## **Supplementary Materials**

**A.6 Managerial Insights and Practical Implications**

Our analysis provides critical insights for practitioners and policymakers in the management of hazmat transportation. Here, we distill key findings and their implications for improving strategies and operations.

**Improved capacity utilization:**

By examining the capacity utilization factor of different transport modes and comparing these with the study by Qu et al. (2014), using analogous data, we observe improved capacity utilization across all modes of transport. This improvement is attributed to strategic measures aimed at minimizing penalties for underutilized capacities. We conducted this comparison by assessing the capacity utilization in the *Min Cost* solution and contrasting it with other studies where the fixed costs of trucks, trains, and barges are set at 100, 100, and 300, respectively. The details of these comparisons are provided in Table A.5.

**Table A.5.** Comparing our results with that of Qu et al. (2014)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Truck |  | Rail |  | Barge |
|  | Capacity utilization (%) |  | Capacity utilization (%) |  | Capacity utilization (%) |
| Qu et al. (2014) | NA |  | 79% |  | 21% |
| The proposed study | 100% |  | 91% |  | 31% |

**Impact of speed on cost and risk:**

* Scenario 1 (all speed levels permitted): Allowing flexibility in speed reduces the overall cost by 2.6% in the *Min Risk* solution and by a substantial 15.4% in the *Min Cost* solution compared to the scenario where only moderate speed is permitted. It is crucial to recognize, however, that this cost reduction comes with increased hazmat transportation risk.
* Scenario 2 (moderate speed only): Limiting speed to moderate levels for three modes of transport results in a significant reduction in hazmat transportation risk – by 2.93 times in the *Min Cost* solution. This highlights the substantial risk posed by overspeeding and underscores and the benefits of moderate speed in mitigating this risk.
* Delay costs and lost sales: Permitting all speed levels leads to lower delay costs and fewer lost sales, facilitating quicker order delivery. The *Min Cost* and *Min Risk* solutions show delay and lost sales costs reduced by 2.9% and 54.6%, respectively, under this scenario. Decision-makers should consider the trade-offs between cost reductions and increased hazmat transportation risk when setting speed policies. Policies that reenforce moderate speeds can help minimize hazmat transportation risks while maintaining operational efficiency.

**Effects of due date adjustments:**

* Shortened due dates (0.5T): Reducing due dates increases the total cost by approximately 59% in the *Min Cost* solution compared to normal due dates. However, the impact lessens in risk-averse solutions, where costs rise by only about 7%.
* Extended due dates (1.5T): Extending due dates eradicates lost sales at higher risk levels (suggesting a buffer that accommodates better planning and risk management) but not at lower ones, where a significant percentage of lost sales still comprises entirely of hazmat. As risk levels decrease, lost sales escalate, peaking at 50.5% at risk level 0 under normal due dates.
* Due date decisions: Decisions about due dates should be made in conjunction with broader risk management and cost optimization strategies to maintain network reliability and minimize the impacts of lost sales and delays.

**Comparison with classic risk formulation:**

Our findings indicate that the widely-used classic risk objective overlooks approximately 38.4% of risks related to overspeeding, underspeeding, and excessive hazmat loads passing across the modal links. Additionally, it tends to miss about 0.1% of population exposure, which can have significant public safety implications. These insights highlight the necessity of integrating comprehensive risk assessment methodologies that include all relevant risk factors, ensuring more accurate and effective management strategies for hazmat transportation. Decision-makers are encouraged to consider these factors in their risk management and operational strategies to enhance safety, reduce costs, and improve service quality in hazmat transportation networks. This holistic approach not only ensures compliance with safety regulations but also supports sustainability in logistics operations.

**References**

Qu, Y., Bektaş, T., & Bennell, J. (2014). Sustainability SI: Multimode Multicommodity Network Design Model for Intermodal Freight Transportation with Transfer and Emission Costs. *Networks and Spatial Economics, 16*(1), 303-329. doi:10.1007/s11067-014-9227-9