

Article

A Simulation-Based Decision-Support Framework for Optimizing Bridge–Ferry Operations Under Maritime-Induced Interruptions: The Port Said–Port Fouad Corridor

Ahmed N. Elbelacy 

Construction and Building Engineering Department, Arab Academy for Science, Technology and Maritime Transport, Port Said 42511, Egypt; ahmednageeb@aast.edu

Abstract

This study presents a field-informed simulation-based decision-support framework for improving transportation operations within the Port Said–Port Fouad bridge–ferry crossing corridor in Egypt. The investigated corridor represents an interruption-sensitive multi-modal transportation system where traffic performance is strongly influenced by maritime navigation activity, bridge-closure events, ferry batch-service operations, fluctuating travel demand, and adaptive traveler behavior. The proposed framework integrates AIS-assisted operational characterization, SUMO-based microscopic traffic simulation, adaptive traveler redistribution, congestion-spillback analysis, XGBoost surrogate modeling, and multi-objective optimization within a unified analytical environment. AIS data were used to identify representative vessel-passage events and bridge-closure periods that supported field calibration of the simulation framework. The methodology explicitly represents bridge-capacity interruptions, ferry operational constraints, multimodal demand redistribution, and corridor-wide congestion dynamics. To reduce the computational burden associated with repeated simulation evaluations, an XGBoost surrogate model was developed to estimate key performance indicators, including transportation delay, vehicle accumulation, ferry waiting time, emissions, and spillback severity. The surrogate model achieved strong predictive performance with a coefficient of determination of $R^2 = 0.965$. Model calibration and within-sample validation were conducted using operational observations collected during a six-day field campaign. The within-sample validation results demonstrated satisfactory agreement between observed and simulated conditions, with an average relative error of approximately 4.8% across major performance indicators. Comparative analyses were performed under existing-operation, rule-based, optimization-based, and adaptive-control scenarios. The results indicate that the proposed framework reduced total transportation delay by 43.8%, peak corridor-wide vehicle accumulation by 65.9%, and estimated CO₂ emissions by 17.4% relative to existing operating conditions. In addition, the framework maintained stable performance under increased demand levels and prolonged bridge-interruption scenarios. Overall, the findings demonstrate the potential of simulation-informed decision support and surrogate-assisted optimization for improving operational efficiency, congestion resilience, and environmental sustainability within interruption-sensitive bridge–ferry transportation systems.



Academic Editors: Predrag Brlek,
Luka Novačko, David Brčić and
Neven Grubišić

Received: 10 June 2026

Revised: 25 July 2026

Accepted: 29 July 2026

Published: 4 August 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: bridge–ferry transportation systems; maritime–urban mobility; floating bridge; ferry operation; AIS; SUMO; XGBoost; surrogate modeling; NSGA-II; adaptive traveler redistribution; congestion spillback; simulation-based decision support

1. Introduction

Urban mobility systems in coastal and canal-based cities increasingly exhibit strong interactions between terrestrial and maritime transportation components. In such environments, transportation performance is influenced not only by roadway demand and infrastructure capacity but also by maritime navigation activity, vessel movements, and interruption-sensitive crossing facilities [1–3]. These characteristics introduce substantial operational complexity, particularly in cities where floating bridges and ferry services constitute essential daily transportation links.

Unlike conventional fixed crossings, floating bridges are periodically interrupted to accommodate maritime traffic, resulting in temporary loss of roadway service capacity while transportation demand continues to accumulate upstream. Such interruptions often generate rapid queue growth, nonlinear congestion escalation, spillback propagation, and delayed post-closure recovery behavior, which are widely recognized as key indicators of transportation congestion and operational performance [4–8]. Consequently, corridor performance becomes strongly dependent on interruption duration, transportation-demand intensity, recovery efficiency, and traveler behavioral adaptation [5,8,9].

Ferry services introduce additional operational complexity because of finite carrying capacity, batch-service operation, loading and unloading processes, maneuvering delays, and operational variability. Within integrated bridge–ferry corridors, congestion conditions in one subsystem directly influence the performance of the other subsystem. During bridge-closure periods, transportation demand is partially redistributed to ferry terminals, frequently generating secondary congestion and extended queues near terminal access roads. Understanding these interactions is therefore essential for effective management of interruption-sensitive transportation systems.

Microscopic traffic-simulation environments such as SUMO have become widely used tools for analyzing transportation-system behavior under dynamic operating conditions because of their ability to represent vehicle interactions, congestion evolution, and multimodal transportation operations [10,11]. Recent studies have increasingly combined microscopic simulation with predictive analytics, transportation optimization, and decision-support applications to improve transportation-system planning and operational management [12,13].

Simulation-based decision-support environments have emerged as valuable tools for evaluating complex mobility systems through the integration of traffic data, simulation platforms, predictive analytics, and operational analysis [12–14]. These approaches have supported improved traffic-state estimation, congestion prediction, transportation planning, and resilience assessment across a wide range of transportation applications [15–18]. Nevertheless, relatively limited attention has been directed toward interruption-sensitive transportation systems involving coupled bridge–ferry operations, maritime-induced capacity disruptions, and multimodal traveler redistribution.

Artificial intelligence and machine-learning approaches have demonstrated considerable potential for transportation-demand estimation, congestion prediction, adaptive traffic management, and operational optimization [19,20]. However, one of the major challenges associated with simulation-based transportation optimization is the substantial computational effort required for repeated high-fidelity microscopic simulation evaluations. This challenge becomes particularly significant when simulation models are embedded within multi-objective optimization procedures involving large numbers of operational scenarios.

To address this limitation, surrogate-assisted approximation techniques have attracted increasing attention in transportation-system optimization research [21,22]. Among these approaches, Extreme Gradient Boosting (XGBoost) has demonstrated strong capability for approximating complex nonlinear system behavior while significantly reducing computa-

tional requirements [23,24]. Transportation optimization further involves multiple competing objectives, including delay reduction, congestion mitigation, emissions minimization, spillback control, and resilience enhancement. Consequently, multi-objective optimization methodologies have become increasingly important in transportation-management applications. Among these approaches, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) has been widely adopted because of its ability to generate Pareto-optimal solutions while maintaining solution diversity and convergence stability [25,26].

Despite recent advances in transportation simulation, optimization, and intelligent mobility management, limited research has addressed interruption-sensitive bridge–ferry transportation systems where maritime operations, multimodal traveler redistribution, storage-capacity limitations, and congestion spillback interact simultaneously. Existing studies have generally focused on ferry operations, movable-bridge impacts, transportation resilience, or urban traffic management separately, whereas integrated decision-support frameworks for coupled bridge–ferry corridors remain relatively scarce.

The Port Said–Port Fouad corridor in Egypt represents a highly representative maritime–urban transportation environment characterized by periodic bridge interruptions, ferry-based multimodal operations, fluctuating transportation demand, and constrained urban roadway infrastructure. The crossing system consists primarily of the Al-Nasr floating bridge and an integrated ferry network operating across the Suez Canal. During peak-demand periods, these operational characteristics frequently generate severe queue accumulation, congestion spillback, and substantial interaction between transportation demand and available crossing capacity.

Recent developments in transportation analytics and intelligent mobility management have highlighted the importance of simulation-based decision-support tools capable of evaluating complex operational interactions under uncertain conditions [16,27,28]. In interruption-sensitive transportation corridors, such tools can support congestion mitigation, operational planning, resilience assessment, and adaptive management while providing a foundation for future digital mapping and data-driven transportation-management initiatives.

Recent advances in intelligent transportation systems have significantly improved the operational management of movable bridges, ferry transportation, and Digital Twin-enabled decision support. In the field of movable bridge operation, recent studies have proposed model-predictive control and predictive scheduling strategies to coordinate bridge-opening regimes with inland vessel navigation, reduce vessel waiting time, and improve the operational efficiency of inland waterway transportation. Integrated draw-bridge scheduling frameworks that jointly consider highway and waterway traffic have also demonstrated potential for mitigating conflicts between road and maritime movements [29–31].

Recent ferry-transportation studies have also addressed cooperative dispatching under operational uncertainty, weather-sensitive ferry operation, and data-driven efficiency assessment. These contributions highlight the importance of ferry-service reliability, loading performance, adverse-weather effects, and intelligent dispatching for resilient waterborne mobility systems [32–34].

At the same time, Digital Twin technologies have become increasingly relevant for intelligent transportation and smart-port management by linking sensing, simulation, predictive analytics, optimization, and decision support within unified operational platforms. Recent studies have emphasized their value for multimodal transportation systems, smart-port operations, and future transportation-management ecosystems [35,36].

