cover the cost of the target solution. When there is sufficient capacity to do so, it initiates the implementation and applies the adaptation solution onwards. If not, the agency holds on to the selected solution, waiting for opportunities to emerge in later time steps to facilitate the necessary capacity.
6. *Agencies assess implementation upon opportunities*. Upon an open opportunity, an agency examines whether the organization has adequate capacity to cover the cost

and implement the target solution with the facilitated resources. An answer of “no” will take the agency to the next time step.

7. *Increase probability of extreme weather.* To align with the evidence that extreme and disastrous weather events are occurring at an accelerated rate (Boustan et al., 2017; Smith, 2017), the probability for extreme weather slightly increase by 0.0001 at the end of each time step.

Figure 6. Flowchart for Modeled Systems of Transit Agency Adaptation



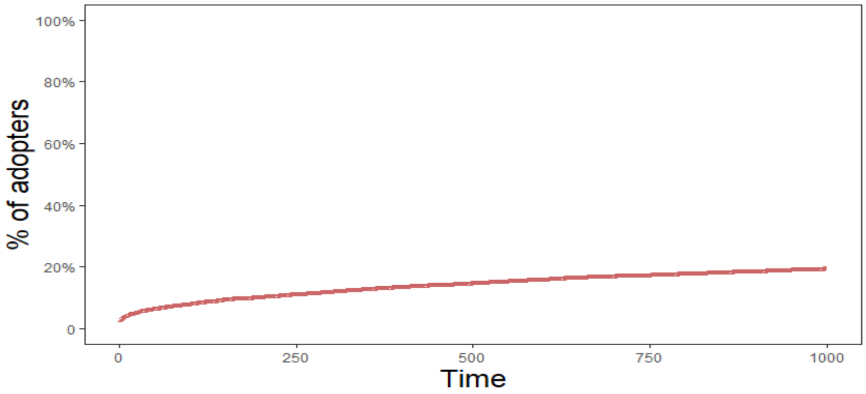
Model Analysis

Baseline model

The model is run for 1000 time steps, representing approximately 40 years in reality. Since one run of the model is a single realization of a process including multiple stochastic elements (Wilensky & Rand, 2015), each model run is repeated 100 times for each experimental condition to generate a distribution of the model outcome. The outcomes across the 100 model runs are averaged to obtain the final outcome for calibration.

The modeling process applies categorical calibration to qualitatively match the outcome with the reference pattern (Railsback & Grimm, 2011). The model is considered adequately calibrated when it produces approximately 20% adapters, as indicated by the 2016 survey data on the transit agencies. The model reproduces the reference pattern as shown in Figure 7. The line indicates the number of agencies that have implemented adaptation. This calibrated model will be used as the baseline case thereafter for subsequent experiments.

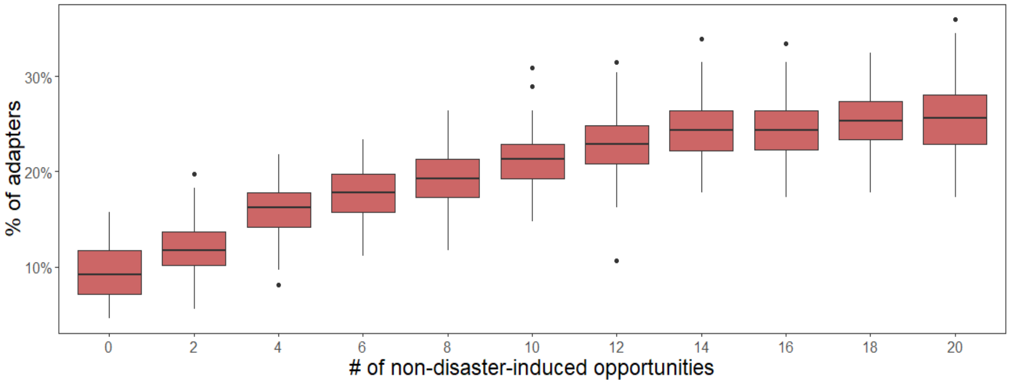
Figure 7. Model Calibration



The baseline model provides insights for the experimentation. The results show that only a small fraction (approximately 30%) of the adapters have sufficient capacity to implement the target adaptation solution once identified. In contrast, seventy percent of the adapters have to wait for opportunities to facilitate necessary capacity for implementation.

Given the necessity of opportunities to enable adaptation among many organizations, especially those induced through arrangement or changes endogenous to an organization’s operations and local contexts, it is natural to expect more opportunities to produce more adapters. To test this assumption, I varied the maximum number of non-disaster-induced opportunities to be distributed across the model run in the model initiation. Figure 8 shows the variations in the proportion of adapters across different maximum numbers of those opportunities, with results aggregated over 100 runs. Notable from the figure is a non-linear relationship between the number of opportunities and resulting percentage of adapters. Starting with zero non-disaster-induced opportunities, an increased number of opportunities can produce more adapters, but the positive effect tapers off after the number increases to a certain level. Note that when organizations can only rely on disaster-induced opportunities (i.e with zero non-disaster-induced opportunities), the proportion of adapters reduces by more than half to less than 10% compared with the baseline model, further suggesting the importance of non-disaster-induced opportunities to enable adaptation.

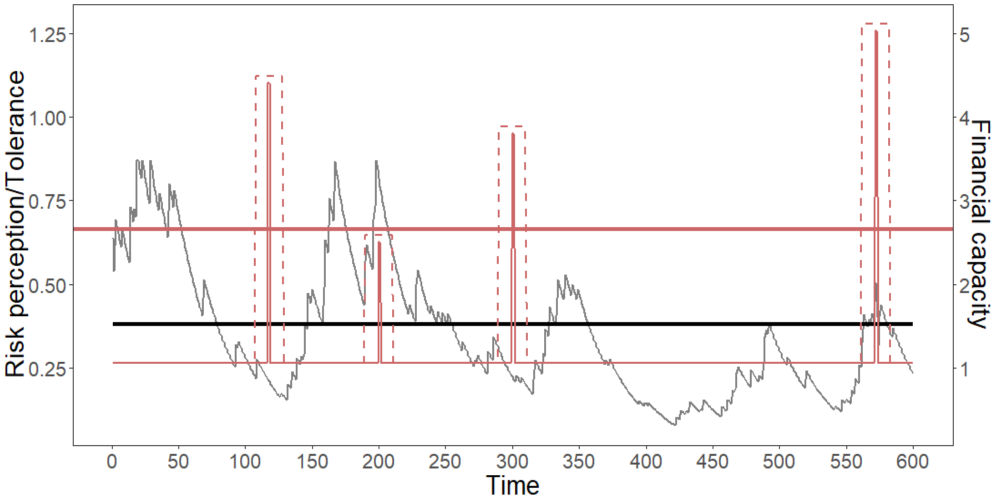
Figure 8. Mean Proportion of Adapters by Condition: Maximum Number of Non-Disaster-Induced Opportunities (100 Runs)



A closer examination of what happens during the opportunities opening suggests explanations for the non-linear relationship. It turns out that only about 7% of all the opportunities are effectively utilized to enable adaptation implementation. There are three conditions in which the opening opportunities can fail to produce adaptation in the beneficiary agency: 1) the agency's risk perception lies below its risk tolerance, the situation of which takes up about 85% of all the missed opportunities; 2) About 9% of the time, even with the additional capacity, the agency is still unable to cover the cost of the target adaptation (i.e. insufficient increase in its capacity); 3) Very rarely does the agency not have solution ready to attach to the opportunity.

Figure 9 illustrate those results by plotting the model dynamics of a randomly chosen adapter. The model was run for 1000 ticks, although the graph only shows the first 600 ticks to facilitate visualization of the spikes. The horizontal and fluctuating black line indicate the agency's risk tolerance and risk perception respectively. The horizontal red line shows the cost of its target adaptation solution and the red line with occasional spikes represents financial capacity. The dashed lines are added around the spikes to suggest the presence of an opportunity. It is clear that the agency has to wait until to the fourth opportunity to implement adaptation, in which the first three opportunities were missed either due to a lack of motivation (the 1st and 3rd opportunity) or insufficient increase in its capacity (the 2nd opportunity).

Figure 9. Model Dynamics of a Random-Selected Adapter



The intuition follows from the baseline model: while opportunities are necessary for most of the agencies to implement adaptation, many opportunities go wasted in terms of the failure to facilitate adaptation. The model dynamics over time suggest the criticality of timing and the confluence of the key elements for adaptation implementation, which can be characterized as problem, opportunities and solutions using the language of garbage can decision making model (Cohen et al., 1972). Additionally, the coupling between opportunities and risk-directed motivation for change is particularly critical for the confluence of the three factors. Building on this insight, the next two computational experiments examine ways in which coupling can be improved.

Lower decay in risk perception

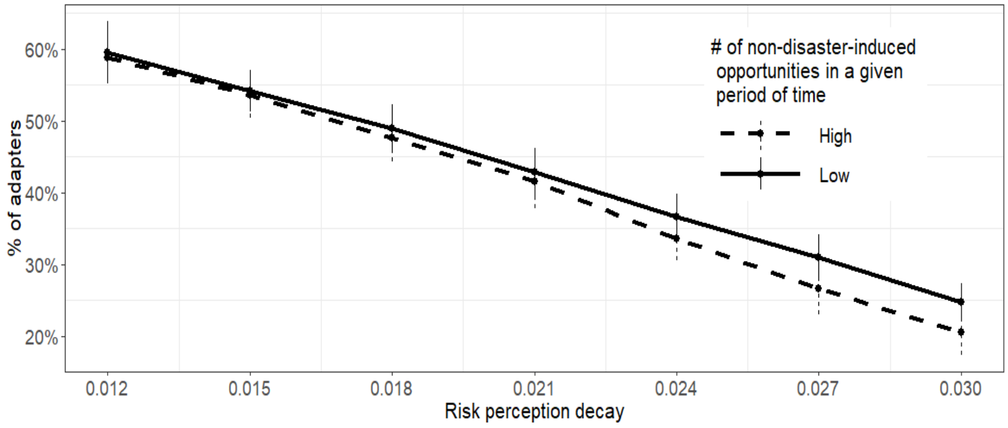
The failure for coupling between opportunities and motivation to act can be traced to the decay in organizational risk perception. In an extended period of time with few extreme weather events to arouse or sustain risk perception, organizations develop a low awareness of risk, become satisfied with their current practices and no longer perceive the need for adaptation. This is exemplified by the model dynamics from approximately the 400th to the 450th ticks in Figure 3.

Scholars have proposed various approaches to enhancing sensemaking about weather risks, ranging from vulnerability assessment, climate change scenario planning, system design to simulation and training (Haasnoot et al., 2015; Kilskar et al., 2018; Melillo et al., 2014). A central goal of the strategies is to raise organizational risk perception and maintain it as a relatively higher level, particularly after the organization has experienced a consecutive series of non-occurrences of extreme weather. Would the level of adaptation improve if organizations can overcome their complacency to a certain extent? A related consideration involves the scarcity of opportunities, which is particularly true for small or bigger but financially stranded agencies. As the managers consistently note during the interviews, some organizations, especially small ones, have to wait for years before coming upon an opportunity, if any. Nevertheless, if an organization can only have one or two opportunities in a given period of time, will the decay in risk perception even help with adaptation? And to what extent?

To better understand how changes in risk perception and the scarcity of opportunities in a given period of time affect the model outcome, Figure 10 shows the mean proportion of adapters across the two conditions with the error bars representing ±1 standard deviation. The model results are aggregated from 100 model runs. The experiment builds on the baseline model to distribute 10 non-disaster-induced opportunities across the 1000 ticks. When opportunities are scarce during a given period of time, the opportunities are approximately evenly distributed, with one opportunity in every 100 time steps. In contrast, in order to have more opportunities in a given period, the experiment randomly selected a continuous series of 300 ticks and distributed all the 10 opportunities within the time interval.

Compared with the baseline model with a decay rate of 0.03, slightly lowering the rate of decay in organizations' risk perception effectively produces more adapters. The positive effect is more pronounced when organizations can have only opportunity in a relatively long period of time (i.e. 100 ticks). Additionally, when the rate of decay is significantly lowered by 50% to 0.015, the model outcomes do not show noticeable distinction between the two patterns of opportunity distribution. Referring back to Figure 9, lowering the decay in the risk perception flattens the downtrending curve and allows an organization's risk perception to stay above its tolerance for a longer period of time, thereby increasing the chance for coupling with the next opportunity. The interaction effects show that maintaining this risk-directed motivation is particularly important if the organization has to wait long before the next opportunity arises.

