

# Transportation resilience to climate change and extreme weather events – Beyond risk and robustness

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## ABSTRACT

The long-term reliability and functioning of transportation systems will increasingly need to consider and plan for climate change and extreme weather events. Transportation systems have largely been designed and operated for historical climate conditions that are now often exceeded. Emerging knowledge of how to plan for climate change largely embraces risk-based thinking favoring more robust infrastructure designs. However, there remain questions about whether this approach is sufficient given the uncertainty and non-stationarity of the climate, and many other driving factors affecting transportation systems (e.g., funding, rapid technological change, population and utilization shifts, etc.). This paper examines existing research and knowledge related to the vulnerability of the transportation system to climate change and extreme weather events and finds that there are both direct and indirect “pathways of disruption.” Direct pathways of disruption consist of both abrupt impacts to physical infrastructure and impacts via non-physical factors such as human health, behavior, and decision making. Similarly, indirect pathways of disruption result from interconnections with other critical infrastructure and social systems. Currently, the direct pathways appear to receive much of the focus in vulnerability and risk assessments, and the predominant approach for addressing these pathways of disruption emphasizes strengthening and armoring infrastructure (robustness) guided by risk analysis. However, our analysis reveals that indirect pathways of disruption can have meaningful impacts, while also being less amenable to robustness-based approaches. As a result, we posit that concepts like flexibility and agility appear to be well suited to complement the status quo of robustness by addressing the indirect and non-physical pathways of disruption that often prove challenging - thereby improving the resilience of transportation systems.

## 1. Introduction

Events like Hurricane Katrina in New Orleans in 2008, Superstorm Sandy in the Northeastern United States in 2012, flooding of Interstate 10 (I-10) in Phoenix in 2014, the Riverside County I-10 bridge washout in 2015, and Hurricanes Harvey and Maria in 2017 have revealed how vulnerable our transportation system can be to extreme events. Over the coming decades, transportation infrastructure (as well as other infrastructure systems) will likely be confronted with a series of grand challenges: they are largely inflexible to changes in utilization and external conditions, receive unstable and insufficient funding, are often used well past their intended lifetime, and are increasingly

interconnected and complex (Chester and Allenby, 2017). These challenges are likely to be exacerbated by destabilizing changes in earth systems (namely climate change) that threaten transportation systems that are aging, underfunded, and designed for historical conditions and predictability (TRB, 2008; Meyer and Weigel, 2011). Despite uncertainty as to how significant the impacts of climate change may be in the future, climate models suggest that even in conservative scenarios (where greenhouse gas emissions are significantly reduced in the short term) extreme events and gradual changes to climate and hydrology are likely to become more severe (Stocker et al., 2013; Melillo et al., 2014). Compounding this challenge is non-stationarity, or the inability to predict current or future conditions based on past trends (Milly et al.,

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2008). Yet efforts to bolster the resilience of transportation systems to climate change and other threats have set off on a path that primarily emphasizes *robustness* – the capacity to prevent disruptions from occurring by emphasizing control, armoring, and strengthening (TRB, 2008; NCHRP, 2011; Meyer and Weigel, 2011; FTA, 2011; FHWA, 2012; Rattanachot et al., 2015; Woods, 2015). For example, roadways, levees, and dams are often built to meet certain design-storm criteria such as a 100-year storm event (i.e. the infrastructure is designed to withstand the magnitude of an event that has a 1% chance of occurring in any given year). This type of robustness-based approach is pragmatic when addressing well-defined and well-understood direct physical vulnerabilities. However, as discussed below, the transportation system also faces several indirect, non-physical, and poorly understood vulnerabilities – all of which are difficult to quantify and less amenable to robustness. For example, how do we design and operate for extreme events if they become more frequent (and intense), raising questions of the relevance of the 100-year design criteria? How can disruptions and undesirable effects be most effectively avoided if a roadway, for example, is designed to withstand a 100-year storm event but drivers only have experience with a 50-year storm event? How productive is it to design transportation infrastructure systems to withstand 100-year storm events if other infrastructure systems (e.g. the electricity and telecommunications sectors) are designed to withstand much weaker storm events? These are just a few questions that begin to highlight the challenges of designing reliable transportation systems in the face of climate change and emphasize issues within the current paradigm of robustness-based approaches.

While robustness is certainly a valuable strategy, perhaps it should not be treated as synonymous with *resilience*. In combination with various potential pathways of disruption, factors like climate non-stationarity, complex and interconnected infrastructure systems (e.g. the outputs of one infrastructure system are often inputs to another and vice versa), and unpredictable/unintuitive human behavior can also limit our ability to fully grasp the possibility of certain circumstances and undermine our ability to effectively implement robustness-based strategies. Instead, in the context of this manuscript, *resilience* is comprised of many non-mutually exclusive regimes, and *adaptive capacity* is considered to be the ability to move between these regimes. In addition to robustness, examples of other resilience regimes include *rebound* – the ability to restore conditions and systems that have been damaged by extreme events; *graceful extensibility* – the ability to extend performance and mitigate the consequences of surprising events to avoid sudden and catastrophic failure; and *sustained adaptability* – the ability to transform, balance, and trade off multiple system dimensions in response to evolving system and environmental conditions over the long term (Woods, 2015; Seager et al., 2017; Eisenberg et al., 2017). With this in mind, we propose moving from a solely robustness-based approach that considers only probabilistic factors toward a resilience-based approach that considers both the probabilistic (events that are relatively frequent and likely) and the ‘possibilistic’ (events that are very rare/unprecedented but still possible). In addition to robustness, we posit that transportation system designers, managers, operators, policy-makers and users may find it beneficial to also incorporate elements of agility and flexibility (defined later), as preconditions for adaptive capacity (the ability to move between resilience regimes). Under this expanded view of resilience, the transportation system may be better suited to face both foreseen and unforeseen disruptions and maintain the safety, efficiency, and services upon which we have come to rely and expect.

The remainder of this paper is outlined as follows. First, we provide an overview of the direct and indirect threats posed to the transportation system by climate change and extreme weather events. Next, we discuss the common responses to these threats and issues/concerns with these common responses. In particular, we outline some of the key limitations associated with a solely robustness-based approach to resilience. Finally, we outline attributes of a resilience-based approach (as

opposed to a robustness-based approach) to designing and managing the transportation system, and identify some challenges and areas of opportunity moving forward. Although there are several hazards of concern to the transportation sector, recent and recurring events draw the focus of this manuscript to extreme weather events and the destabilizing challenges of climate change.

## 2. State-of-the-art for transportation and climate change

Climate change is likely to threaten transportation systems both acutely through extreme weather events and chronically through gradual changes. Hazards are numerous: coastal and urban flooding, heat, cold, drought, and wind, to name a few. We are in the nascent stages of understanding how climate change might affect transportation systems. Although there is a growing body of knowledge related to how climate change might affect the transportation system (see sections below), there still appears to be an opportunity to expand our understanding of vulnerabilities and adaptation strategies related to disruptions from behavioral, information, resource, and interconnected physical systems. Furthermore, considering the long-lasting nature of many infrastructure systems, additional consideration and analysis of the timing and potential impacts of climate change and extreme weather events appear warranted.