Despite these advances, existing studies have typically examined movable-bridge control, ferry dispatching, traffic simulation, and Digital Twin deployment as separate research

streams. Comparatively limited attention has been given to integrated bridge–ferry corridors where maritime-induced bridge closures, ferry batch service, traveler redistribution, congestion spillback, surrogate prediction, and multi-objective operational optimization interact within a single decision-support framework. This study addresses this gap through a field-calibrated simulation-based framework for the Port Said–Port Fouad corridor.

Accordingly, this study proposes a field-calibrated simulation-based decision-support framework for the analysis and optimization of integrated bridge–ferry transportation operations under fluctuating traffic demand and maritime-induced interruptions. The proposed framework integrates simulation, predictive analytics, adaptive traveler behavior modeling, and optimization-assisted decision support within a unified analytical environment. The developed methodology aims to improve transportation efficiency, reduce congestion and emissions impacts, and enhance operational resilience within interruption-sensitive maritime–urban transportation systems.

1.1. Research Gap

Despite significant advances in transportation simulation, intelligent mobility systems, and AI-assisted transportation optimization, important limitations remain in the literature regarding interruption-sensitive bridge–ferry transportation systems.

Most existing transportation studies focus on conventional roadway networks characterized by uninterrupted infrastructure availability and continuous traffic operation. Comparatively limited attention has been directed toward transportation corridors governed by periodic capacity interruptions, such as floating-bridge systems operating in conjunction with ferry services. In such environments, transportation performance is strongly influenced by the interaction between maritime navigation activity, bridge availability, ferry operation, traveler behavior, and network-level congestion propagation.

Furthermore, many existing approaches do not adequately represent the coupled interaction among bridge interruptions, ferry-service operation, traveler redistribution, storage-capacity constraints, and spillback congestion. As a result, the nonlinear congestion formation, oversaturation dynamics, and recovery behavior commonly observed in interruption-sensitive maritime–urban transportation systems are often simplified or overlooked.

Another limitation concerns the representation of ferry operations. Ferry services are frequently modeled using simplified assumptions that neglect batch-service behavior, finite carrying capacity, loading and unloading activities, dispatch-cycle constraints, and operational variability. Such simplifications may reduce the realism of queue accumulation, waiting-time estimation, and demand redistribution analysis within integrated bridge–ferry systems.

In addition, adaptive traveler behavior remains insufficiently incorporated into many transportation-management frameworks. In practice, travelers continuously modify their crossing-mode preferences according to congestion conditions, anticipated waiting times, operational reliability, and infrastructure availability. Ignoring these behavioral responses may reduce the realism of transportation-system evaluation under disruption conditions.

Finally, although surrogate-assisted optimization techniques have demonstrated substantial potential for reducing computational burden in transportation applications, relatively few studies have integrated microscopic traffic simulation, adaptive traveler behavior, congestion-spillback analysis, surrogate modeling, and multi-objective optimization within a unified decision-support framework specifically designed for interruption-sensitive bridge–ferry transportation systems.

1.2. Research Contribution

To address the identified research gaps, this study develops a field-calibrated simulation-based decision-support framework for analyzing and optimizing bridge–ferry transportation operations under fluctuating transportation demand and maritime-induced capacity disruptions. The proposed framework integrates field-informed operational characterization, microscopic traffic simulation, adaptive traveler behavior, surrogate-assisted prediction, and multi-objective optimization within a unified analytical environment.

The principal contributions of this study are summarized as follows:

1. Development of a field-calibrated decision-support framework integrating AIS-assisted operational characterization for bridge-closure identification, SUMO-based microscopic traffic simulation, adaptive traveler redistribution, and spillback-aware congestion analysis.
2. Explicit modeling of the coupled interaction among floating-bridge interruptions, ferry batch-service operations, multimodal traveler behavior, storage-capacity limitations, queue accumulation, and corridor-wide congestion propagation.
3. Integration of an XGBoost-based surrogate model capable of accurately approximating high-fidelity microscopic simulation outputs while substantially reducing the computational effort associated with repeated scenario evaluation and optimization.
4. Application of NSGA-II multi-objective optimization to identify operational strategies that balance transportation efficiency, congestion mitigation, emissions reduction, spillback control, and operational resilience.
5. Demonstration of the proposed framework on the Port Said–Port Fouad corridor, providing a real-world assessment of congestion evolution, traveler redistribution, operational resilience, and bridge–ferry system performance under maritime-induced interruptions.
6. Collectively, these contributions provide a computationally efficient, operationally realistic, and decision-oriented framework for improving congestion management, transportation resilience, and sustainability within interruption-sensitive maritime–urban transportation systems.

1.3. Comparative Positioning of the Proposed Framework

To position the proposed framework within the existing literature, representative studies addressing movable-bridge operations, ferry transportation systems, transportation resilience, and intelligent transportation management were comparatively reviewed. The classification presented in Table 1 was based on the primary methodological components explicitly reported in each study.

The comparison demonstrates that previous studies have primarily focused on individual aspects of bridge operation, ferry-service planning, transportation resilience, or intelligent transportation management. In contrast, the proposed framework integrates bridge-interruption modeling, ferry batch-service representation, adaptive traveler redistribution, microscopic traffic simulation, congestion-spillback analysis, AIS-informed operational characterization, surrogate-assisted prediction, and multi-objective optimization within a unified decision-support environment. Furthermore, the framework is demonstrated using a real-world bridge–ferry transportation corridor, providing a practical basis for congestion mitigation and resilience-oriented operational planning.

Table 1. Comparative positioning of the proposed framework relative to representative studies.

Methodological Capability	Chen et al. [23]	Dehghani et al. [8]	Jørgensen & Solvoll [37]	Ge & Qin [38]	This Study
Bridge-interruption modeling	✓	✓	✗	✗	✓
Ferry-operation representation	✗	✗	✓	✗	✓
Batch-service ferry modeling	✗	✗	✓	✗	✓
Adaptive traveler redistribution	✗	✗	✗	✗	✓
Microscopic traffic simulation	✗	✗	✗	✗	✓
Congestion-spillback analysis	Partial	Partial	✗	✗	✓
AIS-informed operational characterization	✗	✗	✗	✗	✓
Surrogate-assisted prediction	✗	✗	✗	✗	✓
Multi-objective optimization	✗	✗	✗	✗	✓
Real-world bridge–ferry corridor application	✗	✗	✓	✗	✓
Operational resilience assessment	Partial	Partial	✗	Partial	✓
Integrated decision-support framework	✗	✗	✗	Partial	✓

Note: The classification was based on the primary methodological components explicitly reported in the reviewed studies. Symbols ✓, Partial, and ✗ indicate full implementation, limited consideration, and absence of the corresponding capability, respectively.

2. Methodology

The proposed methodology develops a field-informed simulation-based decision support framework for the analysis and operational optimization of an interrupted bridge–ferry transportation corridor operating under fluctuating traffic demand and maritime-induced interruptions. The framework integrates microscopic traffic simulation, dynamic traveler behavior, upstream overflow modeling, surrogate-assisted approximation, and multi-objective operational optimization within an integrated simulation and decision-support environment. Unlike conventional transportation models that assume uninterrupted infrastructure availability, the investigated corridor is governed by time-dependent bridge closures, ferry batch-service operation, storage-constrained congestion accumulation, and adaptive traveler redistribution, all of which contribute to nonlinear queue growth, congestion propagation, and operational instability.

The overall framework architecture is illustrated in Figure 1.

2.1. System Representation and State Variables

The investigated bridge–ferry corridor was represented as a discrete-time dynamic transportation system whose operational state evolves continuously under changing traffic demand, bridge interruptions, ferry-service availability, and congestion conditions. The system was updated at regular operational intervals Δt , enabling continuous tracking of transportation-system behavior throughout the simulation horizon.

At each time step t , the transportation-system state was represented by the following state vector:

$$x_t = [Q_b(t), Q_f(t), \lambda(t), B(t), F(t), S_p(t)]^T$$

where $(Q_b(t))$ and $(Q_f(t))$ denote bridge and ferry queue lengths, respectively; $(\lambda(t))$ represents transportation demand; $(B(t))$ corresponds to bridge operational status; $(F(t))$

denotes ferry-service availability; and $(S_p(t))$ represents upstream overflow conditions within the surrounding roadway network.