Figure 10. Mean Proportion of Adapters by Condition: Decay in Risk Perception and Opportunity Distribution (100 Runs)



Adjust the timing of opportunities

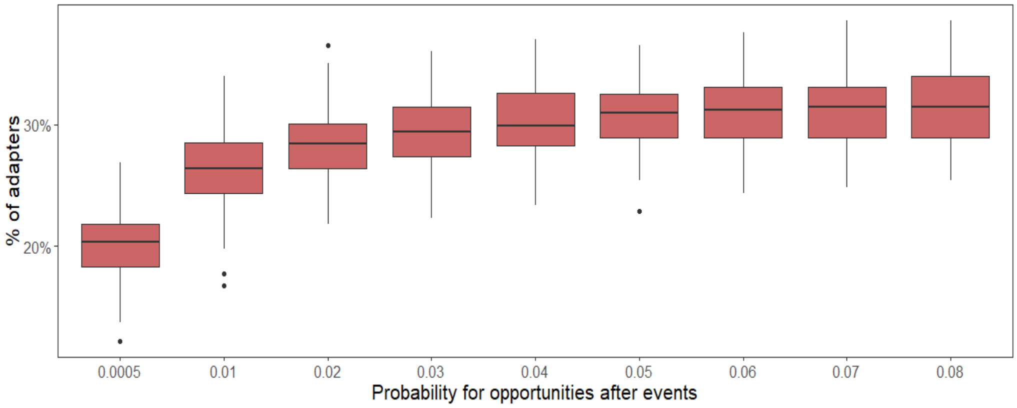
In the baseline model, the distribution of non-disaster-induced opportunities is randomly determined in the model setup, without consideration of organizational climatic conditions and decision contexts. Recent scholarship in the climate adaptation literature increasingly turns attention to the occurrence of extreme weather event as the leverage point to raise awareness of weather risks and motivate planning for adaptation (Albright, 2019; Egan & Mullin, 2017; Howe et al., 2014). Extreme weather events such as hurricanes, floods and severe storms produce a short-live but meaningful shift in people's concerns about weather risks and provides a salient point of information to question prevailing practices (Konisky et al., 2016). If risk awareness campaigns and advocacy for adaptation can be most effective when conducted after an event as the scholars suggests, can we see more adapters if we synchronize opportunities with the occurrences of extreme weather events?

To answer this question, I conducted an experiment to manipulate the way the opportunities are created. Instead of initializing the model with a certain number of non-disaster-induced opportunities randomly distributed across the model duration, the experiment dynamically generates opportunities such that there is a greater chance for opportunities in the wake of an extreme weather event. Building on the evidence that political issue-attention for extreme events to last only 2-3 years (Kimrey, 2016), the model limits the increased probability to two years (i.e. 48 ticks) after an event.

Figure 7 shows how the model results vary with different probabilities of having an opportunity in the wake of a previous event. To pinpoint the effects of timing, the experiment applies the same amount of total fund to be facilitated during the opportunities. The first boxplot shows an equivalent case with the baseline model where all time steps undistinguishably have the same probability of generating an opportunity. The probability of 0.0005 is retrospectively calibrated with the baseline model to match the baseline outcome. The other boxplots respectively raise the probability of having an opportunity after an event, while holding the probability for other ticks at 0.0005. The graph shows that by synchronizing the timing of opportunities based on extreme weather occurrences produces more adapters. The positive effects appear to taper off, partly due to depletion of the additional funding before the model run completes (not shown here in the graph).

Let’s refer back to Figure 9 to understand why this happens. When an extreme weather event occurs, organization raises their risk perception, as indicated by the uptrending segments of the risk perception curve. And the perception goes down slightly in the absence of an event, as shown in the down trending segments of the curve. In cases when extreme events elevate an organization's risk perception above its threshold to prompt motivation to act, increasing the probability of opportunities in its wake means the organization can more effectively capitalize on the motivation before risk perception gradually drops below risk tolerance. For example, in Figure 6 there are some periods of time during which the organization's risk perception is constantly above its risk tolerance, such as the one between the 150th and 200th tick , but adaptation is hindered by the absence or rarity of opportunities. Had there been more opportunities during the time intervals, the organization could see a better chance of having the boosted capacity to implement adaptation. Additionally, even if previous events only raise risk perception to a level slightly lower than the risk tolerance, having more opportunities in the wake still makes adaptation more likely if the temporally proximate events afterwards sufficiently shift the level of risk perception above its threshold. Either way, creating more opportunities in the wake of previous events can facilitate coupling between the opportunities and organizational motivation to act, thereby increasing the number of adapters.

Figure 11. Mean Proportion of Adapters by Condition: Probability of Opportunities after Events (100 Runs)



Discussion

This study combines qualitative interviews and an agent-based model to operationalize the mechanisms crucial to public organization adaptation to extreme weather events. To explain the emerging but limited adaptation practices in public organizations, it emphasizes how micro-level cognition and behavior aggregate to facilitate or impede the diffusion of adaptation across public organizations. Although the modeling is anchored in the empirical setting of transit agencies under the influence of extreme weather, the explanatory mechanisms and assumptions build on the extant theories for broader generalizability. The findings from the qualitative interviews and the computational case study offer insights about the adaptation process as public organizations react to challenges and opportunities in their natural, institutional and social environment. The primary insights are discussed below via the initially identified propositions about organizations' proactive and anticipatory adaptation to extreme events.

Proposition 1 ascribes organizational adaptation to their experience with extreme events and recognizes two mechanisms through which it occurs.

Proposition 1. The experience with frequent and impactful extreme events can drive adaptation through two mechanisms: 1) direct exposure improves risk perception; 2) disasters provide opportunities to overcome the financial constraints on adaptation.

One of the primary contributions of this study is that it articulates in greater detail how experience with frequency and impactful extreme events is a necessary but insufficient condition for adaptation. First, the interviews with transit managers broadly suggest the organization-level risk tolerance. Risk tolerance represents the maximum level of the perceived risk an organizational can tolerate before prompted to change the status quo. The level of an organization’s risk tolerance results from its cost-benefit calculation and reflects its aspiration in planning for weather risks. Organizational risk tolerance is partly determined by the weather hazard profiles facing each organization, but also varies within and between geographical regions. Integrating insights from the interview and theories about organizational changes, it is the discrepancy between risk perception and risk tolerance that determines organizational motivation to adapt, not the absolute level of risk perception per se. The modeling results show cases when organizations have developed some awareness of the risks which is nevertheless absorbed in its high level of risk tolerance. In contrast, there are organizations with a relatively lower level of risk perception that actually adapt due to their even lower risk tolerance.

Second, contrary to the widespread assumption in the policy change and adaptation literature that reform-minded organizations oftentimes have to wait for disasters to open the opportunities for adaptation, the interviews suggest that opportunities come in many forms, among which disasters is only one of the many. All interviewees concurred on the limitations of disasters to facilitate financial capacity and instead point to the opportunities created through changes to the organizations' operations and local contexts. Those opportunities are brought about by the organizations' new budget or grant cycle, bundling of adaptation project to their scheduled construction, design or upgrade, new streams of revenues or partnerships with the other organizations. The endogenous nature of the opportunities allows organizations some flexibility and autonomy in implementing adaptation, instead of having to passively wait for future disasters which may or not may open the opportunities for adaptation.

Incorporating these observation into the agent-based model leads to a third important insight: The potential benefits from both increased risk perception and additional financial resources from both disaster- or non-disaster-related opportunities can be underutilized unless there is effective coupling between the risk-directed motivation to act and the opportunities that facilitate funding for adaptation. Results from the baseline model clearly demonstrates that the majority of the opportunities can go unused when met with a lack of organizational motivation to act. Organizations can perceive the weather risks to far exceed its tolerance but have no access to opportunities to facilitate adaptation implementation, or their risk perception can be wholly absorbed by their risk tolerance, resulting in missed opportunities.

To make the insights practically useful, an important question to ask is: what mechanisms can help promote a higher level of adaptation among public organizations?

The two additional experiments represent an initial attempt to answer this question. The experiments show that a higher level of adaptation is possible through: 1) slowing in decay in organizational risk perception absent stimuli from extreme events; or 2) synchronizing opportunities with the occurrence of extreme events so that more opportunities can arise in the wake of a previous event.

Specifically, the first experiment demonstrates that lowering the decay in risk perception can produce more adapters, the effect of which is reinforced when organizations have scarce opportunities in a given period of time. The findings have important practical implications. Even if policy and managerial interventions can only incrementally slow the decay in risk perception, which is very likely the case in reality, those measures will be effective in stimulating adaptation (see Figure 10). The fact that opportunities are scarce and typically do not appear in abundance in a given period of time heightens the importance of reducing organizational to capitalize on the positive interaction effects between the two conditions.

A few tools and strategies can apply to slow risk perception decay and overcome organizational complacency to a certain extent. To begin with, the time-dependent scenarios for robust adaptation to weather risks suggests a useful decision making tool, as compared to many static endpoint climate change projections (Haasnoot et al., 2015). The scenario planning generates an ensemble of synthetic time-series of the local weather conditions and demonstrate the weather impacts under various climate futures. Through model simulations and game experiments with the key decision makers, the tool is found to raise awareness about the risks associated with climate variability and climate change for organizational decision making. Managers also need to proactively seek and work to make sense of anomalies in their climatic conditions, and critically play the role of sensegivers to influence sensemaking in the organization (Maitlis, 2005). They can do by reframing the weather risks, priming members to signals associated with extreme weather, archiving and stressing lessons learned from complacency regarding extreme weather impacts and adaptation. The communication and engagement need to go hand by hand with concrete examples, stories, narratives and visuals of what weather risks look like and their likely impacts on locally resonant values (Moser et al., 2019; Stigliani & Ravasi, 2012). The organizations can also conduct training or simulation exercises with particular elements focusing on improve individual actors' sensemaking and design programs that support participatory-sensemaking and collective sensemaking (Flandin et al., 2018). Those activities are of particular importance when extreme events do not strike for a long period of time.

The second experiment highlights that opportunities are most effective in facilitating adaptation when created after an extreme weather event. This offers useful guidance for action, which goes beyond the often advised solutions to overcome financial constraints on adaptation through making more funding available, which contradicts the identified barrier (Biesbroek et al., 2013; Moser et al., 2019). Admittedly organizations cannot manipulate the timing of all opening opportunities. But for opportunities they do have control over, the occurrence of extreme events provides an important leverage for adaptation implementation. Organizations can be strategic and thoughtful to enable those opportunities in the aftermath of an extreme weather event, especially when it occurs not too long after the previous events to best capitalize on the cumulative increase in risk perception. The considerations similarly apply to policy programs and grants geared toward enhancing resilience and reducing vulnerability of transportation systems.

Generalizability and Limitations

The model system and characteristics are motivated by observations and processes about adaptation to extreme weather in public transit agencies. But the system feature and propositions build primarily from the broader literature and theories with no specific sectoral focus. For instance, the lack of risk perception and funding are among the biggest barriers to adaptation (Bierbaum et al., 2013; Biesbroek et al., 2013; Mclean & Becker, 2019; Moser et al., 2019). The confluence of risk-directed motivation to act, windows of opportunity and solutions build largely from the garbage can model and multiple stream framework (Cohen et al., 1972; Kingdon, 1984). The generic nature of the theories and insights are likely to apply to other contexts where limited organizational adaptation to extreme events is of central concern.

Although the findings are not solely limited to transit agencies' infrastructure enhancement against extreme weather, three aspects of the model need to be noted in generalizing the findings. First, the model operationalizes adaptation as a proactive and discretionary act organizations undertake in response to the weather risks and changes in their operating contexts. To the extent that adaptation is driven in a more top-down or centralized manner, much of the cognitive barriers and refinement to Proposition 1 will become less relevant as organization shift from risk-based to mandate-direct motivation to adapt. Second, it is recognized that information and coordination hubs to promote and guide adaptation practices, such as those served by FTA official offices, are not present everywhere. In fields where information about novel practices are decentralized and technical assistance or advice is lacking, the role of organizational social networks with peers to facilitate search and identification of solutions will be heightened.

The degree to which the propositions and refinement hold true also depends on the type of adaptation measures examined. Making resilience-enhancing investment in transit infrastructure is capital intensive, hence the predominant budgetary constraint. When it comes to soft adaptations that make administrative, governance and cultural interventions to reduce vulnerability to weather risks, the barrier might be less likely to be overcome through short-lived windows, lessening the direct utility of some one-off opportunities to facilitate change. For example, it would take continuous and sustained engagement, deliberation and collaboration from organizational actors to enable vertical integration of adaptation in a multilevel governance regime (Amundsen et al., 2010; Ziervogel et al., 2019)

Conclusion

The study is premised on the imperative of public organizations to undertake anticipatory and proactive adaptation to foster resilience and reduce vulnerability as the challenges from extreme events intensify. By applying the constructs and theories from the policy change, organizational learning and climate adaptation literatures to the case of transit agency adaptation to extreme weather, the study illustrates the interplay between cognitive and non-cognitive mechanisms in hindering or facilitating organizational adaptation. The insights and refined propositions from the interviews and the agent-based model constitute the contribution of this study. Importantly, the analysis indicates that it is the risk perception in excess of the risk tolerance that forms an organization’s motivation to adapt. The results underscore the criticality of timing and the coupling between risk-directed motivation and opportunities to overcome financial constraints as the predominant barrier to adaptation.

The study makes important contributions to the climate adaptation and management literature. Through the application of ABM, it is able to comprehensively characterize the decision contexts of public organizations by integrating the behavioral, social and institutional mechanisms involved in their adaptation to extreme events. This contrasts with many studies in the domain that investigate only one or two aspects of the mechanisms. The model developed in this study also enables a dynamic view of mechanisms to better represent how organizations’ cognition evolves with their experience with extreme events and interacts with the non-cognitive factors to influence adaptation over an extended period of time. The management literature emphasizes the role of opportunities in enabling adaptation (Cohen et al., 1972; Tyre & Orlikowski, 1994), the study adds to the work by highlighting the importance of risk-directed motivation to act when the challenges are profoundly uncertain and ambiguous.

Moreover, the study tackles the consistent puzzles about the limited adaptation among public organizations: if the experience with extreme events and the aroused risk perception are what it takes to motivate adaptation, then why does adaptation remain limited after organizations have repeatedly encountered extreme events? Under what conditions does the experience with extreme events lead to organizational adaptation?

