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Climate-adaptive planning for the long-term resilience of transportation energy infrastructure

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ABSTRACT

This paper investigates a long-term planning response to the climate-vulnerability of transportation energy infrastructure in the borough of Manhattan, NY. The proposed model, a two-stage stochastic optimization, features a hybrid utility-regret function with increasing relative and decreasing absolute risk aversion. Modeling results suggest (1) investment in early- and late-stage resilience-enhancing solutions as a complementary approach with significant weight on immediate actions, and (2) a decentralized supply chain formation through an early-stage deployment of reservoir tanks within the case study area.

1. Introduction

Repeatedly over the past decade, storms have revealed the vulnerability of the urban built environment to storm-surge flooding along America's seaboard. Among the built environment components, interdependent infrastructures are recognized as vulnerable systems with potential to cause a "debilitating effect on security, national economic security, national public health or safety, or any combination thereof" (United States Department of Homeland Security). Such criticality relates in part to system exposure and resilience in the face of exogenous shocks, and also in part to the type and magnitude of failure imposed by threats.

The motor fuel supply chain (MFSC), aka the transportation energy infrastructure[1], is well-recognized as critical (Energy Sector-Specific Plan 2015, Department of Homeland Security), yet also as highly vulnerable to climatic extremes (National Institute of Standards and Technology). The climate-vulnerable infrastructure of transportation energy may eliminate the operability of transportation system in time of disaster, rippling the failure to pre- (e.g. evacuation and sheltering) and post-event emergency tasks, and hampering the recovery processes (Beheshtian, 2016).

Just within the past five years, two natural disasters (i.e. super-storm Sandy and Hurricane Harvey) have further underscored the vulnerability of the MFSC, and have attracted interest among scholars, practitioners, and policy-makers in revisiting adaptability criteria and resilience standards. By the time it made landfall in New York City (NYC), Sandy was weakened to a post-tropical cyclone (National Hurricane Center), however, its impact on infrastructure, and specifically on the MFSC, was devastating. Even ten days after the storm passed NYC, more than 28% of the city's gas stations had no gasoline to operate, according to the U.S. Energy

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[1] The MFSC refers to the multi-commodity supply chain of gasoline and diesel. The entire chain is divided into up-, mid- and down-stream. Covering far-flung petroleum producing area, finding, lifting, and processing oil and gas from subsurface into surface are considered to be the up-stream's activities. Transportation and storage of crude oil from up-stream plants for further processing by pipeline, railway, road, or tanker are activities in the mid-stream. The down-stream's activities, the focus of this research, include further processing of crude oil and natural gas into the final product, and marketing, delivering, and retailing of the fuel in service stations.

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Information Administration (EIA). Sandy shut down twenty-eight terminals across the region (EIA's Petroleum Terminal Survey), flooded thousands of distribution roads, and submerged many service stations, which together resulted in: limited mobility, cascading failures to dependent critical infrastructures such as transportation systems (Comes and Van de Walle, 2014), and eventually a recovery effort that was slowed down and further complicated. The Hurricane Sandy Rebuilding Task Force estimated that Sandy imposed $30-$50 billion of economic loss (aside from physical damage) due to extensive power outages, liquid fuel shortages, and near-total shutdown of the region's transportation system.

More recently, Hurricane Harvey, the wettest hurricane in the history of the contiguous United States (National Oceanic and Atmospheric Administration) and the only major hurricane to make landfall in the United States since Wilma (2005), severely damaged more than a dozen refineries in the area, and it shut down many facilities, including Motiva, the nation's largest oil refinery. The refinery outages, the closure of several key-ports alongside, damaged gas stations, and flooded roads caused a major fuel shortage. It took the fueling infrastructure weeks to cope with the situation and fully bounce back into a state of business-as-usual. During Hurricane Harvey, the MFSC's failure had a ripple effect on the transportation system, and it inevitably hampered each and every activity conditioned on the functional mobility system, including pre-disaster evacuation process planning, intra-disaster emergency tasks, as well as plans for post-disaster recovery efforts.