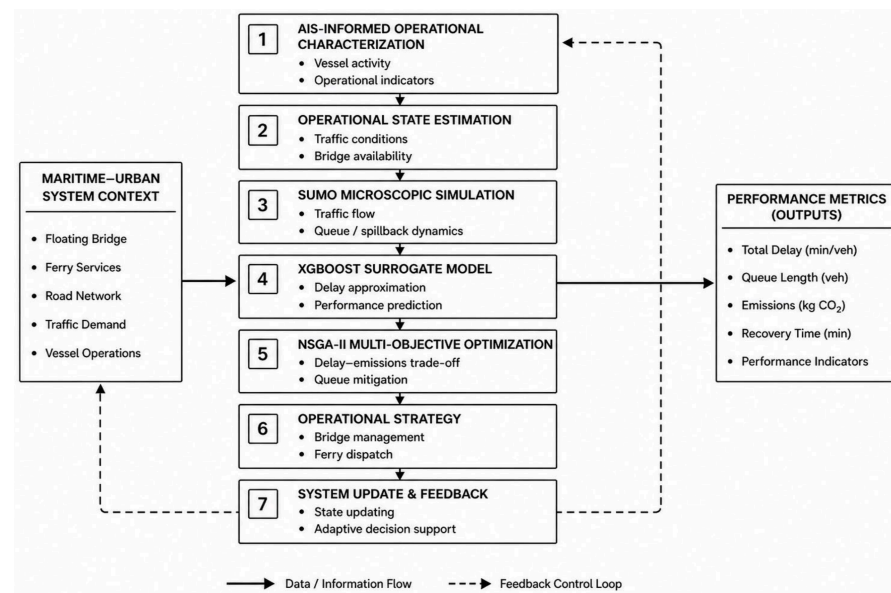


Figure 1. Overall architecture of the proposed framework integrating operational state estimation, microscopic simulation, surrogate-assisted approximation, and multi-objective optimization.

The bridge operational state was defined as:

$$B(t) = \begin{cases} 1, & \text{bridge open to traffic} \\ 0, & \text{bridge closed due to vessel passage} \end{cases}$$

Similarly, ferry operational availability was expressed as:

$$F(t) = \begin{cases} 1, & \text{ferry operation available} \\ 0, & \text{service unavailable or in transfer} \end{cases}$$

The selected state variables capture the principal mechanisms governing congestion evolution within the corridor, including transportation demand, infrastructure availability, queue accumulation, and spillback propagation. This state-space formulation enables continuous representation of transportation-system conditions and provides the foundation for subsequent simulation, congestion assessment, traveler-redistribution modeling, and operational optimization under dynamically varying traffic and maritime conditions.

2.2. Field-Informed Calibration and Validation

Field observations and AIS-informed maritime-operation indicators were used to parameterize the simulation model and define realistic operational ranges for bridge interruptions, ferry operations, traffic demand, queue accumulation, and congestion spillback. Rather than presenting detailed field-observation data in Section 2, the field observation campaign is reported in Section 3.2, whereas the calibration procedure and within-sample validation results are reported in Section 3.3.

Within the methodology, these observations served six main purposes. First, they defined the representative operational states of the bridge and ferry subsystems. Second, they provided realistic ranges for demand fluctuation, closure duration, ferry service characteristics, and storage-constrained congestion behavior. Third, they supported the calibration and within-sample validation procedures used to evaluate whether the simulation

reproduced observed queue growth, ferry waiting behavior, spillback propagation, and post-closure recovery dynamics.

This organization separates the general methodological framework from the case-study implementation. Accordingly, Section 3.2 describes the field observation campaign, whereas Section 3.3 presents the calibration procedure, calibration targets, within-sample validation indicators, and the corresponding validation results.

2.3. Traffic Demand Modeling

Traffic demand was represented as a stochastic time-dependent process incorporating peak-hour variation and operational uncertainty. The traffic-arrival demand at time step t is expressed as:

$$\lambda(t) = \lambda_0 + A \sin\left(\frac{2\pi t}{T}\right) + \varepsilon(t)$$

where λ_0 represents baseline demand, A denotes fluctuation amplitude, T corresponds to the demand-cycle period, and $\varepsilon(t)$ represents stochastic variability.

$$\varepsilon(t) \sim N(0, \sigma^2)$$

The total traffic demand is dynamically distributed between bridge and ferry transportation modes according to traveler mode-choice behavior:

$$\lambda(t) = \lambda_b(t) + \lambda_f(t)$$

This formulation captures temporal demand variability and operational uncertainty within the investigated corridor.

2.4. Bridge Operation and Capacity Discontinuity

Unlike conventional fixed crossings, floating bridge operation introduces time-dependent capacity interruptions associated with maritime navigation activity. The effective bridge discharge capacity is represented as:

$$\mu_b(t) = B(t)\mu_b^{\max}$$

where $\mu_b^{\max}$ represents the maximum bridge discharge capacity during uninterrupted operation.

During bridge-closure periods:

$$B(t) = 0 \Rightarrow \mu_b(t) = 0$$

whereas during normal operation:

$$B(t) = 1 \Rightarrow \mu_b(t) = \mu_b^{\max}$$

Bridge queue dynamics were represented using a conservation-based formulation:

$$\frac{dQ_b(t)}{dt} = \lambda_b(t) - \mu_b(t)$$

During bridge-closure periods, roadway discharge capacity is temporarily interrupted while traffic demand continues to accumulate upstream. This mechanism reproduces the rapid queue growth and delayed recovery behavior observed within interruption-sensitive bridge–ferry corridors.

2.5. Ferry System Modeling

Ferry services were modeled as discrete batch-service transportation systems characterized by intermittent loading, finite carrying capacity, and cyclic transfer operation. The ferry service rate is expressed as:

$$\mu_f(t) = C_f \delta(t - t_d)$$

where C_f denotes ferry carrying capacity and t_d represents ferry departure time.

Ferry queue dynamics follow:

$$\frac{dQ_f(t)}{dt} = \lambda_f(t) - \mu_f(t)$$

while ferry waiting time is approximated as:

$$W_f(t) = \frac{Q_f(t)}{\mu_f(t)}$$

The above expression provides a first-order approximation of ferry waiting conditions. To reflect the batch-service nature of ferry operations, waiting times during inactive intervals were adjusted according to the remaining time until the next scheduled departure, thereby ensuring realistic representation of queue accumulation and release dynamics.

2.6. Queue Dynamics and Congestion Accumulation

Queue evolution within the interrupted bridge–ferry corridor was represented using a conservation-based relationship between traffic arrivals and available discharge capacity. For each transportation subsystem, queue dynamics are expressed as:

$$Q_i(t + \Delta t) = Q_i(t) + [\lambda_i(t) - \mu_i(t)]\Delta t$$

where $Q_i(t)$, $\lambda_i(t)$, and $\mu_i(t)$ denote queue length, arrival demand, and service capacity, respectively.

The total queue accumulation is expressed as:

$$Q_{\text{total}}(t) = Q_b(t) + Q_f(t)$$

where $Q_b(t)$ and $Q_f(t)$ represent bridge and ferry queue lengths, respectively.

An approximate average delay indicator is expressed as:

$$D_{avg}(t) = \sum_i \frac{Q_i(t)}{\mu_i(t)}$$

where ($D_{avg}(t)$) represents an approximate delay indicator derived from queue accumulation and available service capacity. Detailed transportation-delay values reported in the results section were obtained directly from the SUMO microscopic simulation environment. The resulting indicator was used to support evaluation of congestion evolution and corridor performance under varying operational conditions.

2.7. Environmental Performance Assessment

Vehicle emissions were estimated using the emission-output capabilities available within the SUMO simulation environment. Total corridor-wide CO₂ emissions were calculated by aggregating vehicle-level emission estimates throughout each simulation scenario.

The resulting values were employed as an environmental-performance indicator for comparing alternative operational and optimization strategies.

2.8. Upstream Overflow and Network Interaction

Within constrained urban crossing corridors, localized congestion may propagate upstream into adjacent roadway segments and intersections. Spillback conditions occur when accumulated queues exceed the available upstream storage capacity:

$$s_p(t) = \begin{cases} 1, & Q_{\text{total}}(t) > Q_{\text{max}} \\ 0, & \text{otherwise} \end{cases}$$

where Q_{max} represents maximum upstream storage capacity.

To quantify overflow severity, a normalized overflow index was introduced:

$$SI(t) = \frac{Q_{\text{total}}(t)}{Q_{\text{max}}}$$

Values greater than unity indicate oversaturated conditions associated with upstream congestion propagation and network-level performance degradation.