The interviews and model developed in this study uncover how the benefits from extreme events – raised risk perception and possible opportunities – are contingent on the coupling between risk-directed motivation to act and opportunities to enable adaptation. Moreover, the research goes beyond the theoretical insights to generate suggestions for possible intervention to stimulate adaptation.

Finally, this research opens up avenues for future research. The presence of organizational risk tolerance emerges as an important cognitive determinant that interacts with risk perception to determine organizational motivation for adaptation. Compared with the extensive research on risk perception, risk tolerance has received scarce attention in the extant literature. While it is clear that public organizations differ in their levels of risk tolerance, it is far less clear as to what causes the heterogeneity. Future work is invited to examine factors responsible for the heterogeneity and investigate how their effects on risk tolerance evolve with changes in the organizations' environment. Insights and findings from the work can help identify leverage points for policy and managerial intervention to lower organizational tolerance, thereby facilitating motivation for and commitment to adaptation.

Next Steps

This essay continues the efforts to unravel necessary preconditions for organizational adaptation to extreme events. It expands the cognition-mediated model in the first essay through incorporating the institutional and social contexts which interact with organization's experiences and perceptions to promote or hinder adaptation activities. Underlying both essays are the assumptions that proactive and ex-ante adaptation is imperative for public organizations to minimize loss and sustain performance in a turbulent environment. But those assumptions remain largely untested. Important questions remain unanswered about the magnitude of the impacts from the extreme events and the extent to which adaptation matters to mitigating those impacts. The third essay will seek to answer those questions.

CHAPTER 4

PERFORMANCE EVALUATION OF PUBLIC TRANSIT SYSTEMS UNDER EXTREME WEATHER EVENTS: DOES ORGANIZATIONAL ADAPTIVE CAPACITY MATTER?

Introduction

Extreme weather present significant and growing risks to the safety, reliability and efficiency of public transportation infrastructure and operations. Transit system are already experiencing costly impacts from extreme weather such as heavy downpours, tornadoes, hurricanes and severe storms, leading to damaged roads and vehicles, congested traffic, service disruptions or system breakdown. Those impacts are projected to intensify in magnitude, duration and frequency in the coming decades (Smith, 2018). In response to the climatic threats, research and policy in the transit sector have long featured mitigation as a primary means to alleviate the environmental burden of transportation (Hensher & Button, 2003; IPCC, 2007).

More recently, there is a changing orientation in the field towards adaptation measures and strategies to develop organizational adaptive capacity in a worsening climate (Hodges, 2011; Koetse & Rietveld, 2009). Although far from mainstream, adaptation efforts through vulnerability assessment and incorporation of the assessment results in decision making and planning are emerging at the federal, state and local levels (FHWA, 2018; Georgetown Climate Center, 2018; Zimmerman & Faris, 2011). Scholars across a broad range of disciplines have attempted to unravel conditions necessary for adaptation to occur, with a view to reducing barriers and facilitating adaptation to foster resilience and sustainability (Biesbroek et al., 2013; Eisenack et al., 2014; Miao et al., 2018b; Savonis et al., 2014; Zhang et al., 2018).

With adaptation now topical, it is necessary to take a step back to assess the impacts of extreme weather on transit agencies, and more importantly, the extent to which organizational adaptive capacity plays a role in their performance under the influence of extreme weather. There exists an extensive body of scholarship that investigates the effects of weather on public transportation (Guo et al., 2007; Kashfi et al., 2015; Singhal et al., 2014; Stover & McCormack, 2012). Many of the studies address weather impacts on transit ridership, using evidence from case studies on one single transit agency usually within a 3-year timeframe. However, as ridership is jointly determined by service demand and supply, a focus on ridership can confound the impacts of extreme weather on the supply side of transit services. It is not clear, for example, whether the impact on ridership stems from changes in riders' travel behavior or altered patterns of service provisions during extreme weather events.

Also lacking in the literature is a systematic assessment on extreme weather impacts across transit systems over an extended period of time. The temporal dynamics are critical to identification of factors responsible for transit performance variations over time. Notably, given the salience of extreme weather threats and the growing call for adaptive capacity development, an examination of variations in organizational adaptive capacity and their linkages to transit performance can make a fruitful contribution to inform policy and management in future adaptation planning.

This paper applies Stochastic Frontier Analysis (SFA) to quantify the technical efficiency across transit systems under the influence of extreme weather over time. Drawing on the adaptation and organization theory literature, it further investigates the extent to which the efficiency variations are linked to organizational capacity to adapt to weather impacts. Specifically, the effects of formal institution, organizational slack and contracting out are examined. The empirical analysis uses a sample of 108 U.S. motorbus transit systems located in the Midwest and Northeast during the winter season (November-February) from 2008 and 2017, merged with data from 1) National Transit Database (NTD); 2) National Oceania and Atmospheric Administration (NOAA); and 3) Georgetown Climate Center.

Determinants of Transit Technical Inefficiency

Public transit agencies and managers are tasked with numerous societal objectives, such as reducing congestion, conserving energy and improving mobility of the transit-dependent populations. The objectives of US transit agencies translate into great difficulties in applying the economic optimization to evaluate public transit performance (Fielding, 1987; Nolan et al., 2001). This study therefore adopts the technical efficiency to track the system performance over time. Technical efficiency measures the level of outputs an agency can achieve from a given bundle of inputs (Charnes et al., 1978). It is the aspect of production transit agencies have the most control over, as compared to cost or allocative efficiencies that are often subject to political or institutional forces external to the organizations (Karlaftis & McCarthy, 1997; Nolan et al., 2001).

The efficiency of a given producer is compromised when it consumes too much inputs or produces too little outputs. The producer can increase its efficiency by either reducing its inputs or increasing outputs. Owing to the exogenous and non-discretionary nature of extreme weather in transit service production, this paper uses an output-oriented model to evaluate the technical efficiency of transit systems while adjusting for the influence from *extreme weather* and organizational *adaptive capacity*.

Weather impacts

Extreme weather. Extreme weather poses significant threats to transit performance (Hodges, 2011; Meyer et al., 2012). Since transit agencies rely on exposed and vastly dispersed capital assets for service delivery, they are particularly sensitive and vulnerable to radically changing weather conditions. Flooded facilities, ice-covered tracks, clogged drains, wind-blown debris, frozen or overheated engines, damaged signal system, power outage and traffic congestion all compromise an agency’s technical efficiency. The immediate consequences ranges from increased access time, prolonged trip duration, reduced service frequency, trip cancellations to complete system breakdown (Singhal et al., 2014). The localized incidents can further propagate disruptions throughout the interconnected transit systems, at substantial costs to network mobility and efficiency (Koetse & Rietveld, 2009). Moreover, weather impacts build up over time, as repeated stress and strains from recurring extreme weather events lead to degradation of transit assets, including vehicles, support facilities and structures.

In light of the weather impacts, to produce the same level of output can entail more inputs under extreme weather conditions, hence with reduced inefficiency. This means deployment of backup equipment or vehicles to replace the damaged ones in service, contingent personnel dispatches as well as increased fuel consumption due to adverse changes in the vehicles or on the road. The more a transit agency is exposed to extreme events, the more likely its technical efficiency is to suffer.

H1: extreme weather has a negative effect on technical efficiency of transit systems.

Adaptive capacity

However, transit agencies are not invariably passive to weather impacts. Scholars have extensively proposed adaptive capacity as a key mechanism to reducing vulnerability and sustaining performance delivery in face of extreme climatic changes (Gupta et al., 2010; Hill & Engle, 2013; Tompkins, 2005). Adaptive capacity refers to the political, institutional and organizational preconditions necessary to enable adaptation. It is represented by the set of available organizational resources and capabilities as well as institutional arrangement conducive to the design and implementation of adaptation strategies and activities (Adger et al., 2011; Gupta et al., 2010). Organizations with higher adaptive capacity are more able to absorb external shocks, reorganize and sustain performance when extreme events occur. They are also expected to bounce back faster and resume normal service delivery in the aftermath of an event (Gallopín, 2006). The boosted capacity to continue reliable service delivery helps maintain technical efficiency in the case of extreme weather events. Specifically, this research will investigate the effect of formal institutions, organizational slack and contracting out on transit technical efficiency—the three critical components of adaptive capacity.

Formal Institutions. Public organizations operate in complex and overlapping institutional contexts which fundamentally shape their choices and behavior. The formal institutional environment comprises policy, regulations, laws relevant to organization response to extreme weather (North, 1990). Traditionally, public organizations have reacted incrementally and conservatively to extreme weather, either attributing them to isolated occurrences or viewing them as merely acts of God which organizations cannot do anything about (Agarwal et al., 2012; Dovers & Hezri, 2010; Kim, 1998). The upfront investment required for adaptation and non-immediate payoffs further dampens motivation to adapt (Fankhauser, 2010). Formal institutional change is therefore key to overcoming the institutional inertia to stimulate adaptation (McDonald, 2011; Nelson et al., 2007).

A supportive institution for adaptation confers the necessary legitimacy, urges and resources for organizations to undertake adaptation (Meyer & Rowan, 1977). Public organizations, regardless of their experience and norms, are obliged to conform to the institutional expectations through a spectrum of adaptive initiatives, ranging from vulnerability assessment, infrastructure reinforcement, human capital development, organizational restructuring to interorganizational collaboration (Eakin & Lemos, 2006; Kusumasari et al., 2010). Studies have also shown that adaptation enabled by formal institutions can occur at various levels and across scales (Storbjörk & Hedrén, 2011). To the extent the institutional influence is exerted on a range of social actors, the adapting organizations can also accrue substantial benefits from engagement in adaptation from other stakeholders (Eakin & Patt, 2011). In the case of transit agencies, for example, their service delivery can benefit from upsized stormwater treatment facilities, robust electric power grid, sound telecommunication systems as well as forward-thinking in land use regulations that avoid construction in weather hazard prone areas.

H2a: Formal institutional for adaptation has a positive effect on technical efficiency of transit systems.

Organizational Slack. Organizational slack is the resources available to an organization in excess of what is required for the organization's normal operation (Cohen et al., 1972; Cyert & March, 1963). Slack can aid organizations in accommodating the unexpected and evolving demands during extreme weather events, the buffer of which assumes particular important for organizations highly susceptible to abrupt climatic disruptions (Bourgeois, 1981; Egan, 2007; Kraatz & Zajac, 2001). The endowment of physical, fiscal and human resources facilitates an organization's capability to supply a variety of inbound resource sourcing and warehousing (Busch, 2011). Organizations are also able to leverage the operational flexibility in response to slow, interrupted or insufficient supply of resources, surge in demand for certain materials or temporary damage to key components. In the meantime, existing and emerging errors become more tolerable with readily available backup measures and resources, avoiding escalation into bigger problems (Landau, 1969; Stark, 2014).

Besides the immediate benefits, organizational slack can promote adaptation in the longer term. A bigger resource base at its disposal widens the range of response options an organization can deploy in face of environmental uncertainties and turbulence (Bowman & Hurry, 1993). Compared with their resource-limited peers, resource-rich organizations enjoy greater latitude in searching for and experimenting solutions in non-conventional realms. Once adaptation is put on agenda, organizations with greater discretionary resources are more able to execute adaptation activities at various levels of the organization (Eisenack et al., 2014; Gupta et al., 2010). Since it can help absorb shocks during extreme weather events and foster adaptation in the longer term, organizational slack is expected to have a positive impact on transit system efficiency.

H2b: Organizational slack has a positive effect on the technical efficiency of transit systems.

Contracting out. The transit sector has been moving away from public ownership and operations towards contractual arrangements where agencies authorize a third-party, usually a private firm, to operate and manage services. Contracting out can undermine adaptive capacity and organizational performance in a changing climate. First, the decision making and practices in private firms are fundamentally anchored in calculative rationality (Wilson et al., 2010). The rationality fosters a short time horizon in decision processes and breeds structural bias toward economic efficiency, oftentimes at the expense of other goals (Egan, 2010). The overprivileged pursuit of efficiency removes much of the auxiliary resources, leaving the system unprepared for and fragile to unanticipated shocks (Sheffi, 2005). The uncertainties associated with future climatic states and the ambiguous short-term payoffs further scare off adaptation attempts (Slawinski et al., 2017). For example, Inderberg (2011) finds that the involvement of private firms in the management of the Norwegian electricity sector and their prioritization of economic efficiency profoundly hindered the sector’s adaptation to climate change. The typical rigid public-private contractual scheme further limits the room to renegotiate allocation of risks and costs, severely constraining adaptive change during the course of contract implementation (Barlow & Köberle-Gaiser, 2009; Parrado & Reynaers, 2018).

Moreover, outsourcing oftentimes bodes ill for organizational learning, an essential mechanism for organizational adaptation (Berkhout et al., 2006; Gupta et al., 2010). It hollows out agency capacity as a result of structural devolution, loss of agency control and diminished absorptive capacity (Milward & Provan, 2003; Self, 2000). The separation from operations on the ground tends to blind the principals to the emerging risks and problems, thereby limiting their chances to detect vulnerabilities and make adjustments. With diminished knowledge, skills and competence, it is increasingly difficult for agencies to grasp trends in their environment, recognize the value of new information, assimilate it and apply to organizational operations (Cohen & Levinthal, 1990). As such, reliance on contracting is likely to hamper understanding and problem solving based on experience and feedback, reducing the possibility for organizations to make timely adaptation to climatic changes.

H2c: Contracting out has a negative effect on technical efficiency of transit systems.