Governments have responded to the MFSCs climate-vulnerability at different levels to enhance resilience. Federal agencies have been involved mainly by "supporting" private sector efforts to harden the resilience of the energy system. The U.S. Government Accountability Office classified the federal government's role to provide such influence on the private sector – providing information, regulatory oversight, technology research and development, and market incentives and disincentives – as "limited." Asides from the federal government, different states have advanced mechanisms to integrate adaptive measures into their fueling infrastructure. Following super-storm Sandy, New York State (NYS) launched a number of initiatives and passed several regulations to support state-wide hardening and resilience-enhancing strategies for the energy sector. NYS funded two structural strategies: (1) establishing a transfer switch for backup power generation in every downstate gas station within a half mile of a highway exit or hurricane evacuation route, along with onsite backup generators in gas stations in "strategic locations" to provide power when the utility is not available, as subsidized by the New York State Energy Research and Development Authority (NYSERDA) and (2) as part of a pilot program on Long Island, a fuel reservoir tank with 3 million gallons of fuel to supply gasoline during a fuel shortage or prolonged disruption to MFSC, as proposed through a $10 million project by the state governor (NYS Governor 2013).

Many strategies and programs have also been pursued by Texas and Florida following the devastating 2005 hurricane season (Hurricane Katrina in Florida and Hurricane Rita in Texas) and the 2008 hurricane season (hurricanes Ike and Gustav in Texas). Florida, for example, has required service stations within a half mile of evacuation routes to install a backup generator, and Texas created the Fuel Team, "a private-sector partner to the State," to serve as an information clearinghouse and critical communications hub (Hoffman et al., 2009; Hoffman and Bryan, 2013).

The private sector, which controls a majority of MFSC elements, has also invested in hardening and resilience measures. Refiners have built floodwalls along the Houston Ship Channel and around Pascagoula to contain a 100-year storm surge, and have designed elevated substations, control rooms, and pump stations above the likely flood level. The Colonial Pipeline, the largest refined products pipeline system in the U.S., also purchased 12 trailer-mounted portable generators, seven transformers, and miles of associated cabling in 2006. For further details on private sector activities in this area, the reader may consult the, Department of Energy's (DOE's) Report on the Energy Industry Response to Recent Hurricane Seasons (Hoffman, 2010).

Responses to MFSC vulnerability have developed in two separate directions. First, these responses address empirical shortcomings reported by or surveyed through system operators and experts. For instance, the DOE's Office of Electricity Delivery and Energy Reliability (2010) phone-interviewed 14 energy companies to investigate measures for hardening assets and making the energy supply more resilient (Hoffman, 2010). The NYSERDA interviewed terminal operations in NYS to survey terminal vulnerabilities made visible from impacts by Hurricane Sandy, Hurricanes Irene, and tropical-storm Lee. The second type of response is one based on generic strategies commonly taken to enhance a system's 'flexibility' and 'redundancy' (Sheffi and Rice, 2005; Falasca et al., 2008). For instance, the generic properties of a resilient supply chain such as out/multi-sourcing, easy modification of inventory levels, and cross-trained workers have been implemented by different key players in the transportation energy infrastructure.

While these strategies, to some degree, have improved the MFSC's resilience, their effectiveness has been limited, as experienced following the 2017 hurricane season in Houston, TX, and Tampa, FL. Such shortcomings include (1) approaches are too case-specific, in other words, where the MFSC's elements are treated as isolated components operating with no functional or physical interdependence upon other system components, (2) a process where decision-making and physical investment take place in an isolated fashion, and (3) static climate-adaptive strategies that are based only on challenges the MFSCs face at present, despite the dynamic nature of climate change and society.

Advancing fully-integrated strategic planning for a resilient MFSC is currently well out of reach due to several contributing factors. The multi-stakeholder environment of the transportation energy infrastructure obstructs mechanisms for information-sharing or for the creation of institutional equilibria for decisionmakers. The complexity inherent in long-term investment in any asset-intensive infrastructure also contributes to a lack of resilient strategic planning. Despite this, efforts toward one integrated modeling platform can provide decisionmakers, whether from the private or public sector, with a comprehensive grasp of (i) the MFSC's multi-layered structure and inherent interdependencies within and across infrastructure components, (ii*)* its long-term vulnerability to climatic extreme trajectories, and (iii) the dynamics between a system's overall resilience and an optimum portfolio investment. As already discussed, such one approach may not be able to develop an ultimate planning response to the climate-vulnerable MFSCs. Yet an integrated approach aims to provide stakeholders with diverse perspectives and a common ground to facilitate their cross-jurisdictional and multidisciplinary dialogue, and possibly eliminate excess or redundant investment.