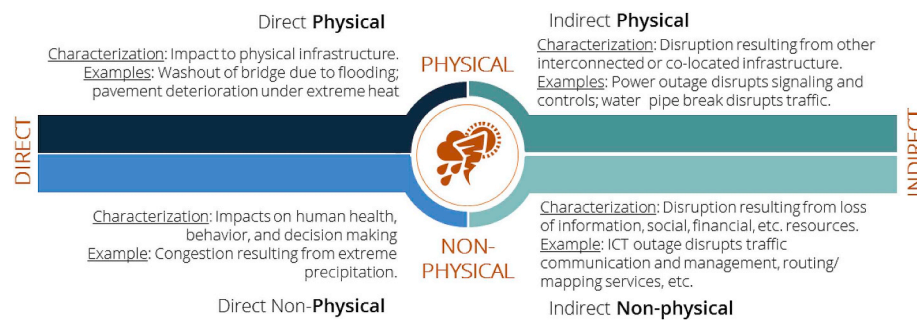
Given the wide geographic extent and numerous mechanisms for impacting transportation systems, infrastructure, passengers, and freight, we focus on temperature change (i.e. changes in average temperature, shifts in seasonal temperature changes, and changes in extreme high and low temperatures), precipitation change (i.e. drought, changes in average precipitation rates, and high precipitation events), and sea level rise/coastal flooding (i.e. gradual rise in sea level over time, storm surge, and tidal flooding). We characterize both direct and indirect impacts that these climate stressors can have on transportation systems. Overall, we provide a systematic overview of the various pathways of disruption that can result from climate change and extreme weather events, and provide a foundation for later discussions about fundamental issues with relying solely on a risk-based approach for minimizing disruption.

### 2.1. Characterization of vulnerabilities

We characterize transportation system vulnerabilities to climate change in four different ways: direct physical pathways of disruption, direct non-physical pathways of disruption, indirect physical pathways of disruption, and indirect non-physical pathways of disruption. For the purposes of this manuscript, a disruption refers to any mechanism by which mobility is reduced or the cost to maintain desired levels of mobility drastically increases. Fig. 1 provides a general definition and example of each of these four pathways of disruption. The following subsections further explore these direct and indirect pathways of disruption in the context of extreme temperatures (both hot and cold), extreme precipitation (including drought), and sea-level rise/coastal flooding. These specific extreme events are chosen because they are widespread and General Circulation Models (GCMs) predict increases in their frequency and intensity in the future (Stocker et al., 2013; Melillo et al., 2014), they are the focus of a majority of the existing studies on this topic (as detailed later), and most historical examples discussed in this paper are related to one of these climate stressors.

### 2.2. Direct pathways of disruption

Direct physical pathways of failure focus on disruptions to the transportation infrastructure itself and appear to receive much of the focus in the existing literature on transportation system vulnerability. Table 1 summarizes some of the most frequently identified direct physical pathways of disruption as well as some proposed adaptation strategies for a variety of climate stressors (TRB, 2008; NCHRP, 2011;



**Fig. 1.** Overview of the four pathways of disruption (direct physical, direct non-physical, indirect physical, and indirect non-physical) to the transportation system as a result of climate change and extreme weather events.

FHWA, 2012; Meyer and Weigel, 2011; FTA, 2011; Rattanachot et al., 2015; Taylor and Philp, 2015).

Although a singular occurrence of the stressors described above can be fairly damaging, impacts can be further exacerbated by the concurrent and/or subsequent occurrence of multiple stressors. For example, the 2017 mudslides along Highway 1 near Big Sur, California were the end result of a problematic sequence of events. An extended drought was immediately followed by unusually heavy winter and spring rainfall. This rainfall contributed to increasingly unstable slopes, and ultimately caused mudslides that resulted in the prolonged closure of the highway (Wamsley, 2017).

The references related to Table 1 can broadly be classified as hazard assessments, where the threats and potential damages are identified but not quantified. From this perspective, there is not enough meaningful information to draw any reasonable conclusions about how stressors and/or adaptation strategies should be prioritized. Successful prioritization of stressors and adaptation strategies requires detailed regional knowledge of the climate, condition of the infrastructure, state of the broader transportation system, budgetary constraints, and the timescale of analysis. Thus, any attempts to fully quantify, compare, and rank the level of risk posed by the stressors in Table 1 are considered outside the scope of this article. However, there are a variety of vulnerability and/or risk assessments related to climate change stressors and the transportation system, where the amount of damage caused by a specific stressor in a specific location is quantified in some way (often probabilistically). For example, Wright and Hogan (2008) analyzed the

impact of sea level rise on transportation infrastructure along the East Coast of the United States and found that over 3800 km of roadways and railways are at risk for temporary or permanent inundation should sea levels increase by 59 cm. Similarly, Suarez et al. (2005) studied the combined effects of coastal flooding (due to sea level rise) and riverine flooding (due to heavy rainfall events) on the performance of the urban transportation system in metropolitan Boston. Ultimately, they estimated that climate induced flooding would almost double the number of delays and lost trips by the year 2100. Schweikert et al. (2014) found that the median cost of not implementing adaptation strategies on paved roadways in Colorado would be \$14.2 million by year 2090. Espinet et al. (2016) estimated that the effects of climate change may result in damages between \$1.3 billion and \$4.9 billion on primary roadways in Mexico between 2015 and 2050. Underwood et al. (2017) estimated that projected temperature increases could raise pavement material selection and maintenance costs across the United States by as much as \$36 billion by the year 2070. Finally, Mallick et al. (2016) used a combination of climate models, system dynamics modeling, and simulation to estimate that changes to maximum air temperatures and annual rainfall are likely to result in an additional 4–12% of roadways needing rehabilitation after 50 years.

As opposed to focusing on impacts to infrastructure, direct non-physical pathways of disruption focus on the effects of weather on human health, behavior, and decision making. Several studies have found that the health of transportation system users and operators can be jeopardized by climate and extreme weather events (TRB, 2008;

**Table 1**

Summary of possible direct physical impacts from extreme weather events and possible adaptation strategies for transportation infrastructure (TRB, 2008; NCHRP, 2011; FHWA, 2012; Meyer and Weigel, 2011; FTA, 2011; Rattanachot et al., 2015; Taylor and Philp, 2015).

	<b>Increase in Maximum Temperatures / Extreme Heat Events</b>	<b>Season Shift in Temperatures</b>	<b>Increased Rainfall / Extreme Precipitation Events</b>	<b>More Intense / Frequent Droughts</b>	<b>Sea Level Rise / Storm Surge / Coastal Flooding</b>
<b>IMPACTS</b>	<ul style="list-style-type: none"> <li>Asphalt cracking</li> <li>Asphalt aging/oxidation</li> <li>Migration of liquid asphalt</li> <li>Asphalt softening/rutting</li> <li>Railway buckling</li> <li>Catenary wire sag</li> <li>Failed expansion joints</li> <li>Concrete pavement blowups</li> </ul>	<ul style="list-style-type: none"> <li>Increased damage from freeze-thaw cycles</li> <li>More frequent landslides/mudslides</li> </ul>	<ul style="list-style-type: none"> <li>Flooding of roadways</li> <li>Overloading of drainage systems</li> <li>Roadway washout</li> <li>Bridge scour/washout</li> <li>Reduced structural integrity from soil moisture</li> <li>More frequent landslides/mudslides</li> </ul>	<ul style="list-style-type: none"> <li>Greater chance of wildfire</li> <li>Road closure from wildfire &amp; reduced visibility</li> <li>Increased flooding in deforested areas</li> <li>More debris in storm water mgmt. systems</li> <li>Reduced pavement integrity due to ground shrinking</li> </ul>	<ul style="list-style-type: none"> <li>More frequent/intense floods in low-lying areas</li> <li>Erosion of road base</li> <li>Erosion of bridge supports/bridge scouring</li> <li>Land subsidence</li> </ul>
<b>ACTIONS</b>	<ul style="list-style-type: none"> <li>Heat-resistant paving materials</li> <li>Alter asphalt composition</li> <li>Switch from asphalt to concrete</li> <li>More frequent maintenance and replacement</li> <li>Increased shading</li> <li>Increase albedo</li> <li>Replace expansion joints</li> </ul>	<ul style="list-style-type: none"> <li>More frequent maintenance/replacement</li> <li>Additional/fortified slope retention structures</li> <li>Alter design standards for more variance</li> <li>Alter asphalt composition</li> </ul>	<ul style="list-style-type: none"> <li>Upgrade road drainage systems</li> <li>Increase culvert capacity</li> <li>Increase pumping capacity for roads and tunnels</li> <li>Alter design-storm criteria</li> <li>Fortify bridge piers and abutments</li> <li>Add green infrastructure/storm retention basins</li> </ul>	<ul style="list-style-type: none"> <li>Vegetation management</li> <li>Upgrade/expand road drainage system</li> <li>Additional/fortified slope retention structures</li> </ul>	<ul style="list-style-type: none"> <li>Expand drainage near low-lying infrastructure</li> <li>Elevate/protect tunnel openings &amp; low-lying areas</li> <li>Add pumping capacity to roads &amp; tunnels</li> <li>Relocation/retreat of roads and infrastructure</li> <li>Add/strengthen levees, seawalls, dikes, etc.</li> </ul>