Data

The research applies a few considerations to the sample selection. Extreme weather events are unusual occurrences that materialize across short time horizons and in great magnitude. The impacts on transit systems, while significant, are likely to be spread thin and difficult to discern if examined against a wide time frame in a given year. A wide time frame also introduces additional heterogeneity in event types and opens the door for countervailing effects among distinct event types or other intervening effects (Nolan et al., 2001). For example, while cold weather and winter driving can significantly reduce fuel economy and increase fuel consumption, the effects are absent under hot weather conditions. To better capture the influence of weather on transit, this research purposively confines the examination to a relatively narrow geographical scope and during a time period when extreme weather impacts are likely to be intensively experienced. The selection also helps ensure homogenous production functions across the sample, as similar weather hazards typically demand similar inputs and technology for service production.

The considerations lead to the selection of transit systems in the Midwest and Northeast during the winter season (i.e. November to February). Transit systems in the two areas face similar weather hazards during winter, primarily in the form of inclement weather and severe storms (Smith, 2018). This research identifies the transit agencies based on the entire list of full reporters to the National Transit Database (NTD), a national repository for data on financial, operating and assets conditions of transit systems across the US. The full reporting transit agencies are required to annually report transit characteristics and monthly operating data to NTD. For a homogeneous set of transit systems, the study includes only fixed-route motorbus (MB) systems in view of the intrinsic bus-rail differences in capacity, technology and infrastructure requirements. Agencies with a motorbus fleet of over 1,000 are removed (n=5) to avoid misleading size-related bias, such as the MTA network systems in New York (Karlaftis & McCarthy, 2002). The final sample includes 108 agencies operating motorbus services in the two regions.

With regard to the temporal dimension, the dataset considered in this study covers a 10-year span from 2008 to 2017, due to the data availability[2]. This time span coincides with a noticeable growth in the occurrence of extreme weather events in the US, according to the National Oceanic and Atmospheric Administration (NOAA, 2018). The use of panel data makes it possible to identify both the cross-sectional and temporal characteristics of the study systems under a changing climate. Moreover, since the emergence of public organization adaptation largely falls within the 10-year time span, the study is capable of capturing the degree to which adaptation initiatives and efforts moderate the weather impacts on organizational performance.

Stochastic Frontier Analysis

The study employs stochastic frontier analysis (SFA) to examine the technical efficiency of transit systems and the influence of the key variables on efficiency variations. SFA is a parametric approach to identify the high and low performers in a given set of entities. It works by estimating the productivity of each entity in the sample based on a specified production function relating input bundles to output. A frontier function is identified when it is impossible to achieve the same output with an input lower than the minimum input required by the production frontier. The process identifies

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[2] The NTD has missing or partial data on some key variables in years before 2008. For example, it reports each agency’s energy consumption only for directly operated services and miss data from contracted services.

the best performer(s) in the sample set. Each of the remaining entities in the sample is compared to its exemplary agency and the difference between their efficiency determines its inefficiency score.

In the current study, extreme weather and the components of organizational adaptive capacity are not immediate inputs in a production function, but represent exogenous variables believed to affect the mean of technical inefficiency. Many empirical analyses have employed a two-step SFA model to first estimate the inefficiency index in the first step, and then regress the index on a vector of exogenous variables in the second step. This approach has been extensively criticized for ignoring the dependence of the inefficiency on the exogenous factors in the first step, leading to bias in estimating the technical efficiency index and hence the second-step regression (Greene, 2008; Wang & Schmidt, 2002). The more recent SFA applications develop the single-step procedure to estimate the relationship between inefficiency and its explanatory variables simultaneously with other parameters in the model (Kumbhakar et al., 2015). This study adopts the one-step SFA procedure to estimate the influence of extreme weather and adaptive capacity on the transit technical efficiency.

Model specification

Given the panel data structure and the need to incorporate heterogeneity in technical inefficiency, the empirical analysis adopts the Battese and Coelli (1995) panel data model. A stochastic frontier production function for firm *i* in time *t* is specified as the following:

$$Y_{it} = f(X_{it}, \beta) + \nu_{it} - \mu_{it}$$

$$\nu_{it} \sim \mathcal{N}(0, \sigma_{\nu}^{2})$$

$$\mu_{it} \sim \mathcal{N}^{+}(\mu, \sigma_{\mu}^{2})$$

where Y_{it} represents the output level of the *i*th agency at the time t, X_{it} is a vector of inputs for firm *i* at time *t* which consist of the standard factors for production such as labor, equipment and capital and β is a vector of unknown parameters to be estimated. $f(*)$ is a parametric function converting the inputs to output. ν_{it} represents random errors in the production process assumed to be *iid* with a $\mathcal{N}(0, \sigma_{\nu}^{2})$ normal distribution. μ_{it} is the non-negative technical inefficiency term.

To incorporate heterogeneity in the inefficiency term, μ_{it} is truncated at zero of the normal distribution $\mathcal{N}(Z_{it}\delta, \sigma_{\mu}^{2})$. The technical inefficiency effect is specified as

$$\mu_{it} = Z_{it}\delta + \omega_{it}$$

where Z_{it} is a vector of explanatory variables that affect technical inefficiency of the firms over time and δ is a vector of unknown coefficients. ω_{it} is a random variable determined by the truncation of the normal distribution $\mathcal{N}(0, \sigma_{\mu}^{2})$ at $-Z_{it}\delta$, such that $\omega_{it} >= -Z_{it}\delta$. This is consistent with μ_{it} being a non-negative variable truncated at the $\mathcal{N}(Z_{it}\delta, \sigma_{\mu}^{2})$ distribution.

The model estimates the parameters β and δ simultaneously with the method of maximum likelihood. The likelihood function is expressed in terms of the variance parameters $\sigma^{2} = \sigma_{\mu}^{2} + \sigma_{\nu}^{2}$ and $\lambda = \sigma_{\mu}^{2}/\sigma^{2}$. The parameter λ is bounded between zero and one. When $\lambda = 0$, the model is reduced to a traditional mean response function in which the vector of Z_{it} is included in the production function (Battese & Coelli, 1995). The technical efficiency of production for *i*th firm at time t is determined as:

$$\mathrm{TE_{it}} = \exp(\mu_{\mathrm{it}}) = \exp(-\mathrm{Z_{it}}\delta - \omega_{\mathrm{it}})$$

The study uses a translog functional form to specify the production function (Christensen et al., 1973). Unlike the commonly applied Cobb-Douglas production function, translog models impose no rigid restrictions such as perfect substitution between production factors. The translog transformation also permits to pass a linear relationship between the output and inputs to a non-linear one to enable more flexibility in the relationships. Moreover, although the study focuses on the effect of the key variables on technical inefficiency, it is possible heterogeneity in those factors also affects the production function (Greene, 2004). The analysis applies a more general model by incorporating the heterogeneity in both the production function and inefficiency distribution and apply post-estimation analysis to assess this treatment.

Drawing on the efficiency studies on the transit sector, the full model for analysis is expressed as[3]:

$$\begin{aligned}\mathrm{VRM}_{it} = {} & \beta_0 + \beta_1\ln(fuel_{it}) + \beta_2\ln(vehicle_{it}) + \beta_3\ln(labor_{it}) + \beta_4\ln(fuel_{it})\ln(vehicle_{it}) \\ & + \beta_5\ln(fuel_{it})\ln(labor_{it}) + \beta_6\ln(vehicle_{it})\ln(labor_{it}) + \frac{1}{2}\beta_7\ln(fuel_{it})^2 \\ & + \frac{1}{2}\beta_8\ln(\mathrm{vehicle_{it}})^2 + \frac{1}{2}\beta_9\ln(\mathrm{labor_{it}})^2 + \beta_{10}\ln(\mathrm{pop.density_{it}}) + \mathrm{Z_{it}}\delta \\ & + \Phi(\mathrm{year.dummies_{it}}) + \nu_{\mathrm{it}} - \mu_{\mathrm{it}}\end{aligned}$$

where the inefficiency model is specified as:

$$\mu_{\mathrm{it}} = \delta_0 + \delta_1\mathrm{extremeweather_{it}} + \delta_2\mathrm{institution_{it}} + \delta_3\mathrm{slack_{it}} + \delta_4\mathrm{contractingout_{it}} + \omega_{\mathrm{it}}.$$

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[3] The cross-product between non-input variables are omitted to control the number of parameters.

The description and measures of the variables are as follows. Unless otherwise specified, the data are obtained from the NTD. The output is measured as vehicle revenue miles (VRM) an agency delivered in each winter during the study period, given its direct susceptibility to dramatic variability in weather conditions. The model includes three frequently used inputs in transit efficiency studies (De Borger et al., 2002). *Fuel* is the total amount of energy consumed in a given winter in gallons. *Vehicles* is the total number of vehicles operated by the agency in the given year, including those used in both directly purchased and contracted services. *Labor* is the total count of employees in the transit for the year[4]. The model also adds the control variable of population density to account for its effect on the production function. Finally, it includes nine terms of year dummies to account for time variations in service production (the model is inestimable with the time term included in the mean of technical inefficiency).

With regard to the exogenous variables Z-vector, *extreme weather frequency* measures the number of extreme events an agency experienced during the winter period of each year. The data is obtained from the NOAA storm events database. The database archives three types of extreme weather events: "1) the occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce. 2) Rare, unusual, weather phenomena that generate media attention, such as snow flurries in South Florida or the

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[4] The measures for labor and fuel are drawn from the NDT annual dataset. The analysis uses the annual measure of labor since it is non-decomposable and relatively stable across a year; it averages the monthly fuel consumption and multiplies it with the number of months (i.e. four) to obtain an aggregate measure of consumption in each winter. NTD also reports monthly data on the use of revenue vehicles, which better accounts for the fluctuation in service supply in different months of the year. To measure *vehicle*, the analysis averaged the number of revenue vehicles used in each winter and rounded it up to the nearest integer.

San Diego coastal area; and 3) other significant meteorological events, such as record maximum or minimum temperatures or precipitation that occur in connection with another event" (National Weather Service, 2018). At present, the database records 48 types of extreme weather events, such as heavy rain, heavy snow, excessive heat, extreme cold, high wind, winter storms, tornadoes, hurricanes and floods. For each event, the database contains a detailed record about its date, event type, geographical location and any known injuries, damage and fatalities. Based on the event details, the study identified events in each sample agency's service area by intersecting the spatial file of transit agencies' service area with the geographical coordinates of the events. The variable *extreme weather frequency* is the aggregate count of extreme weather events in an agency's service area in a given winter.

The measures on the three components of organizational adaptive capacity are informed by the adaptation and transit efficiency literatures. The extent to which transit agencies are bounded by formal institutions to adapt is systematically captured by the state-level adaptation policy to prepare for climate changes. Based on the data from Georgetown Climate Center, *Adaptation Policy* is dummy coded 1 if the state had released an adaptation plan in the year examined. For example, if a state released the adaptation policy in the year 2012, all agencies in the state would receive a value of 1 from 2012 onwards. *Organizational Slack* is measured by the difference between an organization's yearly total fund and its total operating expenditure. The variable *contracting out* is measured by the ratio of contracted vehicle hours (VRH) to total VRH the agency provided in each year. By way of eliminating bias from variation in local area layout, price levels and traffic patterns, the choice of vehicle hours over vehicle miles or revenues can more reliably capture the extent of contractors' involvement in service delivery (McCullough III et al., 1998; Zullo, 2008). It is important to note that this variable concerns only the level of contracting of routine service provisions and is not correlated with the frequency of extreme weather events. The data show a within-group correlation of 0.03 between contracting out and extreme weather frequency.

Analysis and Results

Table 5 reports the summary statistics of the variables. The data show broad heterogeneity among the sample agencies in both the input and exogenous variables. The smallest agencies run a small fleet of three or with less than ten employees, while the largest agency operates up to 851 vehicles and employ over 2000 employees. Small agencies with a bus fleet of less than ten vehicles take up 11% of the entire sample (n=12) and are retained in the stochastic frontier analysis.

With regard to the key variables, agencies experienced from 0 to 44 extreme weather events in a given winter. Climate adaptation plans are widely adopted in the Northeastern states starting from the end of 2008, whereas none of the Midwestern states released an adaptation plan during the ten years. The ratio of contracting out ranges from 0 to 0.84 at a mean of 0.18, with 83% of the agencies providing full in-house services. Organizational slack shows vast variability and contains negative values. In order to log-transform this variable, the analysis added a constant based on this variable's minimum value to make it transformable. The log value of slack ranges from 0 to 20.89.

Table 5. Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
VRM	1,073	1097624.00	1639307.00	35010.00	8218638.00
Fuel	1,073	313877.00	531660.30	2469.67	3273369.00
Vehicles	1,073	90.91	142.18	3	851
Labor	1,073	292.58	498.32	8	2987
Population density	1,073	2262.06	1583.50	161.341	13651.98
Year	1,073	5.49	2.88	1	10
Extreme weather frequency	1,073	1.58	3.95	0	41
Adaptation Plan	1,073	0.18	0.38	0	1.00
Contracting out	1,073	0.01	0.06	0	0.84
Slack	1,073	18600000.00	87300000.00	-49300000	1130000000.00

The analysis was carried out in Stata using the maximum likelihood estimation (Belotti et al., 2013). To compare the effects of the key variables on inefficiency terms, Table 6 displays the parameter estimation for two models, one with the inefficiency model and one without.