The cumulative spillback impact during the simulation horizon is expressed as:

$$SI_{\text{cum}} = \frac{1}{T} \int_0^T SI(t) dt$$

The spillback index provides a quantitative measure of congestion propagation beyond the immediate crossing facilities and into adjacent urban streets. Consequently, it enables assessment of both local operational performance and corridor-wide traffic resilience under interruption-sensitive conditions.

2.9. Dynamic Traveler Redistribution

Traveler behavior was represented using a dynamic mode-choice formulation [39] in which users redistribute between bridge and ferry services according to congestion conditions, waiting times, and infrastructure availability.

The probability of selecting bridge transportation is expressed as:

$$P_b(t) = \frac{\exp[-\theta G_b(t)]}{\exp[-\theta G_b(t)] + \exp[-\theta G_f(t)]}$$

Similarly, ferry-selection probability is given by:

$$P_f(t) = \frac{\exp[-\theta G_f(t)]}{\exp[-\theta G_b(t)] + \exp[-\theta G_f(t)]}$$

where θ represents behavioral sensitivity and $G_b(t)$ and $G_f(t)$ denote generalized mobility costs.

Bridge generalized cost is defined as:

$$G_b(t) = T_b(t) + \alpha Q_b(t)$$

whereas ferry generalized cost is expressed as:

$$G_f(t) = W_f(t) + T_f + \alpha Q_f(t)$$

Traffic redistribution therefore follows:

$$\lambda_b(t) = P_b(t)\lambda(t)$$

and

$$\lambda_f(t) = P_f(t)\lambda(t)$$

This behavioral feedback mechanism enables dynamic traveler redistribution in response to evolving congestion conditions, waiting times, and infrastructure availability. Consequently, the framework captures adaptive user responses during bridge interruptions, ferry-service fluctuations, and post-closure recovery periods.

2.10. Coupled Bridge–Ferry System Dynamics

The bridge and ferry subsystems operate as an integrated interrupted crossing corridor in which operating conditions within one subsystem directly influence congestion accumulation within the other.

The demand-conservation relationship is expressed as:

$$\lambda(t) = \lambda_b(t) + \lambda_f(t)$$

The combined transportation capacity is given by:

$$\mu_{\text{total}}(t) = \mu_b(t) + \mu_f(t)$$

while total queue evolution follows:

$$\frac{dQ_{\text{total}}(t)}{dt} = \lambda(t) - \mu_{\text{total}}(t)$$

This formulation captures system-wide congestion evolution, traveler redistribution, and capacity-interruption effects under dynamically varying bridge and ferry operating conditions.

2.11. Adaptive Decision-Support and Operational Optimization Framework

The proposed framework operates as a simulation-based decision-support environment in which transportation-system states are periodically updated according to evolving traffic demand, bridge availability, ferry operation, and maritime-interruption conditions. The framework integrates operational-state estimation, microscopic traffic simulation, surrogate-assisted prediction, and multi-objective optimization within a unified analytical architecture. Figure 2 illustrates the layered workflow of the proposed framework, including traffic-state estimation, microscopic simulation, surrogate modeling, and operational optimization.

Algorithm 1 summarizes the computational workflow adopted in the proposed simulation-based decision-support framework. Field observations and AIS-assisted bridge-closure information were first used to define representative operating conditions and calibrate the microscopic SUMO model. The calibrated simulation environment subsequently generated representative operational scenarios that were used to train and validate the XGBoost surrogate model. The validated surrogate model was then integrated with the NSGA-II algorithm to efficiently identify Pareto-optimal operational strategies. Finally, the selected balanced solution was re-evaluated using the original calibrated SUMO model and comparatively assessed against the existing-operation, rule-based, optimization-based, and reinforcement-learning benchmark strategies.

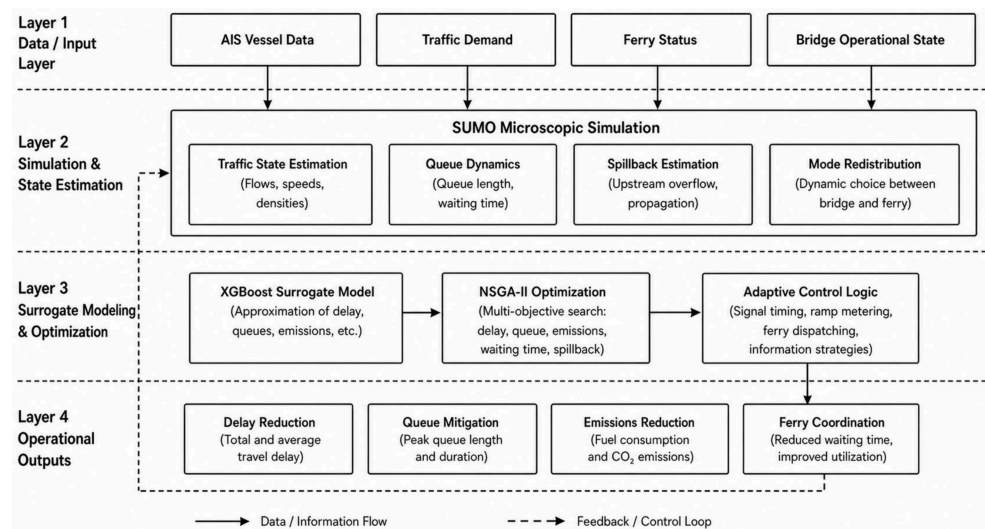


Figure 2. Workflow of the proposed simulation-based decision-support framework integrating traffic-state estimation, microscopic traffic simulation, surrogate-assisted prediction, and multi-objective operational optimization.

Algorithm 1. Surrogate-Assisted Optimization Framework for Bridge–Ferry Operations

- 1: Collect field traffic observations and AIS-assisted bridge-closure information.
- 2: Define representative operational characteristics for:
 - bridge operation;
 - ferry operation;
 - traffic demand;
 - congestion behavior;
 - traveler redistribution.
- 3: Construct the microscopic bridge–ferry transportation model within the SUMO simulation environment.
- 4: Define the transportation-system state vector:

$$\mathbf{x}(t) = [\mathbf{Qb}, \mathbf{Qf}, \lambda, \mathbf{B}, \mathbf{F}, \mathbf{Sp}]^T$$
- 5: Define:
 - stochastic traffic demand;
 - bridge-capacity interruptions;
 - ferry batch-service operation;
 - queue dynamics;
 - congestion accumulation;
 - spillback conditions;
 - dynamic traveler redistribution.
- 6: Couple the bridge and ferry subsystems through demand conservation and combined service capacity.
- 7: Calibrate the SUMO model using field observations.
- 8: Validate the calibrated model against observed operational performance indicators.
- 9: Generate representative operational scenarios by varying:
 - traffic demand;
 - bridge interruptions;
 - operational-control variables;
 - ferry operating conditions.

The general system evolution is represented as:

$$x_{t+1} = f(x_t, u_t, w_t)$$

where x_t denotes the system state vector, u_t represents operational-control actions, and w_t corresponds to stochastic disturbances associated with demand fluctuation and maritime interruptions.

The operational-control vector is defined as:

$$u_t = [u_f(t), u_r(t), u_b(t)]$$

where $u_f(t)$, $u_r(t)$, and $u_b(t)$ represent ferry-dispatch adjustment, demand-redistribution intensity, and bridge-management actions, respectively.

The optimization objective was formulated as a multi-objective minimization problem:

$$J = w_1D + w_2Q + w_3E + w_4SI$$

where D , Q , E , and SI denote delay, vehicle buildup, emissions, and overflow severity, respectively.

An XGBoost-based surrogate model was integrated with NSGA-II optimization to accelerate scenario evaluation and identify Pareto-efficient operational strategies. All objective components were normalized prior to optimization. The resulting framework enables efficient assessment of congestion-mitigation and resilience-oriented transportation-management strategies.

To improve reproducibility, the adopted numerical values of the principal optimization, mode-choice, and demand-generation parameters are summarized in Table 2. Equal weights (0.25 each) were assigned to the four normalized optimization objectives to avoid prioritizing any single performance criterion. The adopted equal-weight configuration was further verified through preliminary optimization and sensitivity analyses to ensure a balanced trade-off among transportation delay, vehicle accumulation, CO₂ emissions, and spillback mitigation without allowing any individual objective to dominate the search process. The mode-choice and demand-generation parameters were selected through field-informed calibration to reproduce the observed peak-period demand variability, bridge–ferry redistribution behavior, and congestion-response patterns recorded during the field observation campaign.