NCHRP, 2011; FHWA, 2012; Meyer and Weigel, 2011; FTA, 2011). For example, heat exhaustion will likely become increasingly possible and may warrant the shift of construction hours and/or season. Similarly, public transit riders may be exposed to unsafe heat conditions while walking to/from a transit stop and/or waiting at the stop for their bus/train (Karner et al., 2015; Fraser and Chester, 2016; Fraser et al., 2016).

The relationship between weather and travel behavior has been extensively studied for years, and has only recently been applied in the context of climate change (Böcker et al., 2013a). For the purposes of this manuscript, weather refers to short-term (daily, hourly, yearly) phenomena, while climate refers to long-term averages and trends. All of the literature referenced below relate to weather, not climate. Thus, although they provide some useful insights into the relationship between temperatures, precipitation, etc. and transportation, there is still some uncertainty surrounding the applicability of these observations in the long run. Avenues of research in this area include weather's impact on system capacity, mode choice, travel distance, accident risk, and trip postponement. Reviews by Koetse and Rietveld (2009) and Böcker et al. (2013b) highlight that although it is a vast field, the existing literature is fragmented and sometimes conflicting in how users respond to various weather perturbations. Though it is generally known that the transportation system performs worse during weather events, the extent of the degraded performance appears dependent on a number of factors including acclimatization of users, timing of the weather event, and, likely, the engineering practices already in place that either implicitly or explicitly control the resilience of existing infrastructure to weather events.

Adverse weather (precipitation, extreme wind, extreme cold, and extreme heat) will generally shift mode choice from active modes to transit and automobiles - potentially putting additional stress on transit systems/roadways and warranting additional consideration when developing transportation policies (Koetse and Rietveld, 2009). Overall, adverse weather conditions appear to result in a small decrease in transit ridership, with the largest sensitivity occurring during weekend and evening trips (Singhal et al., 2014; Arana et al., 2014). In New York City, there is some evidence to suggest that there is a modal switch from automobiles to transit during heavy snow events (Singhal et al., 2014). This modal shift may be caused by driver perceptions of safety and some concern for additional delay (Khattak and De Palma, 1997). In addition to altered user behavior, rain was also found to alter transit system performance by causing decreases in average frequency of buses and increases in average headway and trip duration (Hofmann & O'Mahony, 2005). At the same time, precipitation and winter weather can also lead to a reduction in trip distances, as well as the postponement of non-essential trips leading to reduced traffic volumes across the system (Cools et al., 2010; Al Hassan and Barker, 1999). The additional capacity created may ease the negative impacts on users who continue normal travel. With the exception of extreme heat (Wyon et al., 1996), other types of weather reduce speeds and increase travel times for automobiles and transit. This effect is particularly pronounced during peak travel periods and increases the frequency, severity, and duration of traffic congestion across the system (Koetse and Rietveld, 2009; Böcker et al., 2013b). Adverse weather is also known to increase accident risk. While accident risk is elevated across all adverse weather types, there is a decrease in accident severity during precipitation events (Qiu and Nixon, 2008). The mediating factor is likely a reduction in traffic speed. Conversely, if climate change reduces the number of adverse weather incidents in some regions they are likely to experience opposite effects.

Disaster research has also examined behavior under the most extreme circumstances to better prepare city and regional transportation systems for mass evacuations and system interruptions. While many major cities have well defined plans and evacuation routes, behaviors of individuals ultimately determine the success or failure of an evacuation. Advanced extreme weather projections are becoming increasingly accurate and allow additional lead time for communicating the need for

residents to remain in place or evacuate (Casey, 2015; Patel, 2015; Lubchenko and Hayes, 2012). However, recent events have shown that there are significant challenges with both the communication of the orders in a timely manner, and the compliance of the individuals who receive those orders. The snow storm in January 2014 in Atlanta, Georgia is an excellent example of how this type of disconnect between officials and system users can bring an entire transportation system and recovery efforts to a complete standstill during an extreme weather event (Gobeil, 2014). Ultimately, this storm resulted in at least 13 deaths and left many citizens (including school children) stranded on roadways for several hours (Copeland et al., 2014).

The Atlanta example highlights how direct physical impacts to the transportation infrastructure (i.e. frozen/snow covered roadways) and non-physical impacts on people's decision making and actions can interact with each other to exacerbate a disruption. Some level of disruption was probably inevitable, but the combination of lack of experience with this type of event and a misunderstanding of its timing, severity, and response by citizens ultimately resulted in 800 traffic accidents, 99 school buses full of children still on the road at midnight, at least 2000 students spending the night at their schools, and numerous drivers being stuck in traffic for upwards of 12 hours (CBS News, 2014; Beasley, 2014). It should also be noted that these effects are at least partially dependent on geographic and temporal circumstance. Had this type of snow/freeze event occurred in a location like Minneapolis, Minnesota – where drivers and planners have more experience and comfortability in these types of conditions - it is unlikely that such a disruption would have occurred. Similarly, if this event had occurred in San Antonio, Texas or Phoenix, Arizona, the level of disruption could feasibly have been even larger.

Moving forward, practitioners may need to gain a firm sense of both how a climate stressor may impact infrastructure and how a disruption to certain components may affect people's decisions/behavior and create unwanted feedbacks. In terms of planning and design, the direct effects of weather on people's driving likely warrants additional consideration over the short and long term. In the short term, planning efforts may benefit from further exploration of the varied ways people may react and behave during an extreme weather event – especially events that are rare or unprecedented. In the long term, ascertaining likely responses and appropriate actions to weather and climate events will be a function of both changes in average conditions as well as the emergence of previously unprecedented extremes. In doing so, certain questions may need to be addressed - how quickly and effectively do people get used to what was historically an extreme event becoming more commonplace? Alternatively, what are the implications of a historically commonplace event becoming increasingly rare over time? As an event becomes rarer over time, does that mean it will eventually be considered an 'extreme event' whenever it does occur? The continual evolution of the climate and people's reaction to rare and extreme events help illustrate some of the non-stationarity within the system, and provide some initial insight into why infrastructure planning and operation may need to incorporate both a probabilistic and 'possibilistic' mind set. Additional discussion of non-stationarity and other challenges for traditional probabilistic/risk-based approaches are included later in the manuscript.