Table 6. Parameter Estimates for the Stochastic Frontier and Inefficiency Model

	Model 1	**Model 2**
	Estimate	Estimate
Frontier		
Fuel	-2.357 (0.229)***	-2.373 (0.219)***
Vehicle	1.626 (0.485)***	1.615 (0.475)***
Labor	0.451 (0.45)	0.807 (0.433)
Fuel*Vehicle	-0.173 (0.065)**	-0.207 (0.064)***
Fuel*Labor	0.059 (0.066)	0.018 (0.066)
Vehicle*Labor	0.137 (0.086)	0.317 (0.086)***
Fuel2	0.282 (0.033)***	0.311 (0.032)***
Vehicle2	-0.032 (0.122)	-0.145 (0.119)
Labor2	-0.303 (0.108)**	-0.416 (0.11)***
Population Density	-0.036 (0.006)***	-0.04 (0.006)***
Extreme weather frequency	-0.001 (0.001)	0.058 (0.019)**
Adaptation Plan	-0.05 (0.015)***	-0.153 (0.026)***
Organizational Slack	-0.02 (0.01)*	-0.143 (0.033)***
Contracting out	1.047 (0.132)***	1.502 (0.268)***
Year 2009	-0.001 (0.022)	0.015 (0.022)
Year 2010	0.029 (0.022)	0.035 (0.022)
Year 2011	0.029 (0.022)	0.034 (0.022)
Year 2012	0.031 (0.022)	0.044 (0.022)*
Year 2013	0.041 (0.022)	0.038 (0.023)
Year 2014	0.049 (0.023)*	0.059 (0.023)*
Year 2015	0.07 (0.022)***	0.073 (0.023)***
Year 2016	0.086 (0.022)***	0.089 (0.023)***
Year 2017	0.081 (0.022)***	0.078 (0.023)***
Constant	19.302 (1.005)***	20.839 (1.070)***
Inefficiency		
Extreme weather frequency		0.068 (0.019)***
Adaptation Plan		-0.217 (0.061)***
Organizational Slack		-0.137 (0.036)***
Contracting out		0.637 (0.276)*
Constant		2.515 (0.647)***
Model parameters		
σ_u^2	0.548 (1.233)***	0.022 (0.016)***
σ_v^2	0.016 (0.007)***	0.015 (0.009)***
$\lambda = \sigma_\mu^2/(\sigma_\mu^2 + \sigma_v^2)$	0.972 (1.231)***	0.591 (0.023)***
# of observations	1073	1073
# of parameters	27	31
Log Likelihood	-367.136	-429.756

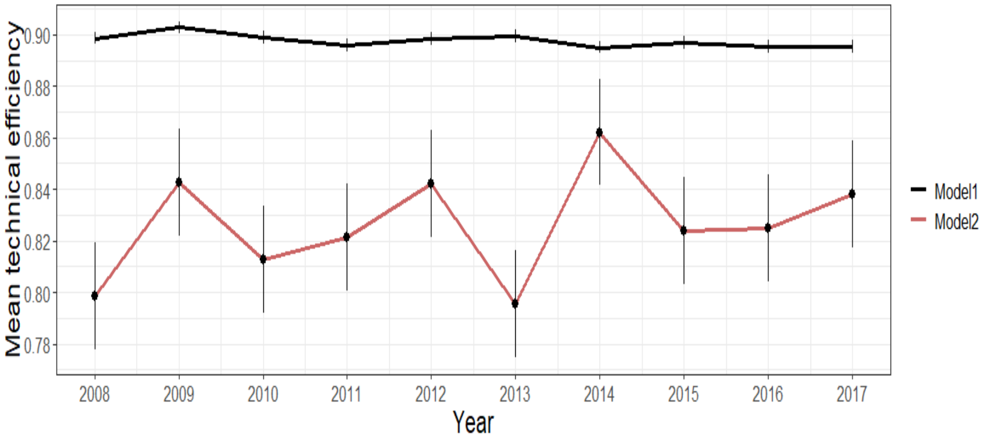
Model 1 incorporates the heterogeneity only in the production frontier with σ_u^2 at 0.551. The incorporation of heterogeneity in the inefficiency term reduces σ_u^2 to 0.022. At the same time, the residual variation σ_v^2 are almost identical in the two models. For both models, the parameter σ_u^2 is significantly different from zero, confirming the appropriateness of the stochastic production frontier. The inefficiency model also appears to provide meaningful explanation for the sources of inefficiency, as suggested by the large portion of variation explained by the exogenous variables.

The loglikelihood-ratio test between the two models shows Model 2 fits the data significantly better than Model 1 (chi-square statistics = 35.73, df=4, p<0.000). The analysis also performed a joint test on the error structure in model 2 to assess the effects on the technical inefficiencies. The null hypothesis assumes that the effects from the exogenous variables on the technical inefficiency are absent from the model. The hypothesis was rejected (chi-square statistics = 35.73, p<0.000).

In the meantime, concerns over the lagged effects of adaptation policy and organizational slack lead to robustness checks on Model 2. Although the model uses measures on adaptation policy and organizational slack based situations in the current year, it is also possible that those factors would not have noticeable effects on agency operations and output until some time later. The use of lagged measures on the two variables is therefore subject to robustness checks (see Appendix H). The two alternative models use a lagged value of adaptation policy and organizational slack by one period respectively, with all other variables unchanged. Overall, the two models show qualitatively similar results on the impacts of the key variables on the production output and efficiency, leading further support to Model 2 in Table 2.

The analysis subsequently estimates the agency-specific technical efficiency based on Model 2 using the Battese and Coelli (1988) estimator $\mathrm{E}[\exp(-\mu_i)|\epsilon_i]$ where $\epsilon_i = \nu_i - \mu_i$. For comparison purposes, Figure 12 graphs the mean technical efficiency over time under the two model specifications, the black and red line indicating the score under Model 1 and Model 2 with the error bars representing ±1 standard deviation respectively. In Model 1, the black line indicates a relatively stable average efficiency level for all the agencies hovering around 0.90, which means that the agencies as whole could increase output by 10% without incurring additional inputs. In contrast, the red curve shows an overall lower average technical efficiency at a mean of 0.83 and standard deviation of 0.14. The noticeable fluctuations also suggest higher variations. The comparison implies that, when adjusting for the influence from extreme weather and their adaptive capacity, the transit agencies are generally moved further away from the efficiency frontier, with some marked differentials across the agencies and over the study period.

Figure 12. Mean Technical Efficiency over Time in Model 1 and Model 2



In the production frontier, the population density exerts a negative influence on the output, likely because buses in denser areas travel at a lower average speed and experience more travel difficulties due to congestion or unexpected contingencies (Barnum et al., 2008). A positive technological change is consistently seen from 2012 to 2017. All the four key variables have a significant effect on the level of service production. The positive effect of extreme weather frequency on output, although surprising at the first glance, can be explained as the consequences of rerouting, prolonged travel, contingency bus dispatches such as emergency evacuations under severe weather conditions. Adaptation policy lowers the level of service output. This might suggest that the institutional requirement for adaptation can divert inputs for service production to adaptation measures that are not immediately associated with increased production. This explains the reluctance or incapability of many public organizations to undertake adaptation (Biesbroek et al., 2013; FHWA, 2016; Moser & Ekstrom, 2010). Agencies with a higher level of contracting out tend to produce more vehicle miles traveled.

The estimated coefficients on the inefficiency model are of particular interest to this study. Note the dependent variable in Model 2 represents inefficiency, so the sign of the coefficients needs to be flipped to interpret the factors' effect on technical efficiency. Hypothesis 1 proposes a negative effect of extreme weather frequency on technical efficiency. The coefficient of extreme weather frequency is positive and significant, suggesting that increased exposure to extreme weather events can lead to increased inefficiency in service delivery, confirming H1. For each additional occurrence of extreme weather event, the technical efficiency can reduce by 0.068.

The set of Hypotheses 2 relate to how adaptive capacity shift the mean inefficiency. Hypothesis H2a posits that a supportive institutional environment can boost technical efficiency. H2a is supported with a negative and significant coefficient on adaptation policy. Agencies in states with a climate adaptation plan overall score 0.217 higher than their counterparts on technical efficiency. H2b expects organizational slack to enhance efficiency through facilitating short-term buffer and longer-term adaptation. The model shows a negative and significant effect of organizational slack on technical efficiency, thereby supporting H2b. Each percent increase in organizational slack is associated with an increase of 0.137 in technical efficiency. Finally, H3c expects organizations with higher levels of contracting out to experience lower technical efficiency under the influence of extreme weather. This hypothesis is corroborated with the negative and significant effect of contracting out on efficiency. For each one percent increase in the ratio of contracting out, the agencies tend to see a reduction of 0.0064 in their technical efficiency.

Discussion

The modeling strategy followed Greene (2004) to apply a more general model by incorporating the heterogeneity from the key variables in the inefficiency term and production function, such that the heterogeneity shifts both the efficiency and level of production. The results are best discussed considering the heterogeneity effects in both models. Note that the opposite signs of effects of a certain variable in the production and efficiency model need to be interpreted with caution, as they may be due to an artefact created in the modeling strategy.

The inefficiency model confirms that increased exposure to extreme events leads to higher technical inefficiency across transit system, which at the same time increases the level of production. The seemingly contradictory findings can be attributed to the organizational coping geared toward maintaining the functionality and continuity of the existing system through local adjustments to the production function (Pelling et al., 2015). For instance, instead of suspending services, agencies can implement rerouting and longer trips to avoid the hard hit areas. Additional dispatches and travels can also occur to assist in unexpected contingencies, such as bus breakdown in the middle of a trip or emergency evacuations. However, at the same time, as H1 suggests, delivering services under radically changing conditions necessitates additional fuel, vehicles and labor to obtain the same level of output, which explains the declined efficiency.

The inefficiency model generates support for the role of adaptive capacity to modulate weather impacts on technical efficiency. Adaptation plan is found to increase technical efficiency. This, in combination with its chilling effect on the level of production, suggests the tensions across temporal scales and strategic tradeoffs in adaptation (Hill & Engle, 2013). The planning and upfront investment of adaptation can lower the absolute level of output through diverting resources ad personnel towards adaptation, thereby limiting the agencies' ability to maintain the existing service or expand to produce more. For instance, the agencies might need to temporarily suspend expansion or services to make resources available to conduct vulnerability assessment, rebuild or replace transit infrastructure or incorporate state-endorsed climate change projections in design and construction of transit projects. On the other hand, however, the temporary decline in output is likely to be compensated by improved technical efficiency as transit agencies become more resilient against a wider range of climatic variability (Folke et al., 2002; Gallopín, 2006). Further benefits can also accrue from adaptation engagement of other sector, especially given the deep dependence of transit operations on many other actors, notably the electric power providers, water treatment services and communication networks.

The results also show a positive effect of organizational slack on technical efficiency. Resource-rich organizations are more able to leverage its assets to not only adequately deliver immediate reactions to extreme weather events, but also make necessary adjustments to better prepare for a turbulent future. The negative effect of slack on the level of production might suggest the source for some of the slack: resources saved from a reduced level of service delivery in the previous periods. The alternative model using the lagged organizational slack in Appendix H, which suggest a bigger effect size of organizational slack on the service output and efficiency, further supporting the possibility.

The negative effect of contracting out on technical efficiency adds to the mixed findings of privatization on transit performance (Hensher & Stanley, 2010; Iseki, 2010; Leland & Smirnova, 2009; Zullo, 2008). Many previous studies are carried out without considering the weather impacts. This is likely to be unproblematic when the effects from sporicidal extreme events are thinned out and there is sufficient time for organizations to make slow adjustment. However, when extreme weather events are concentrated in a narrow period of time as in this study, the intensity and cumulative weather impacts become non-negligible. After adjusting for the agencies' exposure to extreme weather events, the results show that a higher level of contracting out can lead to a lower level of technical efficiency.

Conclusion

A few limitations are acknowledged. First, the study uses a purposive sample on selected transit agencies operating motorbus service in confined geographical areas during winter. Whether the findings are generalizable to agencies operating different modes of services in other regions during different points of time in the year requires empirical investigation. Meanwhile, the difficulties and feasibility associated with data collection confine the study to include only state-level adaptation policies, missing information on the agency-specific adaptation practices. The extent of the likely omitted variable bias, however, is attenuated by the empirical evidence about the limited adaptation practices among even the largest transit agencies in the US (Miao et al., 2018a).

Moreover, the study includes only the extreme weather frequency to measure exposure to extreme weather events. While the duration and magnitude of each event would make a meaningful addition, the estimation was not able to include those measures because of the limitations of NOAA storm event database. The analysis is further limited to include extreme events that are designated in counties or parishes as a result of the database structure (National Weather Service, 2018), leaving out events that are designated in forest zones which could nevertheless exert an influence on the agencies' service provisions. In that sense, the study presents an underestimated measure of the agencies' exposure to extreme weather events.

A final limitation has to do with the modeling strategy. The current model does not distinguish time persistent and time-varying efficiencies. Distinction between the persistent and varying components of inefficiency can generate important insights on the firm operation and guide managerial attention to work activities where their efforts are most likely to make a positive change (Mundlak, 1961). Future research is encouraged to search alternative databases to obtain more comprehensive measures on agencies' experience with extreme weather events, and separate persistent from time-varying inefficiencies using statistical platforms or packages where the model estimation is possible.

Despite those limitations, the study contributes to the literature in several ways. It is one of the few studies on the impact of extreme weather events on transit performance.

By using the NOAA storm events data, which classifies and documents extreme events according to the local, regional and national thresholds, the study gives due consideration to the distinct weather patterns and varying levels of tolerance for climatic variability among the study agencies. This contrasts with most previous studies measuring incremental changes in temperature and precipitation to investigate the effects of weather on transit performance (Guo et al., 2007; Hofmann & O'Mahony, 2005; Stover & McCormack, 2012). The focus on extreme weather has important implications. Weather extremes can lead to nonlinear discontinuous changes in organizational operating environment (Linnenluecke et al., 2012; Winn et al., 2011). Treating weather changes as a continuous and incremental process is not only ill-suited to extreme weather conditions, but also misses the opportunities to capture the resulting discontinuities and their challenges to transit performance.