Table 2. Adopted numerical values of the principal model parameters.

Parameter	Description	Adopted/Calibrated Value
w_1	Weight assigned to transportation delay objective	0.25
w_2	Weight assigned to vehicle-accumulation objective	0.25
w_3	Weight assigned to CO ₂ -emissions objective	0.25
w_4	Weight assigned to spillback-severity objective	0.25
θ	Mode-choice sensitivity parameter	0.15
α	Queue/waiting-time impedance coefficient in generalized cost	1.00
λ_0	Baseline traffic-arrival demand	1000 veh/h
A	Relative demand-fluctuation amplitude	0.20
T	Demand-cycle period	60 min
σ	Standard deviation of stochastic demand noise	0.10

2.12. Field-Informed Behavioral Assumptions

Traveler route-choice behavior during bridge-closure events was represented using generalized operational travel cost, including travel time, expected waiting time, and the operational availability of bridge and ferry services. This representation was adopted to evaluate the relative operational effectiveness of the investigated bridge–ferry management strategies while maintaining a computationally efficient simulation framework suitable for repeated scenario evaluation and optimization.

The adopted behavioral representation is based on field-informed operational assumptions describing aggregate traveler responses observed within the investigated corridor rather than on statistically estimated individual-choice models. Accordingly, route-choice decisions were represented at the aggregate demand level using operational characteristics consistent with the observed functioning of the Port Said–Port Fouad crossing system.

The investigated corridor primarily serves recurrent commuting movements between Port Said and Port Fouad, including work-related and educational trips during peak periods, while discretionary trips (e.g., shopping, personal services, and recreational travel) become relatively more important outside peak demand periods. These operational characteristics were considered when defining representative traffic-demand scenarios used throughout the simulation framework.

Because both the floating bridge and ferry services operate without direct user tolls, monetary travel cost was not explicitly included in the generalized travel-cost formulation. Socioeconomic characteristics, including income level and individual value of time, may nevertheless influence traveler decisions indirectly. However, corridor-specific socioeconomic survey data were not available; therefore, these factors were not explicitly incorporated into the behavioral model adopted in the present study.

Weather conditions were considered indirectly through their influence on transportation-system operation rather than through explicit traveler-preference modeling. Under normal operating conditions, both bridge and ferry services remain available. During severe fog or other adverse maritime conditions, ferry services may be suspended, thereby modifying the available crossing capacity and influencing corridor traffic dynamics.

Consequently, the adopted traveler-behavior representation should be interpreted as an operationally calibrated aggregate-demand model rather than a disaggregate behavioral-choice model. Future developments should integrate stated preference and revealed-preference surveys, mobile-device trajectory data, connected-vehicle information, socioeconomic attributes, and weather-responsive demand models to explicitly represent heterogeneous traveler behavior under bridge-interruption conditions. The principal field-informed operational behavioral assumptions incorporated into the simulation framework are summarized in Table 3.

Table 3. Field-informed operational behavioral assumptions adopted in the simulation framework.

Behavioral Component	Representative Operational Assumption
Dominant peak-period travel	Predominantly work-related and educational commuting
Off-peak travel	Greater proportion of shopping, personal, and recreational trips
Direct travel cost	No tolls for bridge or ferry crossings
Socioeconomic influence	Potential indirect effect through value of time; not explicitly modeled
Traveler redistribution during bridge interruption	Aggregate redistribution calibrated from observed operational conditions within the investigated corridor
Normal operating conditions	Bridge and ferry services available
Adverse maritime weather	Temporary reduction or suspension of ferry operation may occur
Behavioral representation	Field-informed aggregate operational assumptions rather than statistically calibrated individual-choice parameters

3. Study Area, Operational Characteristics, and Model Validation

3.1. Port Said–Port Fouad Crossing Corridor

The investigated transportation corridor is located between Port Said and Port Fouad in northeastern Egypt along the Suez Canal. The corridor represents an interruption-sensitive maritime–urban transportation system in which traffic performance is influenced by the interaction between transportation demand, maritime navigation activity, floating-bridge operation, and ferry services. The crossing system consists of two primary transportation components: the Al-Nasr floating bridge and a ferry-based transportation network operating between both sides of the canal. Unlike conventional fixed crossings, the floating bridge undergoes periodic operational interruptions associated with vessel movements through the Suez Canal navigation corridor. Consequently, corridor performance is governed by time-varying capacity conditions rather than uninterrupted traffic operation. During bridge-closure periods, transportation demand is partially redistributed toward ferry services, generating strong operational coupling between bridge and ferry subsystems. The ferry subsystem operates under finite carrying capacity, batch-service operation, loading–unloading processes, and maneuvering delays. Therefore, congestion evolution within the corridor depends not only on transportation-demand intensity but also on interruption duration, ferry-service capability, storage availability, and traveler-redistribution behavior.

Several vehicle-storage areas support corridor operation. On the Port Said side, ferry-terminal activities are supported by a covered parking facility consisting of multiple parallel waiting lanes used for temporary vehicle accumulation prior to loading. On the Port Fouad side, open parking-storage areas are used for ferry staging and queue management. Under high-demand conditions, these storage facilities may approach saturation, resulting in congestion spillback into adjacent urban streets and intersections.

The strategic importance of the corridor further increases operational complexity because it serves substantial daily mobility demand associated with residential, institutional, commercial, and intercity travel between Port Said and Port Fouad. Consequently, the corridor provides a representative case study for evaluating transportation-system performance, congestion propagation, operational resilience, and adaptive decision-support strategies within interruption-sensitive maritime–urban transportation environments.

Figure 3 illustrates the geographic configuration of the investigated corridor, including the floating bridge and ferry transportation facilities, while Figure 4 presents the ferry-terminal layout and vehicle-storage configuration on both sides of the canal.

3.2. Field Observation Campaign and Operational Data Collection

Field-informed operational observations were collected through a six-day observation campaign conducted within the Port Said–Port Fouad bridge–ferry crossing corridor to characterize the principal operating conditions of the transportation system and support calibration and within-sample validation of the simulation framework. The observations focused on the operational interaction among the Al-Nasr floating bridge, ferry services, vehicle queues, terminal storage areas, and adjacent urban access roads.

The data collection procedure included monitoring bridge-closure events associated with maritime navigation, ferry loading and unloading operations, ferry dispatch cycles, vehicle waiting times, queue accumulation, and congestion spillback near bridge approaches and ferry-terminal access roads. Bridge-interruption characteristics were identified using AIS-assisted vessel movement observations in combination with direct field monitoring of bridge availability. AIS information was employed to identify representative vessel-passage events and bridge-closure periods, while simultaneous field observations were used to verify the corresponding operational conditions.



Figure 3. Geographic and operational configuration of the Port Said–Port Fouad crossing corridor, including floating bridge and ferry transportation infrastructure the red dot in the inset map indicates the location of the study area.