### 2.3. Indirect pathways of disruption

Indirect pathways of disruption emerge as a result of complexities within and interconnections between the transportation system and other critical infrastructure, social, and ecological systems. These pathways of disruption acknowledge that transportation systems do not exist in isolation of other infrastructure and services, and that protecting a transportation system against a particular hazard may not be sufficient if the systems it depends upon are not also protected. In addition to addressing direct pathways of disruption, there appears to be an opportunity to widen the scope of analysis and expand our



understanding of the indirect impacts that climate change and extreme weather events may have on the transportation system. Indirect pathways manifest because of the interconnection between energy, water, transportation and other critical infrastructure systems (EPRI, 2002a; EPRI, 2002b; Scott and Pasqualetti, 2010; Scott et al., 2011; Averyt et al., 2011; Scown et al., 2011; Bartos and Chester, 2014; Morris and Barthelemy, 2014). For example, outages in the electric power sector can lead to disruptions in transportation, communications, water supply, and fuel supply (Pate et al., 2007; Morris and Barthelemy, 2013). Ultimately, these interconnected failures can have severely detrimental socio-economic impacts (Chang et al., 2006; Zimmerman and Restrepo, 2006; Miles et al., 2012). With the exception of Scown et al. (2011) and Morris and Barthelemy (2014), existing literature related to infrastructure interconnectedness has not placed specific emphasis on the transportation sector. Similarly, with the exception of Bartos and Chester (2014), previous analysis on this topic has not focused on vulnerabilities specifically related to extreme weather events and how those vulnerabilities may propagate through different infrastructure systems. Thus, the remainder of this section aims to build on the existing body of knowledge by exploring infrastructure interconnectedness further – particularly in the context of climate change vulnerability and resilience from the perspective of the transportation system – see Fig. 2. For legibility, Fig. 2 only depicts interconnections with the transportation sector (e.g. interconnections that exist between the water and electric power systems are not included), and is not exhaustive as it only depicts interconnections with the water (upper left), electric power (upper right), oil and gas (lower right), and Information Communication Technology (ICT) sectors (lower left).

Similar to above, we classify indirect vulnerabilities and pathways of disruption as either physical or non-physical. More specifically, we adopt terminology developed by Rinaldi et al. (2001) to further characterize transportation interconnectedness as physical, geographic, cyber, and logical.

Indirect physical pathways of disruption occur when there is a disruption to a critical infrastructure that is physically and/or geographically interconnected to the transportation system. Physical interconnectedness refers to situations in which the output of one infrastructure system is a direct input to another (Rinaldi et al., 2001). For example, a natural gas pipeline and a natural gas power plant could be considered physically interconnected - the pipeline supplies the fuel for electricity generation and the electricity from the power plant operates the compressor stations along the pipeline.

For the transportation system, one of the strongest physical interconnections is to the electric power sector. Reliable electric power

contributes to the reliable operation of traffic signals, gasoline pumps, electric rail systems, electric vehicles, and rail crossings (Spirre Clark et al., 2018; TRB, 2011) – not to mention any ICT systems upon which the transportation system also relies (see discussion in next section). Any disruption to these transportation components can ultimately lead to increased congestion, roadway closures, reduced road safety, limited availability of fuel for evacuation and emergency power generation, and inhibited access to emergency services and response crews (TRB, 2011). For example, the Arizona-Southern California blackout in September 2011 resulted in disruptions to the electric streetcar system and substantial traffic delays in the San Diego area (FERC/NERC, 2012; Spirre Clark et al., 2018). Consideration of the interconnectedness between the transportation system and the electric power system is likely to become increasingly important because it has been shown that the electric power sector can be vulnerable to a variety of different climate stressors such as extreme heat (Bartos et al., 2016), wildfires (induced by drought and extreme heat), and altered water resource availability (Maliszewski et al., 2012; Westerling, 2016; Sathaye et al., 2011; Bartos & Chester, 2014, 2015). Aside from being a crucial input to operation and management of the transportation system, electricity can also serve as a vital power source for vehicles. As electric vehicles and electrically powered public transportation increase in prevalence, the interconnection between the transportation and electric power systems will continue to grow. Therefore, climate-induced vulnerabilities and outages to the electric power sector can also introduce additional vulnerability to the transportation system, and vice versa.

The other indirect physical pathway we examine is geographic interconnectedness, which refers to multiple infrastructure systems that are in close proximity to one another (Rinaldi et al., 2001). For example, fiber-optic cables, water pipes, and electric transmission lines may all be buried underneath a road or along a road right-of-way (Rinaldi et al., 2001). This type of scenario played out in Houston, Texas and several other locations when high temperatures and dry conditions are believed to have contributed to the rupture of several water mains. Although the summertime average is 200 water main breaks per day, Houston was experiencing 700 water main breaks a day. This elevated level of water main breaks was believed to be the result of a combination of old/under maintained infrastructure and climate/weather induced factors like greater pressure in the system due to increased water usage coupled with soil shrinkage due to dry conditions (Llanos, 2011; Patterson, 2011). In the context of climate change, geographic interconnectedness could result in a variety of failure modes. For example, land subsidence due to extreme drought conditions could cause an underground water main to break, which in

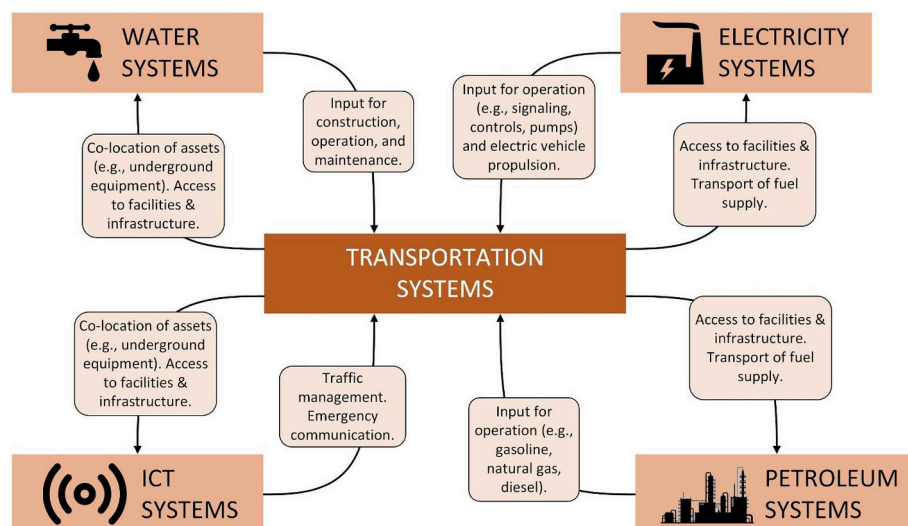


Fig. 2. Overview of common interconnections between the transportation system and other critical infrastructure systems.

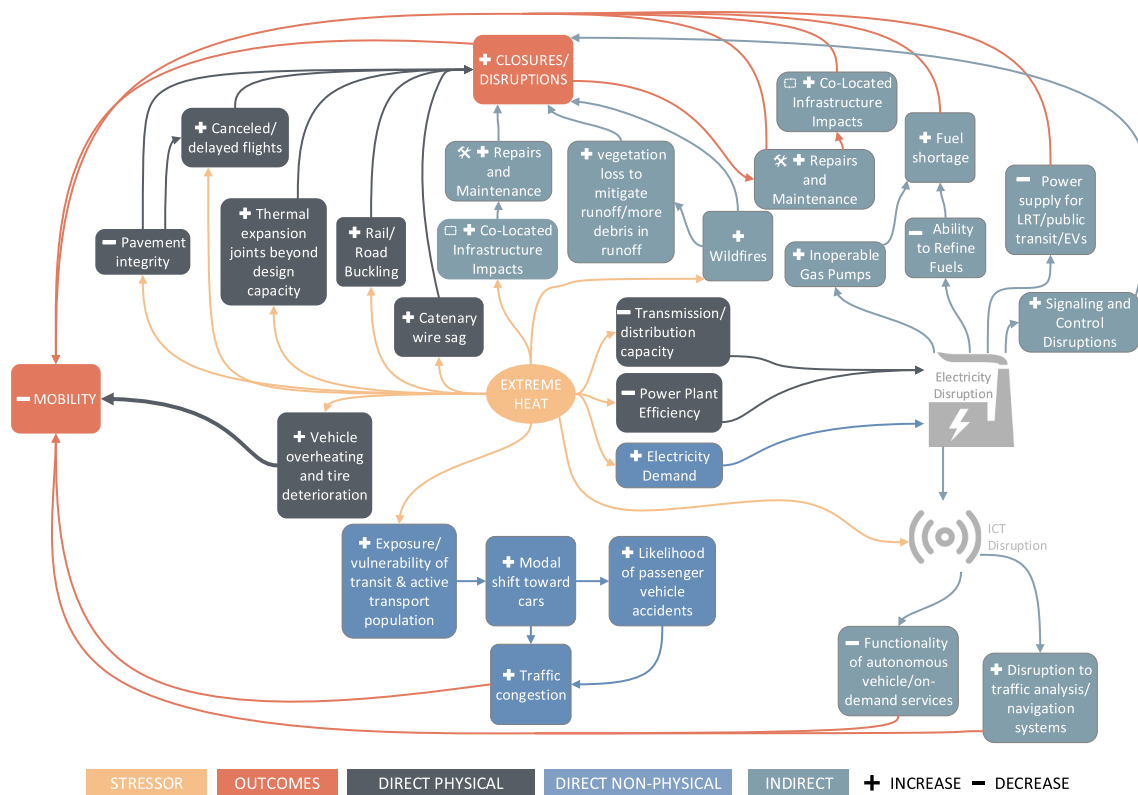


Fig. 3. Illustrative direct and indirect “Pathways of Disruption” related to extreme heat.