With transit agencies increasingly called upon to adapt to weather risks (FHWA, 2018; Meyer et al., 2012), the study confirms the necessity of adaptation with empirical evidence that each additional extreme weather event can reduce the transit technical efficiency by 0.068. The use of the general model to estimate the exogenous effects on both the production function and efficiency distribution helps uncover organizational coping mechanisms during extreme weather shocks. About 6 percent more vehicle revenue miles need to be delivered for each additional extreme weather occurrence. Through making local adjustments to the production function, coping has the advantage to meet pressing demands and maintain functionality while undergoing the changes (Chhetri et al., 2019). At the same time, however, it is important to recognize that coping is inadequate to prevent future monetary or physical damage. It can further become increasingly expensive and unsustainable as repeated extreme weather events exacerbate those damages. The situations becomes more severe when coping diverts resources from longer-term adaptation, masks the real vulnerability of the system and counters any incentives or attempts for adaptive change (Adger et al., 2011; Linnenluecke & Griffiths, 2010).

The study goes beyond the quantification of the weather impacts to investigate the role of adaptive capacity in shaping the relationships between extreme weather and performance. As such, the study does not only empirically confirm the necessity for adaptation to reduce weather impacts, but also provides insights about how to do so. First, the findings make explicit the tensions between adaptation policies with a longer-term vision and coping behavior aimed at addressing proximate causes of disruptions. We should not be surprised that the nearer term benefits can usually override longer term visions, a recurring barrier to adaptation across many of the climate adaptation studies (Adger et al., 2011; Dovers & Hezri, 2010; Hill & Engle, 2013; Magnan et al., 2016). It is expected that the evidence of the positive effect of adaptation policies on organizational performance despite the short-term costs can incentivize adaptation policy making and implementation.

Meanwhile, the study also helps transit management gain a more detailed understanding of the implications of organizational slack and contracting out as they navigate a worsening climate with increasing frequency and magnitude of extreme weather events. The chilling effects of contracting out on efficiency is of particular importance to agencies with high levels of outsourced services, especially those that rely 100% on contractors for service provision. It is time for the agencies to incorporate extreme weather considerations in their outsourcing decisions and contractual arrangement. The agencies' inability to keep up with the challenges from extreme weather events would warrant the need for adaptive capacity building (Zhang et al., 2018). The study invites future research to investigate other adaptation pathways for transit agencies to maintain or improve performance as the operating environment deteriorates.

CHAPTER 5

CONCLUSION

Extreme events have become and will continue to be a salient threat to today's public administration. The escalating challenges undermine the adequacy of the prevailing emergency management and urgently require a paradigm shift from an incident response mode to more proactive and anticipatory adaptation (Boin & Lodge, 2016; McEntire, 2008). On the other hand, however, extensive evidence points to the slow and rare adaptation in public organization (Hill & Engle, 2013; McEntire et al., 2010; Somers, 2009; Welch et al., 2016). If adaptation is the right strategic choice in the face of a worsening environment, why have public organizations taken limited action to raise preparedness and resilience?

This three-essay dissertation sets out to tackle this central puzzle by investigating distinct aspects of public organization adaptation to extreme events, all based on data and observations from US public transit agencies under the influence of extreme weather. The first essay builds a theoretical framework to uncover the pathways through which extreme events impacts organizations and identify the key learning mechanisms involved in adaptation. Using a structural equation model on data from a 2016 national survey on the largest transit agencies, the study highlights the critical role of risk perception in channeling environmental signal to organizational adaptive responses. The second essay examines how adaptation unfolds in interrelated contexts consisting of the natural hazards, organizations, policies and social networks. It combines an agent-based model with qualitative interviews to examine the process of adaptation over time. The study underscores the criticality of timing and the coupling between risk-directed motivation and opportunities as the predominant barrier to adaptation. The third essay switches the focus to organizational outcomes. It employs a stochastic frontier analysis to quantify the impacts of extreme events on organizational performance and assess the extent to which organizational adaptive capacity modulates the impacts. Using a panel dataset on a selected sample of US transit agencies and extreme weather from 2008 to 2017, the results confirm the negative impacts of extreme weather on transit agency performance as well as the positive effects of adaptive capacity in mitigating those impacts.

The three essays build on each other, progressively advancing our understanding about public organization adaptation to extreme events. The first essay predicts organizational adaptive response based on their direct experience with extreme events. The results show that even if an organization experiences more extreme events and suffers more impacts, adaptation is not likely to occur if the organization does not perceive the systematic risks associated with the extreme events and becomes concerned about the impacts. However, the use of cross-sectional data confines this study to a static view of risk perception, which deviates from the empirical evidence about the dynamics in risk perception process (Haasnoot et al., 2015; Rogers, 1997). This study also leaves open the question regarding the absence of adaptation when an organization's risk perception is high after repeated extreme events. Under conditions of high risk perception, how does adaptation occur or not occur?

The second essay addresses the limitations by enabling a dynamic view of risk perception. Combining an agent-based model and qualitative interviews with key decision makers, it explicitly simulates how risk perception evolves with organizations' experience with extreme events as well as their efficacy in dealing with the impacts. Moreover, building on the extant theories and the interview insights, the study extends beyond risk perception to include risk tolerance, opportunities to overcome financial constraints and social learning involved in organizational adaptation. As such, it enables an integrated framework about how public organization adaptation unfolds over time in a complex and interrelated system consisting of the hazards, organizations, institutions and social networks. The integration better articulates why the experience with frequency and impactful extreme events is a necessary but insufficient condition for organization adaptation. The analysis indicates that although the experience can raise organizational perception of risks, the risk perception needs to be examined relative to risk tolerance to determine organizations' motivation to adapt. The results further pinpoint the coupling between the motivation and opportunities to overcome financial constraints as the predominant limiting factor to adaptation.

The findings suggest two conditions under which high risk perception can fail to produce adaptation: 1) The organization has an even higher risk tolerance so that an action threshold is not reached; 2) The organization has exceeded the action threshold, but lacks the financial capacity to implement adaptation, which can occur with or without the opening of opportunities to overcome the constraints. This essay goes beyond theoretical insights to identify micro-level mechanisms with most leverage in promoting adaptation practices among public organizations. Specifically, the experiments suggest that a higher level of diffusion is possible by: 1) lowering the decay in organizational risk perception; and 2) synchronizing the opportunities with extreme weather occurrences. The first two essays focus on identifying preconditions for organizational adaptation, with the implicit assumptions that public organizations are experiencing negative consequences from extreme events and that adaptation can help build adaptive capacity and sustain performance under environmental turbulence. However, both assumptions remain largely untested. The third essay examines the assumptions by quantifying the impacts of extreme weather and organizational adaptive capacity on organizational performance. The analysis results validate the two assumptions and lend empirical support to research efforts geared toward identifying mechanisms through which organizational adaptation occurs. The study also complements the previous two essays through unmasking organizational coping under extreme weather and the tensions across temporal scales in adaptation planning: adaptation might hurt organization's output in the short term, but it can improve the organization's efficiency in the longer term. In particular, the findings about the coping behavior reinforce the model implementation in essay two where organizations lean toward better coping solutions before resorting to adaptation. Those results also generate additional insights about the barriers to adaptation, further explicating the limited diffusion of adaptation practices in public organizations.

Broader Applicability to Other Areas

Taken together, this dissertation develops a comprehensive and integrative understanding about public organization adaptation to extreme events. Despite its empirical focus on public transit agencies under the influence of extreme weather, the theoretical frameworks and insights have the promise for broader generalizability. The theory development throughout this dissertation primarily build on generic theories in the field of public administration, policy change, organization learning as well as climate adaptation. To the extent public organizations are susceptible to perturbations and disruptions from their environment, the framework about how extreme events impact public organizations and how public organizations can reduce vulnerability through adaptation has wider applicability. Salient examples are organizations with exposed, fixed and networked physical assets such as those in water, energy and communications sectors. Findings from the dissertation should also improve appreciation of the mechanisms and barriers involved in adaptation in other types of public organizations, especially when hard adaptations are concerned.

On the other hand, extreme weather shares with many other types of extreme events in their increased frequency, severity and salience, such as disease outbreaks, infrastructure failures and cyberattacks. Those events are also associated with profound uncertainties and complexities which persistently plague the decision making and planning for adaptation. Typically the need for adaptation is not recognized until the event has manifested and the damage already been done, as has been woefully demonstrated amid the ongoing COVID-19 pandemic worldwide. Those common characteristics help broaden the generalizability of theories and findings in this dissertation. Future work is invited to apply the theories and findings to other sectors and other types of extreme events to examine their applicability. It is also anticipated that the applications will form the baseline for comparative research and open the door for theory development.

Contribution to Theory

A primary objective of this dissertation to unravel preconditions and mechanisms through which public organization adaptation takes place. One major takeaway is that public organizations typically have to adapt after experiencing extreme events. Adaptation without experience is difficult as the threats and risks associated with extreme events only become evident and relevant after they manifest themselves with significant impacts. The lean administrative and operational systems, other pressing needs public organizations have to accommodate as well as the lack of publics around issues on extreme events lead to slow and scarce adaptation to extreme events in the public sector. Since watching others going through extreme events or disasters generally does not raise an organization’s risk perception, the complacency about extreme events usually goes unchallenged in routine situations. But herein lies the danger of complacency: when extreme events actually strike, many public organizations find themselves unprepared for and overwhelmed by the extraordinary demands to provide protection for life and property, with dire consequences to the society at large.

While the experience with extreme events can elevate an organization’s risk perception, diminish complacency and increase the opportunities to overcome financial constraints, those benefits can fail to produce adaptation. The reasons are twofold. On the one hand, an organization’s risk perception can be absorbed by its risk tolerance, either because the tolerance is too high for its risk perception to ever reach the action threshold or because the decay in risk perception gradually drags it down the threshold. Significant decay in risk perception and resulting complacency can even occur in disaster-prone area when extreme events do not strike for a relatively extended period of time. On the other hand, a risk-directed motivation to adapt can arise when the organization does not have sufficient financial capacity to conduct the target adaptation. While waiting for opportunities, the organization's risk perception can adjust downwards, dragging it below the threshold so as to miss the upcoming opportunities. Alternatively, the motivation can converge with future opportunities which nevertheless do not generate or facilitate enough additional financial capacity to implement the adaptation.

This dissertation makes contributions to both the public administration and adaptation literatures. With regard to the field of public administration, it contributes an alternative approach by emphasizing the escalating vulnerabilities and the imperative of ex-ante organizational adaptation as the challenges intensify. It does so through 1) orienting attention to the non-random generation of risks, recurrence of extreme events and commonality across various event types, thereby distinguishing from most public administration research that focus on one-off episodes (Christensen et al., 2016; Stark, 2014); 2) systematically theorizing and examining the functioning of public organizations in a turbulent environment. This approach opens the door to connecting the study on extreme events with mainstream organization and management theories and build knowledge that can apply across seemingly unique risk settings. The theoretical insights about how and why adaptation to extreme events occurs or not can be generalized to other sectors and other types of event types. As public organizations grapple with the new normal characterized with ever-growing challenges from extreme events, the paradigm shift from ex-post response to ex-ante adaptation promises to enhance the chances for organizations to accommodate the changes and without incurring too much disruption or failure (Boin & Van Eeten, 2013; Somers, 2009).

The dissertation's approach is organizational, drawing primarily from organization theories and focusing on the decision making and behavior of public organizations. It is one of the few theoretically informed empirical research efforts on core public organizational adaptation and resilience (Boin & Van Eeten, 2013; Christensen et al., 2016). Some might point out the existence of generic approaches evident in the theory of high reliability organizations (HROs) or normal accidents (Perrow, 1984; Rijpma, 1997; Roe, 2016). But those theories are devoted to generation of risks and accidents endogenous to complex systems with predictable vulnerabilities, lacking applicable lessons and guidance for externally induced perturbations and shocks some of which the organization has never experienced or anticipated. HROs such as nuclear power plants and aircraft carriers are characterized with a preoccupation with errors and failures, a collective commitment to reliability, high technical competence as well as institutionalized practices to manage hazardous operations and materials (Boin, 2009; Frederickson & LaPorte, 2002). Their resources, competence and consistency in delivering high reliable performance would be difficult or impossible to replicate and maintain elsewhere (Egan, 2007).

Moreover, the dissertation takes an interdisciplinary approach to study adaptation, both theoretically and methodologically. Theoretically, it incorporates insights from public administration, policy change, organization theory, adaptation and transportation literatures to inform understanding and theorizing about how public organizations are impacted and respond to extreme events. The integration matches up with the reality of extreme events management in the public sector that plays out in overlapping organizational, political and institutional contexts and is better able to illuminate the mechanisms under which adaptation occurs. Methodologically, it applies multiple methods to disentangle the complexity and dynamics involved in organizational adaptation to extreme events. By doing so, the dissertation enables insights and advances understanding about public organization adaptation to extreme events in ways that are otherwise inaccessible.