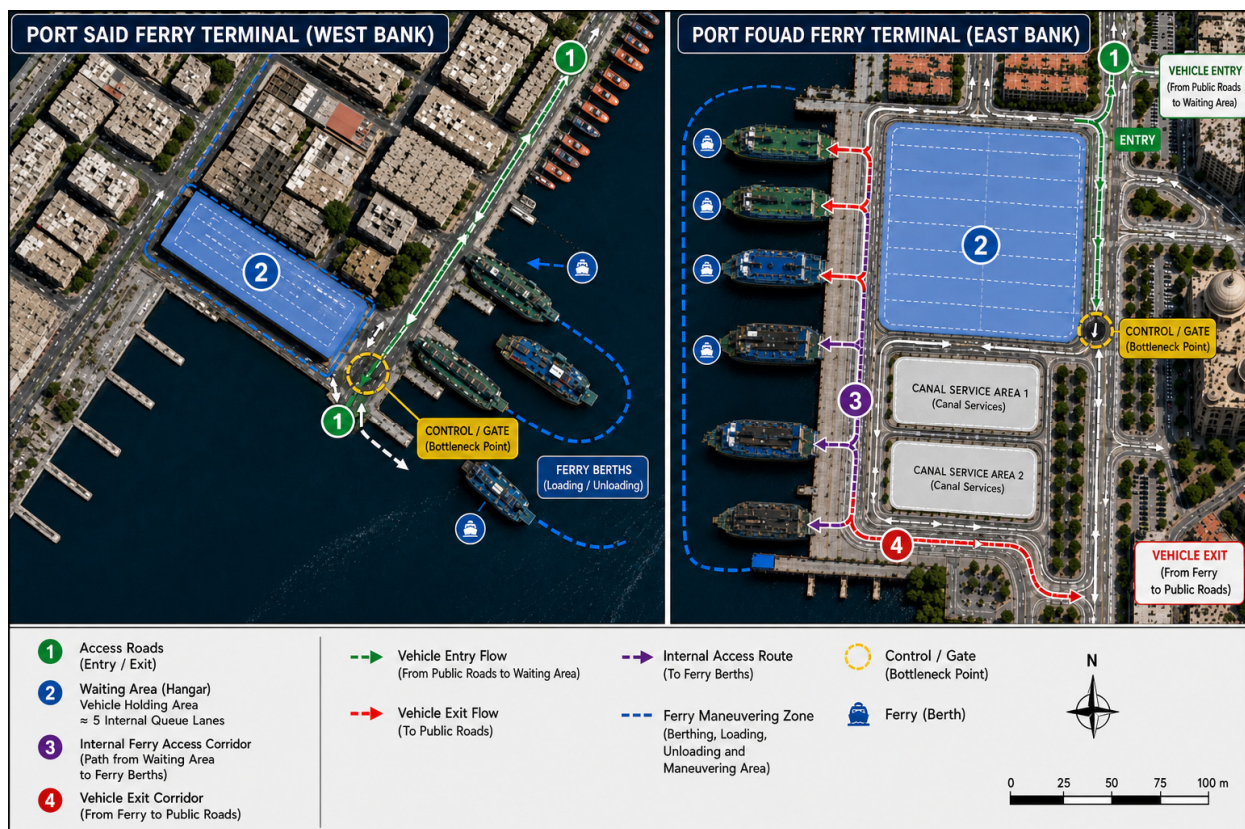


Figure 4. Ferry-terminal operational layout and vehicle-storage configuration on both sides of the crossing corridor.

Because unrestricted access to continuous raw AIS databases for the Suez Canal is limited, the present study relied on field observations supported by publicly accessible AIS information to characterize representative maritime operation patterns. Only vessel passages requiring floating-bridge opening were considered for operational characterization. AIS-assisted observations were used exclusively to determine the timing and duration of representative bridge-interruption events and were not employed as direct dynamic inputs to the microscopic traffic simulation.

AIS-Assisted Data Collection and Quality-Control Procedure

To ensure the consistency of the operational observations, AIS-assisted vessel records were subjected to basic quality-control procedures before being used for simulation calibration. Repeated observations of the same vessel passage, incomplete observations, and records with inconsistent bridge-closure timing were excluded from the operational dataset. The remaining vessel-passage observations were cross-checked against simultaneous field observations of bridge operation to verify consistency between vessel movements and actual bridge-opening events. This quality-control procedure ensured that only representative and operationally consistent bridge-interruption events were retained for calibration and validation of the simulation framework.

During the observation campaign, approximately five bridge-closure events per day were recorded, resulting in approximately 30 representative bridge-interruption events over the six-day monitoring period. The average bridge-closure duration was approximately 25 min, while the maximum observed interruption reached approximately 60 min.

Ferry operations were observed by recording the number of active ferries, approximate vehicle capacity per ferry, loading and unloading durations, crossing times, and terminal waiting conditions. During daytime operation, approximately eight ferries were active, with an estimated carrying capacity of 20–30 vehicles per ferry cycle. Average ferry-crossing times ranged between 12 and 15 min, while loading and unloading activities required approximately 5 min at each terminal.

The observed operational indicators were subsequently used to define representative input parameters for the SUMO microscopic simulation model. These parameters included bridge-closure frequency and duration, ferry carrying capacity, ferry service cycle time, peak-period queue accumulation, ferry waiting time, and congestion propagation conditions.

Queue accumulation and waiting-time observations were used to calibrate and validate the simulated congestion response. Under normal operating conditions, ferry waiting times were typically within 10–12 min, whereas prolonged bridge interruptions and peak-demand periods increased waiting times to approximately 20–25 min. Severe congestion episodes produced corridor-wide vehicle accumulation and spillback into adjacent urban streets, with the maximum observed queue extending to approximately 1 km upstream of the bridge approaches. These observations served as calibration targets to ensure that the simulation reproduced realistic queue growth, ferry waiting behavior, congestion propagation, and post-closure recovery dynamics.

Although the present study does not rely on continuous real-time synchronization with live sensing infrastructure, the collected operational observations provided a realistic empirical basis for model parameterization, calibration, and validation. Consequently, the developed simulation environment should be interpreted as a field-calibrated simulation-based decision-support framework capable of reproducing representative corridor operating conditions and supporting operational planning, congestion assessment, and transportation-management analysis. Table 4 summarizes the representative operational characteristics used in the present study.

Table 4. Representative operational characteristics derived from the field observation campaign and AIS-assisted operational characterization.

Parameter	Representative Value
Observation period	6 days
Average bridge interruptions per day	~5 events/day
Average bridge-closure duration	~25 min
Maximum observed bridge-closure duration	~60 min
Operational ferries (daytime)	~8 ferries
Operational ferries (nighttime)	~2 ferries
Ferry carrying capacity	20–30 vehicles/ferry
Average ferry-crossing duration	12–15 min
Loading/unloading duration	~5 min
Maximum observed queue length	~1 km
Peak-period congestion condition	Severe oversaturation
Congestion spillback occurrence	Frequent during prolonged interruptions

Table 5 summarizes the AIS-assisted bridge-interruption observations and the corresponding quality-control procedures.

Table 5. Summary of AIS-assisted bridge-interruption observations and quality-control procedures.

Parameter	Representative Value
AIS-supported observation period	6 days
Representative bridge-interruption events retained	~30
Mean bridge interruptions per day	~5
Mean bridge-closure duration	~25 min
Maximum bridge-closure duration	~60 min
AIS observation purpose	Identification of vessel-passage events and bridge-closure periods
Vessel selection criterion	Vessel passages requiring floating-bridge opening
Data quality control	Duplicate observations removed; incomplete observations excluded; bridge-closure timing cross-checked with field observations
Role in the proposed framework	Calibration and validation of the SUMO model (not direct model input)

It should be noted that AIS-assisted observations were not directly used as dynamic inputs to the SUMO, XGBoost, or NSGA-II models. Instead, they were employed to identify representative vessel-passage events and bridge-closure periods during the field observation campaign. The resulting operational characteristics were subsequently used to calibrate and validate the SUMO-based microscopic simulation model, thereby providing a realistic representation of maritime-induced traffic interruptions within the investigated corridor.

3.3. Calibration and Within-Sample Validation

To evaluate the ability of the proposed framework to reproduce realistic transportation-system behavior, the simulation environment was calibrated and subsequently evaluated through within-sample validation using operational observations collected from the Port Said–Port Fouad crossing corridor. The calibration process focused on reproducing representative congestion patterns, queue accumulation behavior, ferry waiting conditions, and post-interruption recovery dynamics observed during bridge-interruption events and peak-demand periods.

The field observations described in Section 3.2 were subsequently used for model calibration and within-sample validation. These observations provided representative operational ranges for bridge interruptions, ferry operations, queue accumulation, waiting times, congestion spillback, and transportation-system recovery under both normal and peak-demand conditions.

The calibration procedure incorporated operational characteristics associated with bridge interruptions, ferry operations, traffic-demand fluctuations, queue accumulation, spillback occurrence, and transportation-system recovery. Simulation parameters were iteratively adjusted until the simulated system behavior reproduced representative corridor conditions while maintaining model stability and computational efficiency.

Bridge-operation parameters were calibrated according to observed interruption frequency and closure durations associated with vessel movements within the Suez Canal navigation corridor. Similarly, ferry operational characteristics, including carrying capacity, loading duration, unloading duration, crossing time, and dispatch frequency, were calibrated using representative operational conditions observed within the investigated transportation system.

Traffic-demand parameters were further adjusted to reproduce realistic peak-period congestion accumulation and recovery patterns observed near bridge approaches, ferry terminals, and adjacent roadway segments. Spillback thresholds were calibrated according to the effective storage capacity available within upstream roadway sections and ferry-terminal waiting areas.

Table 6 presents a comparison between field-informed observations and simulated transportation-system behavior used for calibration assessment.

Table 6. Calibration targets based on field observations and corresponding simulated operational ranges.