turn could result in the flooding/closure of a major roadway. The loss of the roadway may then result in delays and congestion throughout the transportation system that ultimately inhibit the ability of response crews to repair the broken water main and roadway segment. Elements of this type of detrimental feedback loop were seen when a water main burst near the UCLA campus in July 2014 that resulted in 75,000 gallons per minute flowing onto the street and flooding parts of UCLA's campus. The flood waters from the pipeline resulted in the closure of Sunset Boulevard and stranded some people in their cars for several hours. Increased traffic near the scene delayed the arrival of response crews and added to the time between the initial rupture and the sealing of the pipe (Owens et al., 2014).

Indirect non-physical failures occur when there is a disruption to an infrastructure system that has cyber and/or logical interconnectedness with the transportation system. Cyber interconnectedness occurs when the state of one infrastructure system depends on data/information from another infrastructure system(s) – often the ICT sector (Rinaldi et al., 2001). For example, a loss of ICT capacities could potentially disrupt traffic routing and control systems in the transportation sector. Cyber interconnectedness is analogous to physical interconnectedness, except the primary input-output exchange between systems is data/information – hence its classification as non-physical.

Although more work is needed on the subject, ICT infrastructure is believed to be vulnerable to a variety of climate stressors. For example, underground components may be susceptible to flooding and/or land shifting/subsidence from drought or rising water tables (Fu et al., 2016). Similarly, high humidity can increase the risk of short-circuiting and extreme temperatures can lead to more frequent component failure (Fu et al., 2016). Should any of these failures occur, there is also the possibility of corresponding failures in the transportation system due to cyber interconnectedness. More specifically, disruptions to ICT can lead to disruptions in traffic management systems, roadside communication systems, real-time traffic monitoring/information systems, real-time public transit tracking systems, GPS and route mapping service, ride sharing services like Uber, and autonomous vehicle systems (Fu et al.,

2016). Vulnerabilities via the ICT system are likely to increase as ICT becomes more integrated in daily life and we move toward “smart cities” and the “internet of things (Dawson, 2014).” In other words, as more and more data about how people function, interact, and move through cities is integrated into the design, management, and operation of infrastructure and social systems, the more vulnerable these systems are to disruptions to the flow of information, especially when operation and management rely on real-time data. Thus, any disruption to the collection, sharing, and analysis of these data could prove detrimental to the effective functioning of urban systems.

Logical interconnectedness occurs when the state of one system is related to the state of another system via mechanisms (e.g. social, financial, political mechanisms) that cannot be classified as physical, geographic, or cyber (Rinaldi et al., 2001). For example, the fuel sector and the transportation sector could be considered to be logically interconnected via economic mechanisms. If gasoline prices are lower, people tend to drive more, thereby increasing roadway congestion and motor vehicle fatalities (Grabowski and Morrissey, 2004). Similarly, taxes on gasoline are often a large source of funding for transportation infrastructure. Thus, the extent to which people are driving more (and consuming more gasoline) at least partially determines how much money is available to maintain and build roadways. One potential way that logical interconnectedness could contribute to climate-induced vulnerability in the transportation system would be the establishment of policy that allows for continued/increased groundwater withdrawal during a severe drought. The simultaneous lowering of the water table and drying out of the soil could ultimately lead to ground subsidence, shifting, and possibly sinkholes that result in water main ruptures and cracking, and ultimately the flooding and damage of roadways. Similarly, economic and policy decisions that place less emphasis on sustainable funding for infrastructure installation, maintenance, and upgrades could potentially be logical mechanisms that ultimately exacerbate the impact and level of disruption that climate change and extreme events have on transportation and other critical infrastructure systems.

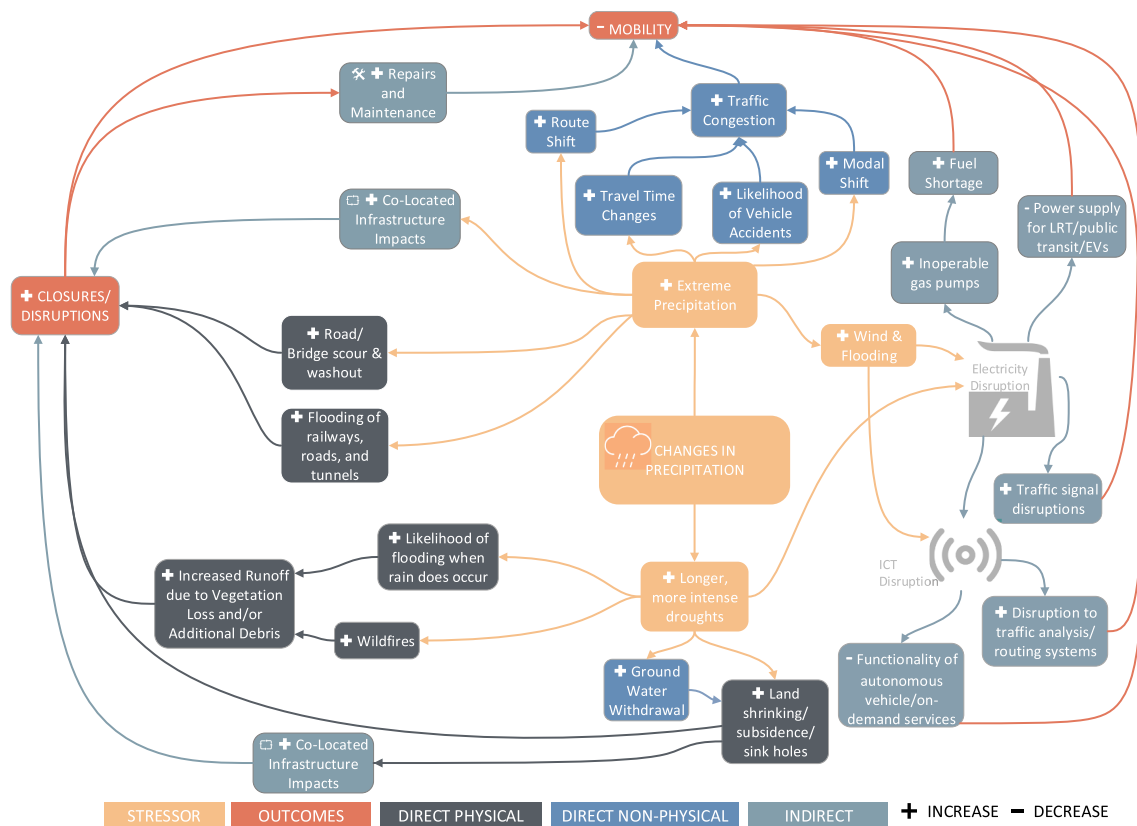


Fig. 4. Illustrative direct and indirect “Pathways of Disruption” related to extreme precipitation and drought.

