Risk-Informed Stochastic Programming with Applications to Inland Flash Flooding of Roadway Freight Networks – Project 10

Exhibit D

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Center Name: Center for Freight Transportation for Efficient and Resilient Supply Chain (FERSC)

Research Priority: Improving Mobility of People and Goods

Principal Investigator(s): Mingzhou Jin (UTK)

Project Partners: TDOT

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Project Description: From a practical perspective, annual US freight volume is expected to grow by at least 50% in the next 25 years (US Bureau of Statistics) [1], putting even more pressure on the already-strained road network system. Ensuring supply chain resilience through freight mobility in the face of disruptions is critical for national security and the economy (White House Report 14017, 2021) [2]. The proposed research will give stakeholders a tool to identify strategic investment opportunities for enhancing roadway resilience against the effects of climate change. The proposed research will fill two main gaps in the literature. First, transportation resilience research has nearly exclusively focused on the impact that climate change will have on coastal regions through sea level rise. The proposed research will explicitly focus on the inland impact namely from flooding caused by more frequent high-intensity storms through both a short- and long-term lens, pioneering a new focus for preparation against climate change. Second, current decision-making frameworks struggle in the presence of low-probability, high-impact events (such as flash flooding), either by ignoring these events and suffering the full brunt of their impact or by overemphasizing them and wasting resources. Our proposed research exploits the benefits of each approach by biasing our scenario generation toward extreme events, providing a more complete understanding of system vulnerabilities and opportunities for strategic investment without increasing model size too much. The approach can be applied to any long-tail distribution and can account for stakeholder risk postures.

The goal is to enhance the resiliency of the U.S. ground freight transportation system against climate change, particularly against flash flooding caused by high-intensity storms that are projected to become more frequent. We will do this by introducing a new decision-making framework called Risk-Informed Stochastic Programming (RISP) for modeling high-impact, low- probability events and applying it to identify opportunities for increasing infrastructure resilience without taking a myopic view of the future. The major contribution of this research is introducing new sampling procedures for continuous and heavily right-skewed uncertainty spaces, allowing decision makers to incorporate expected but unquantifiable changes in event probabilities (e.g., those related to climate change), as well as stakeholder risk postures, into scenario generation and influencing optimal decisions. In addition, this research will incorporate the personal agency of drivers, recognizing that users choose routes to provide the most personal, not system, benefit. At the level of practice, this proposed modeling framework will help the State Departments of Transportation (DOTs), metropolitan planning organizations (MPOs) throughout the nation, and freight companies to better plan routes and investments to enhance the resilience of the road transportation system against climate change. The project will use the State of Tennessee as a case and support Tennessee DOT planning.

Our proposed research utilizes stochastic programming to handle optimization in the presence of uncertainty, data, and statistical analysis to characterize and sample rare events, and GIS software to map topographical information onto existing road networks.

Research Plan: The whole project will have the following six tasks.
Task 1: Data Collection: Five types of data will be collected: (1) network data, including length, free-flow speed, capacity, and current condition for each highway segment in Tennessee; (2) climate data, namely rainfall return

period graphs constructed from past and projected data; (3) topographic data; (4) OD data for each pair of nodes in the network based on Freight Analysis Framework (FAF) 5; and (5) investment data, including viable projects, cost, and protection level for each network link.

Task 2: Route Generation: We will generate a portfolio of alternative routes for each OD pair considering both route distance and similarity. The distance concern is for network efficiency while the heterogeneity can improve network resilience.

Task 3: Scenario Creation: We will sample events from the rainfall return period data and map them onto the network to determine inundation patterns. The sample scenario creation will consider the risk attitude toward rare events with large consequences.

Task 4: Optimization Model and Solution Method Development: We will develop a Risk-Informed Stochastic Program (RISP) to determine the optimal investment decisions to minimize the impact of inland flooding due to climate change. The RISP model will have two stages. The first stage considers infrastructure investment decisions and the second stage route traffic under each disruption scenario. We expect a high computational burden caused by the large size and nonlinearity of RISP. We will develop a decomposition-based solution method to attack the computational complexity.

Task 5: Model and Algorithm Evaluation: Out-of-sample RISP performance will be evaluated based on metrics including investment decisions, average total cost, and average disruption duration and compared to expected value stochastic programming and robust optimization.

Task 6: Dashboard Development: Finally, we will develop a dashboard that visually indicates the most important investment locations given a user-defined budget and risk posture, allowing stakeholders to understand a variety of scenarios while highlighting the most resilient links of the network for route planning.

US DOT Priorities: Improving Mobility of People and Goods. The proposed research aligns with each of the FERSC research thrusts. First, we address freight as a system by explicitly considering the impact of disruptions and the need for supply chain resilience in light of continued supply chain growth in the planning and investment process. Second, our decision-making framework acknowledges and accounts for stakeholder behaviors by recognizing that shippers will choose delivery routes that minimize their travel time without considering overall system performance. Third, we plan to drive freight innovation by sharing and exploiting data about future challenges (i.e., flash flooding) to the supply chain to drive coordination between public and private planning and decision-making to enhance overall resilience.

Outputs: First, the technical innovations and findings will be published in an academic journal, presented at conferences, and incorporated into the curriculum. Second, we will develop a tool that can be used by DOTs, MPOs, and freight companies to identify strategic opportunities for enhancing supply chain resilience through both infrastructure investment and freight route planning.

The proposed research will be shared through two major thrusts corresponding to the categories of impacts. From a practice perspective, the results of our model will be developed into a user-friendly decision-making tool that can be transferred to TDOT, MPOs, and freight companies to guide investment and development discussions, as well as route planning, to enhance the resiliency of the freight supply chain at a state level. The academic findings (sampling and model innovations) will be published, presented at conferences, and incorporated into the curriculum at the University of Tennessee (UT). The major findings from the proposed research will be integrated into the UT Supply Chain Engineering course during lectures on resilience.

Outcomes/Impacts: The proposed research will aid fund allocation for TDOT and MPOs throughout the state to prepare for the projected increase of high-intensity storms, many of which will cause flash floods. While this project specifically considers the impact of flash flooding on freight transportation, it has potential benefits for commuter traffic by ensuring sufficient and viable routes exist for freight traffic despite disruptions. In addition, freight companies and associations can benefit from this research by identifying and utilizing the most resilient transportation routes to increase the reliability of their operations.