Operational Parameter	Observed Range	Simulated Range
Floating bridge closure duration (min)	15–25	18–24
Peak corridor-wide vehicle accumulation (veh)	1100–1500	1180–1420
Ferry waiting time (min)	10–22	12–20
Post-closure recovery duration (min)	35–60	38–57
Spillback propagation level	Moderate–High	Moderate–High

The operational ranges summarized in Table 6 served as the primary calibration targets used to align simulated transportation-system behavior with representative corridor operating conditions. More severe operational scenarios, including prolonged bridge interruptions, elevated transportation demand, and extended ferry waiting periods, were subsequently investigated through sensitivity and robustness analyses.

The calibration results indicate that the developed simulation environment successfully reproduced representative congestion evolution, queue accumulation, ferry waiting behavior, spillback occurrence, and post-interruption recovery characteristics observed within the investigated corridor.

To further evaluate model consistency, the calibrated framework was validated using several transportation-performance indicators, including average bridge queue length, peak corridor-wide vehicle accumulation, average ferry waiting time, recovery duration following bridge reopening, spillback occurrence frequency, and the average corridor-wide cumulative transportation delay during the field observation period.

In the present study, peak vehicle accumulation refers to the total number of vehicles simultaneously stored within the corridor, including bridge approaches, ferry-terminal waiting areas, access roads, and upstream roadway segments affected by congestion spillback. Consequently, corridor-wide vehicle accumulation differs from the visible queue length observed along a single roadway segment.

Table 7 summarizes the comparison between observed and simulated operational indicators used for within-sample model validation.

Table 7. Observed versus simulated operational performance indicators used for within-sample validation.

Performance Indicator	Observed Value	Simulated Value	Relative Error (%)
Average bridge queue length (veh)	412	395	4.1
Peak corridor-wide vehicle accumulation (veh)	1340	1275	4.9
Average ferry waiting time (min)	18.6	17.9	3.8
Recovery duration after bridge reopening (min)	46	49	6.5
Spillback occurrence frequency (%)	31.2	29.4	5.8
Average corridor-wide cumulative transportation delay during the field observation period (veh·min)	12,430	11,980	3.6

The within-sample validation results demonstrate good agreement between simulated and observed operating conditions, with relative errors ranging from 3.6% to 6.5% and a mean relative validation error of approximately 4.8% across all investigated transportation-performance indicators. The calibrated simulation framework successfully reproduced key operational characteristics of the Port Said–Port Fouad bridge–ferry corridor, including queue accumulation, ferry waiting behavior, congestion spillback, cumulative transportation delay, and post-interruption recovery dynamics. The relatively low deviations between observed and simulated values indicate that the proposed framework provides a realistic and internally consistent representation of corridor operations under maritime-induced bridge interruptions and can therefore be reliably employed for scenario evaluation, operational optimization, and transportation decision-support applications.

Figure 5 illustrates the comparison between observed and simulated transportation-system behavior within the investigated corridor.

The XGBoost surrogate model was evaluated using 60 additional SUMO-generated scenarios that were excluded from model development, training, and testing. The obtained indicators, including $R^2 = 0.965$, normalized RMSE = 0.084, normalized MAE = 0.051, and MAPE = 4.7%, demonstrate strong agreement between the surrogate predictions and the corresponding microscopic simulation outputs within the investigated input domain. These results support the use of the surrogate as a computationally efficient approximation engine for the subsequent optimization stage. Table 8 summarizes the validation metrics of the XGBoost surrogate approximation framework.

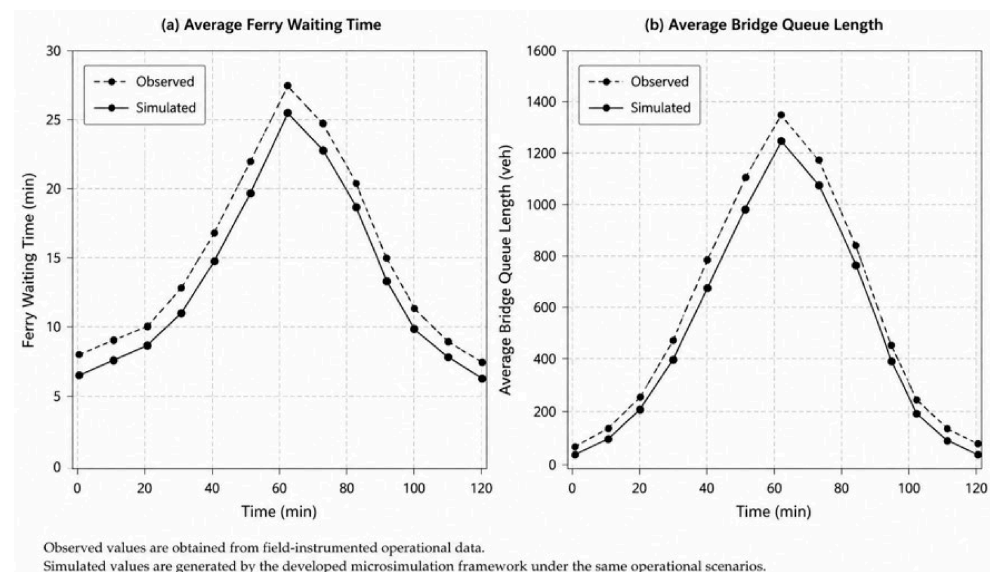


Figure 5. Comparison between field-informed operational observations and simulated transportation-system behavior within the Port Said–Port Fouad corridor.

Table 8. Statistical validation metrics of the XGBoost surrogate approximation framework.

Validation Metric	Value
Coefficient of Determination (R^2)	0.965
Root Mean Square Error (RMSE)	0.084 (normalized)
Mean Absolute Error (MAE)	0.051 (normalized)
Mean Absolute Percentage Error (MAPE)	4.7%
Validation Data Points	60 additional scenarios
Cross-Validation Consistency	Not separately reported; performance assessed using held-out testing and additional validation datasets

Because the surrogate model demonstrated high predictive accuracy on both the held-out testing data and the 60 additional validation scenarios, it was subsequently employed as a computationally efficient approximation engine during the NSGA-II optimization stage. This integration enabled rapid evaluation of large numbers of candidate solutions while preserving acceptable agreement with the corresponding high-fidelity microscopic simulation outputs within the investigated input domain.

The principal configuration and implementation characteristics of the XGBoost surrogate model adopted in the present study are summarized in Table 9.

Table 9. Configuration of the XGBoost surrogate model adopted in the present study.

Item	Description/Value
Simulation platform	SUMO microscopic traffic simulation
Learning algorithm	Extreme Gradient Boosting (XGBoost) regression
Data source	500 SUMO scenarios for model development plus 60 additional validation scenarios (560 total)
Training dataset	400 scenarios (80% of the 500-scenario development dataset)

Table 9. Cont.

Item	Description/Value
Testing dataset	100 scenarios (20% of the 500-scenario development dataset)
Validation dataset	60 additional SUMO scenarios excluded from model development
Input variables	Bridge-closure duration, traffic-demand level, ferry-service capacity, ferry-dispatch interval, and traveler-redistribution parameter
Output variables	Transportation delay, vehicle accumulation, ferry waiting time, CO ₂ emissions, spillback index, and recovery time
Objective function	reg:squarederror
Number of boosting trees (n_estimators)	200
Maximum tree depth (max_depth)	6
Learning rate	0.05
Subsample ratio	0.80
Column sampling ratio (colsample_bytree)	0.80
Hyperparameter selection	Hyperparameters were determined through iterative preliminary tuning to achieve stable predictive performance while minimizing overfitting
Performance metrics	Coefficient of determination (R^2), normalized RMSE, normalized MAE, and Mean Absolute Percentage Error (MAPE)
Model performance	$R^2 = 0.965$; normalized RMSE = 0.084; normalized MAE = 0.051; MAPE = 4.7%

Figure 6 illustrates validation performance of the developed XGBoost surrogate approximation framework against microscopic simulation outputs.