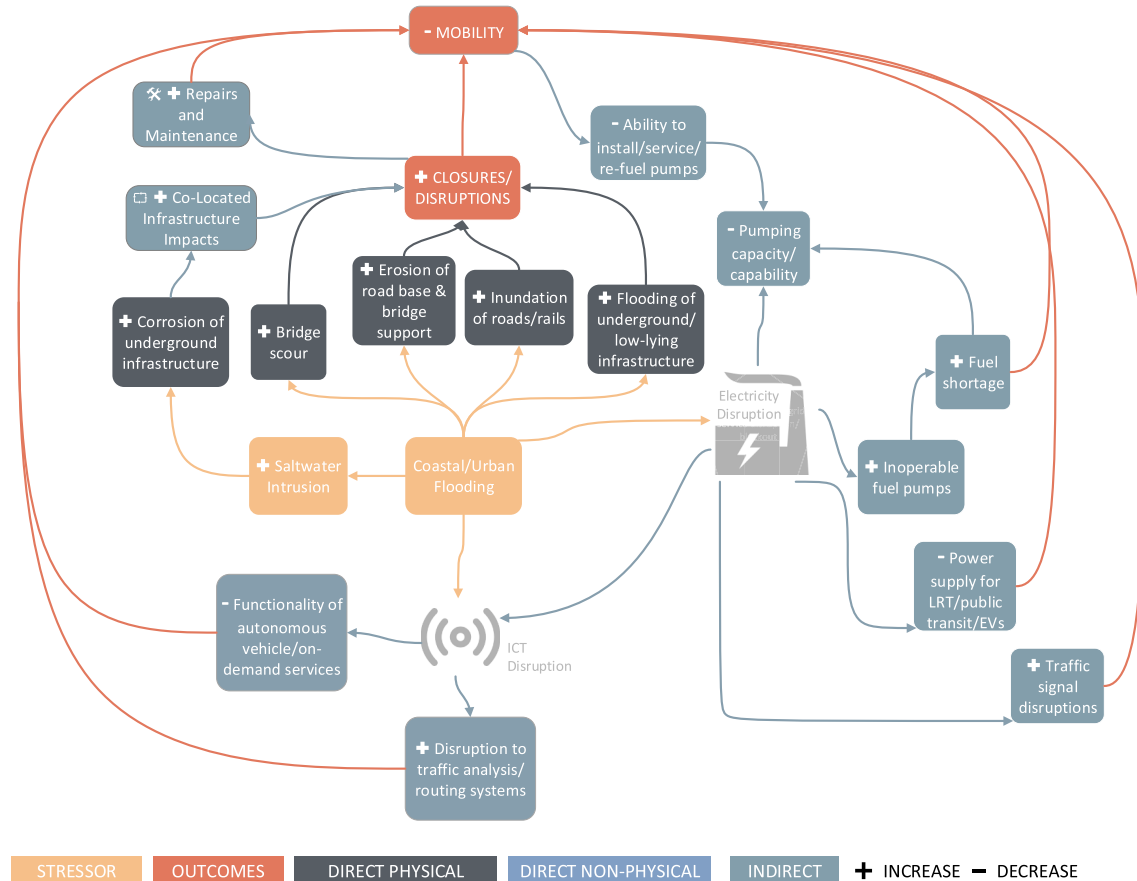


Fig. 5. Illustrative direct and indirect “Pathways of Disruption” related to coastal flooding.

Figs. 3–5 help further illustrate the array of possible direct and indirect pathways of disruption that can result from extreme heat, intense precipitation, drought, and coastal flooding. Orange boxes and arrows indicate climate stressors, dark blue arrows and boxes indicate direct physical pathways of disruption, light blue arrows and boxes indicate direct non-physical pathways of disruption, green arrows and boxes indicate indirect pathways of disruption, and red arrows and boxes indicate outcomes. The wrench and hammer symbols indicate maintenance and repair. The cyclical arrow symbols (e.g., in the “Co-Located Infrastructure Impacts” boxes) indicate interconnections with other infrastructure systems. Note that the colors used in Figs. 3–5 correspond to the colors used in Fig. 1 to depict direct/indirect and physical/non-physical pathways of disruption. Addition signs indicate an increase in a vulnerability/service/outcome and subtraction signs indicate a decrease. Although these figures are not exhaustive in their representation of all possible interconnections and pathways of disruption associated with given climate stressors, they help illustrate the consideration of risk and vulnerability from a broader perspective – not just direct physical pathways.

#### 2.4. Drawbacks of an emphasis on robustness

The United States Federal Highway Administration's (FHWA) Climate Resilience Pilot Program has been critical in developing an understanding of risks and vulnerabilities related to climate change and provides a useful resource for assessing common approaches to climate risks in the transportation sector (FHWA, 2012; FHWA, 2016). From 2011 to 2015, two dozen state and local transportation agencies have participated in the pilot program to evaluate and address regional impacts of various climate stressors to their transportation assets. See Table A1 in the appendix for more details about the hazards, type of analysis, assets, pathways of disruption, and time periods included in the pilot projects. A review of the policies and strategies developed by the state and local transportation agencies as part of the FHWA pilot program reveals two key findings: 1) current assessments primarily focus on the direct physical vulnerabilities of transportation assets—only 3 of the projects included consideration of indirect and/or non-physical pathways of disruption; and 2) emphasis is often placed on robustness (i.e. strengthening and fortifying assets in the face of increased risk of failure) when developing adaptation and resilience strategies. Some additional takeaways from FHWA pilot programs include: extreme heat will negatively impact pavement performance, reduce construction hours, and reduce worker safety (Arizona DOT, 2015); increased vulnerability to inundation, erosion, and scour from increased precipitation and sea level rise along coastal transportation assets is documented in multiple studies (Washington State DOT, 2011; Oahu MPO, 2011; Caltrans, 2014; Connecticut DOT, 2014; FHWA, 2015); 87.2 miles of Northern Texas rail track will be considered ‘high risk’ to extreme heat by 2100 (North Central Texas Council of Governments (NCTCG, 2015); climate models forecast that Iowa flood basins containing the six most critical interstate and highway routes will be exposed to streamflow that surpasses current design standards in their current design life (Iowa DOT, 2015).

Ongoing climate resilience efforts appear to emphasize risk-based and robustness-based approaches (i.e. strengthening and fortifying assets in the face of increased likelihood of failure) for assessing and addressing vulnerabilities associated with climate change and extreme weather events. For example, the Iowa DOT FHWA pilot program focuses on quantifying and lowering the future probability of overtopping and bridge scour by stating that the “primary engineering metric of interest is the 100-year flow” and emphasizes raising the grade of bridges and roadways as the primary adaptation strategy (Iowa DOT, 2015). While a robustness-based approach is particularly well-suited for direct physical pathways of disruption, it is less desirable for addressing indirect and non-physical pathways of disruption. Robustness-based approaches are primarily effective in the presence of reasonable

understanding of the probabilities and impacts of failures. However, as discussed below, there are several factors that reduce our ability to fully assess vulnerability and risk, thereby limiting the applicability and effectiveness of robustness-based approaches. Additionally, even with a reasonable understanding of the probabilities associated with various threats, there may still be physical, economic, or political constraints that inhibit the implementation of a robustness-based approach.