This dissertation also contributes to the adaptation literature. The adaptation literature has a primary focus on adjustments to relatively continuous and incremental changes to achieve better fit with the environment. Most adaptation studies feature adaptation to changes in the political, economic, social and technological parameters, with little focus on changes in the natural environment (Linnenluecke et al., 2012). Figuring prominently in this line of research is the dealing with gradual, average and relatively continuous environmental changes (Nelson et al., 2007; Rayner & Prins, 2007; Smithers & Smit, 1997). But changes in the mean environmental conditions are most noticeably experienced when they materialize across short time horizons and in great magnitude, such as extreme weather events (Yohe & Tol, 2002). In domains of climate change and other natural hazards, it is to those dramatic variabilities that many adaptations are usually made (Berrang-Ford et al., 2011; Smit et al., 2000). Additionally, the deep-rooted notions of "business as usual", in which extreme events are treated through strategic scanning or crisis management, helps to perpetuate a false sense of security and blind organizations to the exacerbation of vulnerability in a changing environment (Meyer et al., 2005; Roux-Dufort, 2007).

The paucity of attention to discontinuous and non-linear changes makes the extant literature an inadequate reference for researchers and practitioners to conceptualize and analyze adaptation in those circumstances. This dissertation contributes to the organizational adaptation literature with a systematic and focused investigation on extreme events large enough to punctuate the presumed equilibrium and sensitize problem perception. Giving due consideration to the peculiar characteristics of extreme events and their implications, it provides a conceptual foundation for understanding adaptation to increasingly discontinuous changes. In particular, the dissertation offers theoretical and practical insights about the mechanisms promoting organizational adaptation to changes associated with extreme environmental conditions.

The focus on public organizations also contributes to the adaptation literature. There exists an extensive literature on adaptation by individuals or households to extreme changes in the natural environment, notably in the areas of agriculture, water and energy (Below et al., 2012; Deressa et al., 2009; Grothmann & Patt, 2005; Mertz et al., 2009; Meza & Silva, 2009). When it comes to other levels of analysis, the attention to communities and societies stands out (Adger et al., 2005; Hill & Engle, 2013; Naess et al., 2005; Pelling & High, 2005). Notably missing in the examination are the role of the meso-level actors and variables in mediating and coordinating the planning and implementation of adaptation. Although organizations are the primary social actors involved in choosing and enacting responses to extreme events, studies on organizational adaptation are only starting to gain a larger presence in the management and adaptation literature (Bremer & Linnenluecke, 2017; Galbreath, 2014; Hoffmann et al., 2009; Linnenluecke & Griffiths, 2010; Winn et al., 2011), with very few of those studies focusing on public organizations. However, ultimately public organizations are the predominant actors in providing or stimulating adaptation to adverse changes in the natural environment (Daddi et al., 2019; Dovers & Hezri, 2010; Klein et al., 2017). They differ from private firms in terms of their multidimensional goals, political constraints and institutional embeddedness, all of which can differentially and remarkably shape their adaptive behavior and therefore warrant separate treatment.

Finally, since there a marked degree of separation of adaptation studies from public management and policy development from the cognate sectors (e.g. emergency management, transportation and water) (Dovers & Hezri, 2010), this dissertation fills this crucial gap through unpacking the processes of adaptation within public policy and administrative systems at the subnational jurisdictional scales. The ultimate purpose of research inquiry on adaptation is to inform public managers and policy makers on the necessary conditions and measures through which adaptation can be accomplished. By imbuing the research with a public administration lens, this dissertation generates insights about what should be done and what is feasible among public organizations which are critical to influence on-the-ground managerial and policy change and implementation.

Contribution to Practice

To begin with, this dissertation validates the major assumptions in many of the adaptation studies. It confirms the negative impacts from extreme events on public organizations and role of adaptive capacity in modulating those impacts. Given its empirical setting in the transit sector, transit agencies stand to benefit from a quantitative assessment of the influence of extreme events on their performance (i.e. extreme weather in this case). As organizational change and innovation are best triggered in conditions of underperformance or performance decline (Meier et al., 2015; Nicholson-Crotty et al., 2017; Singla et al., 2018), quantitative understanding of weather-induced impacts is expected to strengthen the motivational basis for adaptive response.

Moreover, the dissertation provides empirical evidence for the effectiveness of adaptive capacity in mitigating extreme weather impacts. As such, it extends beyond the commonly applied techniques that evaluate adaptation efforts through analyzing government documents (Baker et al., 2012; Brouwer et al., 2013; Reckien et al., 2014; Stults & Woodruff, 2017). The findings about the chilling effects of contracting out on organizational performance signifies the importance of public organizations to incorporate considerations about weather risks in their outsourcing decisions and implementation details. In order to form a more comprehensive and timely understating of the threats from extreme events and their growing vulnerability, contracting organizations need to install mechanisms to gain more information and control about their operations and service delivery. Intentional efforts are also required to foster adaptive capacity, both independently and in collaboration with the contractors. Those implications are particularly important for organization with a heavy reliance or 100% reliance on contractors for service delivery. Additionally, the positive effect of formal institution on organizational performance reinforces the needs for public organizations to conduct proactive and deliberate adaptation, despite the likely short-term compromise in the organizations' service output. The quantitative evidence of the tradeoff between the coping and adaptation is expected to lend confidence to policy makers and managers sitting on the fence between the two options.

More importantly, the dissertation generates insights on interventions to promote adaptation among public organizations. First of all, it demonstrates the criticality of risk perception in translating environmental signals to organizational adaptive behavior. The findings further show that lowering risk perception decay can effectively stimulate adaptation. The ups and downs in risk perception as a result of their experience with extreme events underline the important of applying transient (i.e. time-dependent) scenario planning to accommodate the dynamics in environmental change and human decision making process (Haasnoot et al., 2015). Those tools construct boundary conditions and integrate time-series climate to simulate climate conditions under varying scenarios, instead of relying on static endpoint projections. Meanwhile, given their significant effect on formulating organizational interpretation of environmental change, public managers need to take on the role of active sense-givers to raise attention to and concerns about extreme events. As previous studies suggest (Tisch & Galbreath, 2018; Weick, 1988), they can do so through priming members to notice the threats and framing them in a way that appeals to the organization's values and norms. Effective communication needs to include the use of concrete examples and material artefacts, such as visualizations, simulation tools and archival of lessons learned from previous events. In addition to use of factual information and cost-benefit analyses, it is also critical to link the communication with specific reference events, such the most recent extreme events, to evoke memories and emotions about the disruptions and consequences (Roeser, 2012; Vasileiadou & Botzen, 2014).

This dissertation also demonstrates that synchronizing opportunities to event occurrence can produce more adapters. Reform-minded public organizations should be strategic and deliberate in timing their adaptation project, which would be most effective for implementing adaptation when set in the wake of an extreme event. The same strategy also applies to policy programs and grants, particularly those geared toward the raising public organizations' resilience against further shocks.

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APPENDIX A

CRITERIA FOR INFRASTRUCTURE-BASED CAPACITY

The respondents were asked to rate the state-of-good-repair of their agency's infrastructure, using the following scales:

- Poor - Asset is past its useful life and is in need of immediate repair or replacement; may have critically damaged component(s)
- Marginal - Asset reaching or just past the end of its useful life; increasing number of defective or deteriorated component(s) and increasing maintenance needs
- Adequate - Asset has reached its mid-life (condition 3.5); some moderately defective or deteriorated component(s)
- Good - Asset showing minimal signs of wear; some (slightly) defective or deteriorated component(s)
- Excellent - New asset; no visible defects

APPENDIX B

SUMMARY STATISTICS ON RISK PERCEPTION

	# of Respondents	Proportion
Risk perception 1		
Category 1	23	0.08
Category 2	47	0.16
Category 3	89	0.29
Category 4	111	0.37
Category 5	33	0.11
Risk perception 2		
Category 1	12	0.04
Category 2	37	0.12
Category 3	133	0.45
Category 4	104	0.35
Category 5	13	0.04
Risk perception 3		
Category 1	16	0.05
Category 2	49	0.16
Category 3	89	0.30
Category 4	123	0.41
Category 5	24	0.08

APPENDIX C

MAJOR STAGES AND STEPS TO BUILD AN AGENT-BASED MODEL

Figure 4 shows the major stages and steps involved in building an agent-based model. The process is described as follows.

1) Specification and formalization. In this early stage, researchers need to precisely specify the reference pattern and identify the research question. Typical research questions are concerned about explaining how social phenomena observed at the system level can emerge from behavior and interactions at the level of its constitutive units. Extensive literature review follows to discover plausible and testable causal mechanisms underlying the social phenomena. Understanding of the causal mechanisms can help researchers specify the behavioral rule for agents and generate theoretical propositions to be tested. A final procedure in this stage is to express the behavioral rules in a formal language, using logics or mathematics.

2) Modeling, verification and experimentation. Once the behavioral rules are formalized, the research encode them into a computer language to build a formal model. Verification, which examines whether computer code correctly implements the model formulation, is a critical activity to avoid error in the computer code and ensure the validity of model results. When the agent-based model can generate an outcome congruent with the reference pattern, it indicates that the micro-level specification can provide a candidate explanation for the emergent macro pattern of interest.

3) Calibration and validation. Calibration involves tuning model parameters to align model outcome with the reference pattern being modeled. Both qualitative and quantitative matching can apply in calibration, depending on the objective of study and the levels of data resolution available. Model validation concerns the extent to which the

computerized program represents the real system (i.e. the target) and can be relied on to understand its behavior. Since the simulated model is only an approximation of the target system and process, validation is a key process to build a case for the credibility and usefulness of the model under certain conditions. Model validation can ensure the theories, behavioral rules, initial conditions and structures incorporated in the model reproduce the representative behavior of the system. The computationally generated output can also be compared with either the empirical data or the reference pattern to check if the model captures the essential system features (Railsback & Grimm, 2011).

APPENDIX D

INTERVIEW SUBJECT SAMPLE DISTRIBUTION

Region	**Agency**	**Location**	**Position**	**ID**
West	Agency 1	Big City	Senior Transportation Engineer	Interviewee 1
Midwest	Agency 2	Big City	Strategic Director	Interviewee 2
West	Agency 3	Big City	Emergency Management Director	Interviewee 3
West	Agency 3	Big City	Director of Risk Management	Interviewee 4
West	Agency 4	Big City	Chief Sustainability Officer	Interviewee 5
South	Agency 5	Big City	Assistant General Manager of Operations and Maintenance	Interviewee 6
West	Agency 6	Medium City	Customer Service and Contract Compliance Manager	Interviewee 7
West	Agency 7	Big City	Assistant Chief Operating Officer	Interviewee 8
West	Agency 7	Big City	Emergency Management Director	Interviewee 9
West	Agency 7	Big City	Environmental Engineer	Interviewee 10
South	Agency 8	Medium City	Deputy Chief of Transportation	Interviewee 11
South	Agency 8	Medium City	CEO	Interviewee 12
Northeast	Agency 9	Big City	Manager of Emergency Preparedness	Interviewee 13
Northeast	Agency 9	Big City	Director of Planning	Interviewee 14
Northeast	Agency 9	Big City	Acting General Manager	Interviewee 15
West	Agency 10	Big City	Emergency management specialist	Interviewee 16
West	Agency 10	Big City	Civil Design Manager	Interviewee 17
West	Agency 10	Big City	Director of Public Safety	Interviewee 18
South	Agency11	Big City	Director State of Good Repair	Interviewee 19

APPENDIX E

INITIAL INTERVIEW PROTOCOL

1. Has your agency implemented any measures to enhance resilience of the transit facilities or infrastructure against extreme weather impacts? If so, what are those?

2. When did your agency implement those resilience measures? What motivated the decision?

3. How did your agency identify the resilience measures, given there are a wide range of resilience measures an organization can undertake? What are the criteria for selecting the measures?

4. To what extent is the identification and selection of resilience measures influenced by other agencies, particularly transit agencies? How would you characterize the role of the regional FTA office or other hubs in this search process for resilience measures?

5. After your agency has decided on a resilience measure, what would it do when there are insufficient resources or capacity to implement the identified solution? Do you have any workaround strategies?

6. Do weather disasters help your agency obtain additional funding to implement resilience projects? In what ways? For example, I know there are FEMA funds through disaster declaration as well as FTA Emergency Relief funding (ER). Since your service area is prone to weather disasters, I wonder if disasters can help obtain additional funding to implement the resilience measures?

7. Would it be possible for agencies to fail to obtain funding in the wake of weather disasters, be it the ER or other funding? How?

8. Finally, what do you see as the biggest challenges for transit agencies to incorporate resilience measures in their operations and planning against extreme weather impacts?