Some of the confounding factors that inhibit our ability to form reasonable uncertainty estimates and effectively implement a robustness-based approach include non-stationarity, unforeseen population and demographic shifts, complexity and interconnectedness of infrastructure systems, and uncertain human behavior/response during extreme events. We loosely define non-stationarity as the inability to accurately predict current and future conditions based on past trends. More specifically, in the context of climate change, historically observed average, minimum, and maximum temperature and precipitation values are likely to become increasingly less indicative/predictive of future values. For example, Milly et al. (2008) highlight that predicting precipitation and rates of river discharge are becoming increasingly difficult as a result of climate change. Non-stationarity is particularly troubling for physical infrastructure that is typically designed to a certain statistically determined criteria (e.g. bridges designed to withstand flooding with a 100-year return period). However, with climate change and climate non-stationarity, what has historically been a 100-year storm event might now end up being closer to a 50-year or even a 200-year storm event. For example, the Iowa DOT FHWA Pilot Project found that, over its lifetime, the return period for flooding on the I-80 bridge over the Cedar River is expected to change from a 1.6% likelihood each year (60-year flood) to a 10% likelihood each year (10-year flood) (Iowa DOT, 2015). The rain storms that flooded Interstate 10 in downtown Phoenix in September 2014 and led to the failure of the Interstate 10 bridge in Riverside County in 2015 were both considered 1000-year events (at least for certain locations and durations) (FCDMC, 2014; Kelman, 2016).

Related to non-stationarity, uncertainty surrounding the utilization of transportation services (which is driven by changes in population, demographics, and preferences) can also make successful implementation of/robustness-based design difficult. Transportation (and other) infrastructure is often planned on decadal scales, is highly centralized, and is highly fixed/rigid. As a result, infrastructure that cannot easily adapt to drastic changes in utilization can result in systems that are either oversized or undersized (Chester and Allenby, 2017). For example, the population in Las Vegas, Nevada increased by 321% between 1980 and 2010 (Berube et al., 2010), while the per commuter annual hours of traffic delay has increased by 254% over roughly the same time period (Schrank et al., 2015). These values highlight two things: 1) although population and infrastructure planning projections are constantly revisited, anticipating and planning for such a large increase in population can be difficult – especially considering the long-lasting and fixed nature of most infrastructure; and 2) to the extent that the comparison between population increase and per commuter annual traffic delay can be used as a proxy for how well the infrastructure was able to keep up with increasing demand, it appears that the transportation infrastructure in Las Vegas is over utilized – assuming small/zero change in per commuter annual hours of traffic delay over time is indicative of infrastructure that is properly sized/utilized to meet changing demand.

Aside from changes in population, changes in technology and people's preferences can also make planning difficult. For example, fueling systems and infrastructure are potentially on the verge of a major transformation as electric vehicles continue to grow in market share. Similarly, the emergence of autonomous vehicles is likely to result in several (albeit uncertain) changes to our transportation infrastructure. For example, much less space may be needed for parking if subscription services to autonomous fleets gain traction, or increased infrastructure capacity may be needed if large numbers of people decide to live in



rural or exurban areas and commute to urban areas via autonomous vehicles. With all this in mind, it is not hard to see how infrastructure designed in the context of specific population, technology, and preference trends could quickly be at a disconnect with modern and future demands – especially if changes occur at a faster rate than can be reacted to or anticipated. In the context of risk management, these types of uncertainties can make it very difficult to accurately assess the damages of potential future disruptions, which in turn make it difficult to weigh and assess possible mitigation strategies.

Uncertainty about the potential impacts of various types of hazards is further exacerbated by the increasing interconnectedness of critical infrastructure systems (Chester and Allenby, 2017; Spirre Clark et al., 2018). Related to the earlier discussion on interconnectedness and indirect pathways of failure, efforts have been made to model and quantify interconnectedness of critical infrastructure systems. However, they are often at a national-scale and/or analogs for real systems (Holden et al., 2013; Shin et al., 2014; Haines & Jiang, 2001; Barker & Haines, 2009a, 2009b; Franchina et al., 2011; Lin et al., 2016; Nguyen et al., 2013; Frydenlund et al., 2016; Pederson et al., 2006; Gomez et al., 2014; Masucci et al., 2016). In order to fully employ a robustness-based approach, advancements are still needed in order to reasonably quantify the likelihood and impacts of these pathways of failure to a degree that is conducive to the decision-making process.

Finally, uncertainty about the potential impacts of various hazards is increased by the sometimes unpredictable and/or unintuitive human behavior responses to disruptions and extreme events. Earlier discussions about non-physical indirect pathways of failure provided an overview of the existing work on the relationship between weather and travel behavior. While this work is insightful, there are still gaps that inhibit how well it can be applied to robustness-based approaches. In particular, the vast majority of the existing literature is related to ‘typical’ and/or observed weather. There are very few studies related to extreme events and/or climate change – especially in the United States. Relating to non-stationarity, a general understanding of travel behavior under ‘typical’ conditions does not ensure that the same patterns will hold in ‘atypical’ or extreme circumstances. We again point to the January 2014 snow storm in Atlanta that crippled the city’s transportation system as an example of how rare and extreme events can lead to unexpected behavior from travelers and uncertain decision making from system operators. The 2007 I-35 bridge collapse in Minnesota provides a non-climate example of how major disruptions can result in unanticipated and unintuitive behavior from travelers. After the bridge collapsed, traffic flow and volume oscillation occurred, but the scale and longevity of the oscillation depended on the area of analysis and the amount of alternative routes available. Despite varying degrees of traffic oscillations in the region, overall demand within the I-494/I-694 beltway remained relatively unchanged. Similarly, the reopening of the I-35W bridge did not generate a significant oscillation in traffic (Zhu et al., 2010).

### 3. From robustness to resilience

With the combination of direct and indirect pathways of disruption, non-stationarity, unforeseen population and demographic shifts, interconnectedness of infrastructure systems, and uncertain human behavior/response during extreme events, we posit that a robustness-based approach to resilience is increasingly inadequate to fully address the complex, emergent, and evolving threats our transportation systems face. Expanding on concepts of complex adaptive systems and dynamic adaptive planning (Gell-Mann, 1994; Wall et al., 2015), we propose that incorporating elements of flexibility and agility, in addition to robustness, may help transportation systems move closer to goals of resilience. Flexibility is broadly defined as the ability to reconfigure and alter system parameters in order to absorb and react to foreseeable changes and uncertainties, and agility is broadly defined as the ability to adapt and evolve in an environment of continuous and unanticipated changes

(Bernardes and Hanna, 2009; Richards, 1996; Chester and Allenby, 2017). Within this framing, we consider flexibility and agility to be preconditions for a system’s adaptive capacity, and although they are similar on some levels, there are two important distinctions: 1) flexibility relates to changes that are expected (or at least able to be anticipated), while agility relates to changes that are unexpected or unforeseen; and 2) flexibility is facilitated by the existing systems and protocols in place, while agility is facilitated by a fundamental altering of the existing systems and protocols (or even the creation of new systems and protocols altogether). As an illustrative example, flexibility in the context of sea level rise and coastal flooding would describe a system’s innate abilities to absorb, react, and/or respond to both the most likely amount of sea level rise and the possible range of sea level rise (e.g. according to NOAA (Parris et al., 2012), plan for roughly 3 feet of sea level rise by 2100 but also have the ability to handle 1–6.6 feet). On the other hand, agility in the context of sea level rise and coastal flooding would describe a system’s innate abilities to absorb, react, and/or respond to an unforeseen amount of sea level (e.g. over 20 feet of sea level rise resulting from the unexpected rapid decline of the Greenland ice sheet or parts of the Antarctic ice sheet (NSIDC, 2017)). In a more extreme example, agility would also describe a system’s ability to handle unexpected or unprecedented events outside the realm of sea level rise – with a majority of the focus on sea level rise, how well does the system respond to an unprecedented earth quake?

Following Chester and Allenby (2017), an agile and flexible transportation system would have the following traits that help determine its ability to 1) recognize external changes and threats (responsiveness), and 2) take the appropriate action once the changes and threats have been recognized (competency and organic organizational structure) (Ashby, 1956, 1960; Lawrence and Lorsch, 1967; Hatch, 1997; Vecchio, 2006; Sherehiy et al., 2007):

- *Responsiveness* – the ability to sense, perceive, and anticipate changes/disruptions
- *Modular, Connective, and Compatible Technical Structures* – integration and cooperation within and across both internal and external entities, empowered people and processes within and across both internal and external entities, cultures of inquiry and experimentation
- *Organic and Experimental Organizational Culture* – informal and open communication, few levels of hierarchy, distributed decision making, fluid role definitions, empowered people and processes, and cultures of inquiry and experimentation

The applicability, ease of implementation, and extent to which these traits can be strengthened will likely vary from situation to situation, and in many cases will not be a transition that can be made easily. The obdurate, fixed, and long-standing nature of many infrastructure systems (and the entities that manage them) are forces with which we must reconcile. In other words, to introduce flexibility and agility (and ultimately resilience) we first need to address the “lock-in” inherent in our infrastructure systems. Although more research is needed on the subject of infrastructure lock-in and how to break it, some initial options might include higher versatility and re-configurability in terms of the variety of operations that people and physical infrastructure can perform, higher substitutability and modularity among infrastructure components (which is likely to be aided by higher levels of standardization and interoperability), higher levels of internal and external cooperation and integration, higher levels of workforce and user training, and higher levels of job rotation within and across critical infrastructure systems.

Although a majority of examples of agility and flexibility are found in Operations Management and Information Systems literature (Chung et al., 2003; Duncan, 1995; Giachetti et al., 2003; Bernardes and Hanna, 2009; Sherehiy et al., 2007; Yusuf et al., 1999), there are emerging examples in the transportation sector. Relating back to the pathways of

disruption outlined earlier, the incorporation of phase change materials in pavements increases performance in regions with frequent freeze-thaw cycles and enhances the suitability of pavements to a wider range of potential climates (Bentz and Turpin, 2007). Similarly, permeable pavements can potentially reduce the likelihood of roadway flooding in the face of extreme precipitation (Li et al., 2013). From a more systems-level perspective, HDR, Inc. has proposed the concept of “modular lanes,” which use digital roadway markings and information communication technologies to allow for the easy adjustment of lane directionality, lane size and quantity, establishment of designated lanes for transit or emergency vehicles, etc. as different transportation demands and needs arise. Overall, the “modular lanes” are expected to enhance the system's ability to “adapt to the inevitable, but as yet defined, changes that the transportation system will encounter over time (ITS International, 2016),” and may prove very effective at minimizing a variety of direct and indirect pathways of disruption. Similarly, companies like Uber and Waymo are pioneering autonomous vehicle systems that are likely to increase the versatility and substitutability of our transportation options. Next Future Transportation, Inc. (2017) envisions a new version of public transportation that relies on self-driving modules to provide on-demand service to users and does not follow defined routes. This type of modal flexibility could be beneficial in reducing disruptions in the public transportation sector related to extreme heat (lost power from blackouts, catenary wire sag, etc.), extreme precipitation (roadway flooding, bridge scour, etc.), or any number of other stressors. More specifically linked to climate and extreme weather events, the Stormwater Management and Road Tunnel (SMART) Tunnel in Kuala Lumpur, Malaysia serves the dual purpose of being a motorway and a conveyor/reservoir for flood water (SMART Motorway Tunnel, 2017). Finally, changes to physical infrastructure should also be complemented by behavioral and organizational structure changes. For example, a highway system in Spain explicitly incorporated concepts of flexibility into the design by providing options for upgrading the infrastructure at various stages of its lifetime in response to uncertainty about future traffic growth and discount rates (Fawcett et al., 2015).

By suggesting the inclusion of flexibility and agility into the design and operation of transportation systems, we propose moving from a paradigm of risk and robustness - the probabilistic - toward a paradigm of resilience in which flexibility and agility facilitate the movement between different regimes (e.g. rebound, robustness, graceful extensibility, or other) based on environmental and systemic cues - the ‘possibilistic’. Said differently, perhaps the ultimate goal should not necessarily be to rebound as quickly as possible or be as robust as possible, but to incorporate concepts of flexibility and agility in order to move more effectively across resilience regimes (adaptive capacity) as dictated by the magnitude and type of threat facing the system. However, in overcoming the system lock-in that can prevent these transitions from happening, some questions remain. Arteta and Giachetti (2004) suggest that complexity is the inverse of agility. Considering transportation (and other infrastructure systems) appear likely to only increase in complexity, can transportation (and other) systems be made less complex while still maintaining desired levels of service? If so, how? If not, how can we still move toward flexibility/agility/resilience (even if we never fully get there)? Even if we are successfully able to move beyond a complete reliance on robustness, what methods will facilitate the prioritization and allocation of resources that will still be necessary to manage and respond to extreme events – tasks that are traditionally aided by risk analysis?

#### 4. Conclusion

This manuscript primarily seeks to identify opportunities for expanding thinking and analysis related to vulnerability assessment and resilience in the transportation sector, as well as frame and encourage continued research related to both direct and indirect pathways of disruption and the incorporation of flexibility and agility into

transportation infrastructure and management. Overall, this paper has analyzed and synthesized existing research and knowledge related to the vulnerability of the transportation system to climate change and extreme weather events, conceptualized and assessed both direct and indirect “pathways of disruption” within transportation systems, identified potential challenges associated with a robustness-only approach to resilience, and outlined how concepts like flexibility and agility may serve as effective complements to robustness strategies. To our knowledge, this is the first paper to clearly identify and delineate hazards to transportation systems in the context of both direct and indirect/physical and non-physical pathways of disruption. Considering that the first step in any type of risk/resilience assessment is acknowledging and identifying possible hazards, the concepts presented in this manuscript appear well suited for aiding in the development of more complete risk and resilience assessments within the transportation sector. In the absence of strong/reliable data, we were unable to fully quantify the risks associated with indirect hazards and compare them to the risks associated with direct hazards. As a result, we propose a resilience-based approach and recommend collection of data and additional analysis of interdependencies and indirect pathways of disruption as a good avenue for future analysis and inquiry.

Currently, the direct pathways of disruption appear to receive more focus and assessment than the indirect pathways, and the predominant approach for addressing these pathways of disruption emphasizes robustness guided by risk analysis. However, examples like the Arizona-Southern California blackout reveal that the indirect pathways of disruption related to interconnected systems can cause notable disruptions. While the examples and literature cited in this manuscript tend to be U.S. centric, the analysis, concepts, and conclusions of this manuscript can be broadly applicable. The concepts of interconnected infrastructure or direct/indirect pathways of disruption are not unique to a specific location. Similarly, concepts like non-stationarity, unforeseen population and demographic shifts, complexity, and uncertain human behavior/response may limit the effectiveness and reliability of robustness-based strategies and are not unique to specific countries or regions. As a result, we posit that concepts like flexibility and agility appear to be well suited to complement robustness efforts by addressing the indirect and non-physical pathways of disruption that often prove challenging.

With the rapid progression of technology, changes in climate, and shifting demands, infrastructure systems will likely become more complex and interconnected while also facing a constant series of evolving challenges and threats. As a result, it may become increasingly necessary for infrastructure systems and managers to not only gain a better understanding interconnectedness and the resulting indirect vulnerabilities, but also develop responses and adaptation strategies that do not solely rely on robustness and risk analysis. In doing so, they may be able to develop more impactful and holistic adaptation and resilience strategies.

Moving forward, additional work is still needed in order to transform the idea of moving beyond robustness (toward resilience) from the abstract to the implementable. In particular, the body of knowledge would benefit from gaining a better understanding of when robustness is particularly suitable and when it is not. Work is also needed to gain a better idea of specific actions that can be taken to develop and enhance flexibility and agility – particularly in the context of different critical infrastructure systems. Finally, methods are still needed to properly assess (either qualitatively or quantitatively) the effectiveness of robustness, agility, and flexibility in order to help decision makers determine the most appropriate course of action.

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## Appendix A. Supplementary data

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