APPENDIX F

CONCEPTUAL FRAMEWORK: SYSTEM FEATURES , CONSTRUCTS AND COMPUTATIONAL REPRESENTATION

System Features	Construct and assumptions	Computer representation
Risk perception: A model of adaptation in public organizations to extreme weather events needs to capture the organizational perception of extreme weather risks.	1. The considerable uncertainty and ambiguity associated with extreme events, combined with the institutional and culture inertia in dealing with risk events, makes risk perception a necessary cognitive precondition for adaptation. 2. Risk perception channels the environmental stimuli to organizational adaptation. That is, experience with extreme weather increases risk perception, which in turn can prompt motivation for adaptation. 3. Risk perception is a joint function of the frequency of extreme events and their impact on the organization.	1. Risk perception is operationalized as the product between an organization's *expected* probability of extreme weather and the impact on the organization of the extreme weather occurs. 2. Each organization raises its expected probability of extreme weather when experiencing an extreme weather event, and slightly lowers the expected probability in the case of non-occurrence. 2. Each organization starts with a solution of varying levels of efficacy to mitigate weather impacts. The impact from extreme weather is determined by the gap between an organization's solution efficacy and the weather intensity, such that a higher solution efficacy can better reduce the weather impacts.
Risk tolerance: A model of adaptation in public organizations to extreme weather events needs to capture organizations' tolerance about extreme weather risks.	1.Risk tolerance is the upper limit of an organization's perceived risk beyond which changes will be worth pursuing for their anticipated benefits as compared to the status quo. 2. Organization differ in their levels of risk tolerance, both within and between geographical regions.	1. Each organization is initialized with a certain level of risk tolerance through a random normal distribution. To recognize the influence of weather hazard profiles on risk tolerance, agencies in the same region share the common mean for determining their level of risk tolerance. 2. To reflect the varying weather hazards across regions, the common mean for risk tolerance is set to be lowest in the South and highest in the West, with Northeast and Midwest in the middle.
Financial constraints: A model of adaptation in public organizations to extreme weather events requires capturing the opportunities that facilitate financial resources for adaptation	1. Limited financial resource is a recurring non-cognitive barrier to adaptation 2. Political attention is scarce and limited and extreme weather events usually do not feature high on political agenda, hence inadequate resource support for adaptation. 3. Weather disasters open the opportunities for organizations to capitalize on the political attention and momentum for action, thereby boosting their financial capacity for adaptation.	1. The model follows the garbage can model (Cohen et al., 1972) to represents the organizations, solutions, opportunities. 2. Motivated by weather risks, each organization can switch to adaptation to more effectively mitigate weather impacts. When an organization does not have sufficient capacity to implement the target adaptation, it waits for the opportunities to come by. 3. The model includes two types of opportunities: 1) Disaster-induced opportunities which become available when a weather disaster receives presidential disaster

	4. Opportunities can also open in the absence of weather disasters, due to factors more endogenous to each organization’s operations and local contexts.	declaration; 2) Non-disaster-induced opportunities which are randomly distributed across the model run during the model initialization. 4. A window for adaptation emerges when three conditions are met: 1) An organization’s risk perception is higher than its tolerance; 2) The organization has an adaptation solution ready; 3) The opportunities facilitates sufficient financial resources to carry out the adaptation.
Social learning: A model of adaptation in public organizations to extreme events requires incorporation of social learning from other organizations	Organizations also learn about adaptation tools and strategies from their connections. This type of learning is not restricted to geographical proximity.	1. The model initiates three networks for each agency: 1) ties with peer organizations in the same region; 2) ties with organizations in other region; 3) ties with the information and coordination hub in their region. 2. In their search for alternative solutions, each organization can access the adaptation practices from their three types of network.

APPENDIX G

MODEL ELEMENTS

Attributes	**Description**	**Initial value**
Transit agency		
Financial	Capacity based on resource endowment and system characteristics to implement a certain solution	Floating point ranging from 0.016 to 4.184
Risk tolerance	The maximum level of perceived risk acceptable to a given agency	Normal distribution with a certain regional mean and standard deviation of 0.1. The regional mean ranges from 0.4 to 0.7.
Expected extreme weather probability	The probability at which an agency expects to have an extreme weather event. Note it can deviate from the true probability of extreme weather	Initial value equals the objective extreme weather probability
Disaster declaration rate	The percentage of disasters that receive presidential declaration	Floating point ranging from 0 to 0.076
Worst weather intensity	The maximum level of weather intensity an organization typically plans for.	8th percentile in the weather intensity vector sorted from high to low, suggesting an agency plans to offset the risk of extreme weather events that have an 8% of chance of occurrence.
Impact reduction	The extent to which an agency can reduce the impact from the worst weather scenario through improving coping solutions	Floating point ranging from 0.10 to 0.40
Maximum impact reduction	The maximum extent to which an agency can reduce the impact from the worst weather scenario through coping	0.4
Scanning Range	The range at which an agency can reach out to seek adaptation solutions.	4
Minimum number of a certain type of network ties	This specifies the minimum number of ties an agency has within or outside their region, which is entered in the algorithm to generate networks where organizations with bigger capacity are better connected.	1
Maximum number of non-disaster-induced opportunities	The maximum number of opportunities induced by non-disaster forces.	10
Natural environment		
Extreme weather probability	The probability at which an extreme weather event occurs to each agency in a given time step	Floating point ranging from 0 to 0.145.

Weather disaster probability	The probability at which a weather disaster occurs to each agency in a given time step	Floating point ranging from 0 to 0.111
Solution		
Efficacy	The efficacy of a solution to mitigate extreme weather impact. Coping solutions have lower efficacy than adaptation solutions.	Efficacy for coping solutions: Floating point ranging from 0.05 to 1
		Efficacy for adaptation solutions: Floating point ranging from 1.5 to 3.
Cost	The cost required for implementing a certain solution. Coping solutions cost less than adaptation solutions.	Cost for coping solutions are initiated as lower than an agency's capacity, so that all agencies are able to implement coping solutions.
		Cost for adaptation solutions: floating point ranging from 2 to 6.
Adaptation	A Boolean variable indicating the two types of solutions (i.e. coping versus adaptation).	(0,1)

APPENDIX H

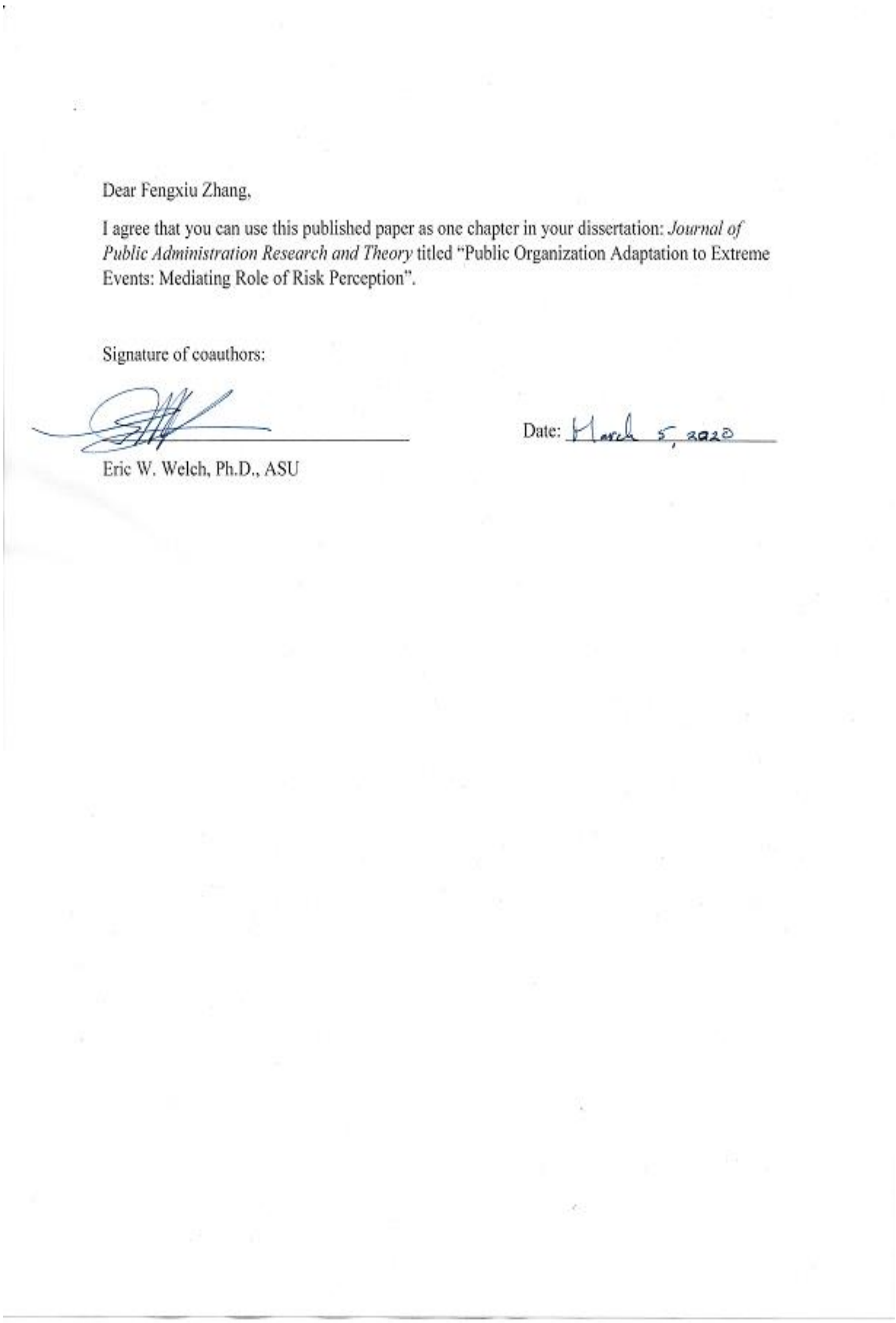
THE SFA MODEL USING LAGGED MEASURES

The two models in the table lag the value of adaptation policy and organizational slack by one period respectively, with all other variables unchanged.

	Lagged adaptation policy Estimate	**Lagged organizational slack** Estimate
Frontier		
Fuel	-2.389 (0.218)***	-2.334 (0.219)***
Vehicle	1.576 (0.476)***	1.613 (0.477)***
Labor	0.838 (0.434)	0.79 (0.435)
Fuel*Vehicle	-0.201 (0.064)**	-0.208 (0.064)***
Fuel*Labor	0.013 (0.066)	0.019 (0.066)
Vehicle*Labor	0.313 (0.086)***	0.319 (0.086)***
Fuel2	0.156 (0.016)***	0.153 (0.016)***
Vehicle2	-0.075 (0.06)	-0.073 (0.06)
Labor2	-0.204 (0.055)***	-0.208 (0.055)***
Population Density	-0.037 (0.006)***	-0.04 (0.006)***
Extreme weather frequency	0.057 (0.018)**	0.054 (0.022)*
Adaptation Plan	-0.152 (0.027)***	-0.151 (0.026)***
Organizational Slack	-0.142 (0.032)***	-0.15 (0.033)***
Contracting out	1.484 (0.288)***	1.489 (0.266)***
Year 2009	0.015 (0.022)	0.013 (0.022)
Year 2010	0.035 (0.022)	0.034 (0.022)
Year 2011	0.027 (0.022)	0.034 (0.022)
Year 2012	0.037 (0.022)	0.045 (0.022)*
Year 2013	0.036 (0.023)	0.037 (0.023)
Year 2014	0.054 (0.023)*	0.06 (0.023)**
Year 2015	0.07 (0.023)**	0.073 (0.023)***
Year 2016	0.087 (0.023)***	0.09 (0.023)***
Year 2017	0.075 (0.023)***	0.077 (0.023)***
Constant	20.883 (1.066)***	20.782 (1.075)***
Inefficiency		
Extreme weather frequency	0.067 (0.018)***	0.064 (0.021)**
Adaptation Plan	-0.238 (0.066)***	0.212 (0.063)***
Organizational Slack (Lag)	-0.136 (0.035)***	- 0.153 (-0.038)***
Contracting out	0.607 (0.293)*	0.63 (0.275)*
Constant	2.5 (0.634)***	2.805 (0.674)***
Model parameters		
σ_u^2	0.022 (0.017)***	0.023 (0.016)***
σ_v^2	0.015 (0.009)***	0.015 (0.009)***
$\lambda = \sigma_\mu^2/(\sigma_\mu^2 + \sigma_\nu^2)$	0.589 (0.023)***	0.604 (0.023)***
# of observations	1073	1073
# of parameters	31	31
Log Likelihood	-426.8473	- 429. 0058

APPENDIX I

COAUTHOR PERMISSION TO USE THE PUBLISHED WORK



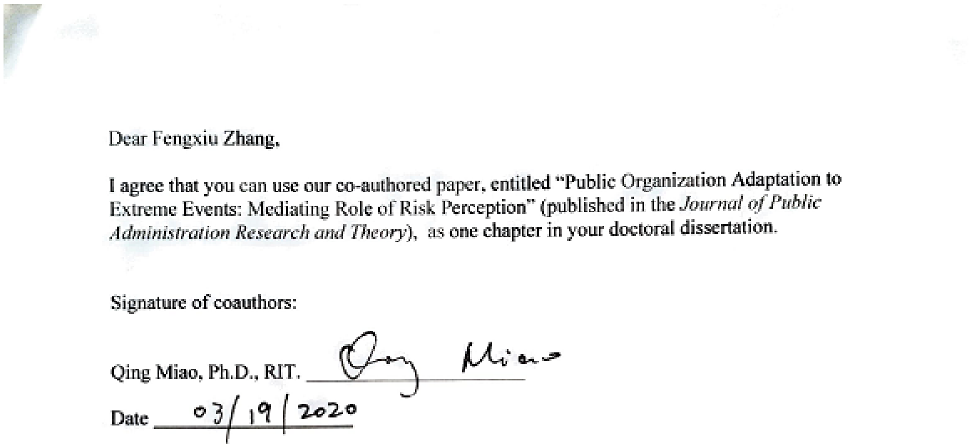
Dear Fengxiu Zhang,

I agree that you can use this published paper as one chapter in your dissertation: *Journal of Public Administration Research and Theory* titled "Public Organization Adaptation to Extreme Events: Mediating Role of Risk Perception".

Signature of coauthors:

Eric W. Welch, Ph.D., ASU

Date: March 5, 2020



Dear Fengxiu Zhang,

I agree that you can use our co-authored paper, entitled "Public Organization Adaptation to Extreme Events: Mediating Role of Risk Perception" (published in the *Journal of Public Administration Research and Theory*), as one chapter in your doctoral dissertation.

Signature of coauthors:

Qing Miao, Ph.D., RIT. Qing Miao
Date 03/19/2020