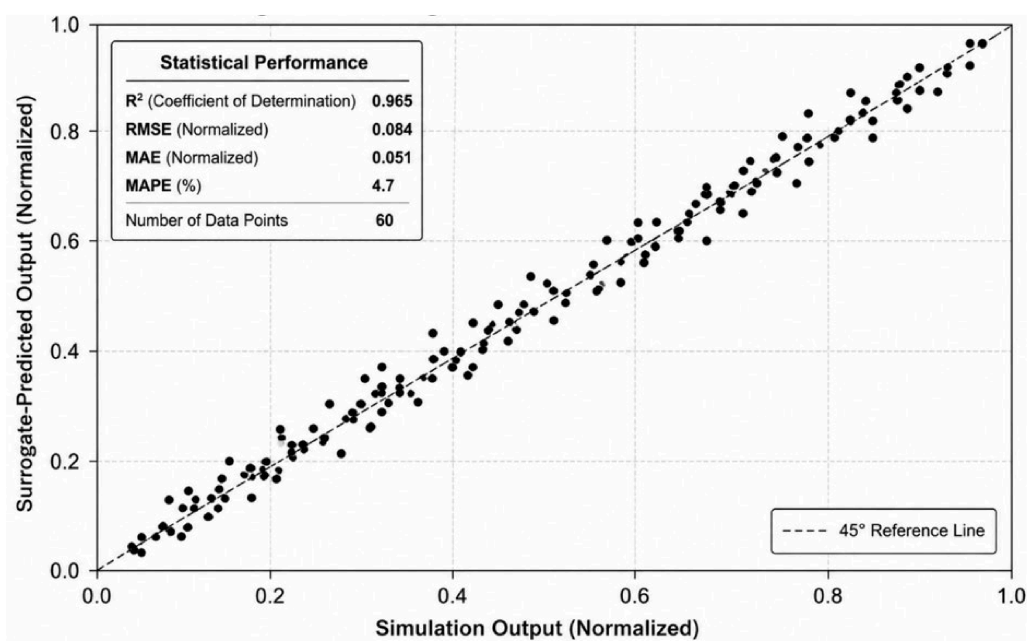


Figure 6. Comparison between XGBoost surrogate predictions and microscopic simulation outputs for 60 validation data points.

3.4. Computational Efficiency of the Surrogate-Assisted Framework

To assess the computational efficiency of the proposed surrogate-assisted framework, the average evaluation time required for a single operational scenario was compared between the high-fidelity SUMO microscopic simulation and the trained XGBoost surrogate model within the same computational environment. As summarized in Table 10, a single SUMO simulation required an average of 12.5 s per scenario, whereas the XGBoost surrogate generated predictions in approximately 0.10 s. This corresponds to a 125-fold computational speedup, or a 99.2% reduction in evaluation time per scenario. These timing values are implementation- and hardware-dependent and are reported to characterize the relative computational benefit within the adopted environment.

Table 10. Computational efficiency comparison between the high-fidelity SUMO simulation and the XGBoost surrogate model.

Performance Metric	SUMO Simulation	XGBoost Surrogate
Average evaluation time per scenario(s)	12.5	0.10
Relative computational efficiency	1×	125× faster
Typical application	High-fidelity microscopic simulation	Rapid surrogate prediction
Role in the proposed framework	Reference traffic simulation	NSGA-II optimization engine

This substantial computational acceleration enabled rapid evaluation of candidate solutions throughout the NSGA-II optimization process, thereby avoiding repeated execution of computationally expensive microscopic traffic simulations. Consequently, the proposed surrogate-assisted framework substantially reduced the computational cost of scenario evaluation while preserving high predictive accuracy ($R^2 = 0.965$), demonstrating its suitability for efficient large-scale multi-objective optimization of interruption-sensitive bridge–ferry transportation systems.

3.5. Operational Realism Assessment

In addition to statistical validation, the practical realism of the proposed framework was assessed by examining whether the simulated transportation-system behavior remained consistent with the operational characteristics observed within the Port Said–Port Fouad corridor. Particular attention was given to congestion formation, queue accumulation, ferry waiting dynamics, congestion spillback, bridge-interruption effects, and post-closure recovery behavior.

The calibrated simulation environment successfully reproduced several characteristic operational patterns observed during the field observation campaign. These patterns included rapid queue accumulation during bridge-closure periods, increased utilization of ferry services during capacity interruptions, progressive congestion spillback under over-saturated conditions, and gradual recovery following bridge reopening. Furthermore, the simulated traveler-redistribution behavior remained consistent with observed operational responses to changing congestion and waiting-time conditions.

The realism assessment therefore complements the within-sample statistical validation results by demonstrating that the framework not only reproduces key numerical performance indicators but also captures the dominant operational mechanisms governing corridor behavior. Consequently, the developed simulation environment provides a physically plausible and operationally representative basis for comparative scenario evaluation, transportation planning, and decision-support applications within interruption-sensitive bridge–ferry transportation systems.

3.6. Robustness and Stochastic Validation

To further evaluate framework reliability under uncertain operating conditions, additional robustness and stochastic-validation analyses were conducted. Because the investigated corridor is influenced by fluctuating transportation demand, ferry-service variability, bridge interruptions, and adaptive traveler behavior, repeated stochastic simulation experiments were performed to assess model stability, reproducibility, and sensitivity to operational uncertainty.

A total of 30 independent simulation replications were conducted for each investigated scenario. Thirty replications were considered sufficient to obtain statistically stable estimates of transportation-performance indicators while accounting for stochastic variability in demand, ferry operations, bridge interruptions, and traveler responses. Random variability was introduced into vehicle-arrival patterns, ferry dispatch timing, loading efficiency, bridge-closure duration, and transportation-demand intensity to reproduce representative operational fluctuations observed within the corridor.

Four representative operating conditions were investigated:

- Low-demand conditions;
- Normal operating conditions;
- High-demand conditions;
- Prolonged bridge-interruption conditions.

Transportation-system performance was evaluated using scenario-level mean transportation delay, queue accumulation, and spillback severity as the primary performance indicators. Table 11 summarizes the scenario-based robustness validation results for the proposed framework.

Table 11. Scenario-based robustness validation results for the proposed framework.

Scenario	Scenario-Level Mean Transportation Delay (veh·min)	Standard Deviation	Coefficient of Variation (%)	Mean Queue Length (veh)
Low Demand	4280	215	5.0	185
Normal Demand	6980	340	4.9	470
High Demand	11,420	690	6.0	1020
Prolonged Bridge Interruption	16,830	1120	6.7	1480

Values represent the mean transportation delay obtained from 30 independent stochastic simulation replications for each investigated operating scenario.

The obtained results demonstrate stable and physically consistent framework behavior across all investigated scenarios. The coefficient of variation remained below approximately 7% under all operating conditions, indicating limited dispersion of simulation outcomes and satisfactory reproducibility despite stochastic variability in transportation demand, ferry operation, and interruption characteristics. These findings suggest that the observed performance trends are primarily governed by underlying transportation-system dynamics rather than random simulation variability.

Under low-demand conditions, congestion remained limited and spillback effects were negligible. As transportation demand increased, scenario-level mean transportation delay and queue accumulation exhibited nonlinear growth due to the combined influence of bridge interruptions, ferry-capacity limitations, and storage-area saturation. The prolonged bridge-interruption scenario produced the highest congestion levels because

of sustained demand redistribution toward ferry services and progressive spillback into adjacent urban streets.

The robustness assessment provides additional confidence that the operational improvements reported in the subsequent results and optimization analyses are not dependent on a specific realization of transportation demand or interruption patterns but remain consistently observable across a broad range of plausible operating conditions. Overall, the robustness analysis confirms that the proposed framework maintains stable operational behavior, realistic congestion-response characteristics, and satisfactory reproducibility under a wide range of transportation and interruption conditions.

3.7. Simulation Environment

The proposed framework was implemented using the SUMO microscopic traffic-simulation platform integrated with XGBoost surrogate modeling and NSGA-II multi-objective optimization. The simulation environment was designed to represent the operational interaction between bridge interruptions, ferry services, transportation demand, traveler redistribution, and congestion propagation within the Port Said–Port Fouad crossing corridor.

The developed transportation network incorporated the principal operational components of the investigated corridor, including bridge approaches, ferry-terminal access roads, upstream urban intersections, vehicle-storage areas, and multimodal interactions between bridge and ferry transportation modes. Dynamic updates were applied throughout the simulation process to represent changes in vehicle routing, transportation demand, bridge operational status, ferry-service availability, queue accumulation, and traveler redistribution behavior.

Bridge interruptions were modeled as temporary reductions in corridor capacity associated with maritime navigation activity, while ferry services were represented through batch-service operation, finite carrying capacity, loading–unloading processes, and dispatch-cycle constraints. These operational characteristics enabled realistic simulation of congestion formation, queue accumulation, spillback propagation, and post-interruption recovery dynamics.

Reinforcement-learning benchmark controller: To provide a meaningful comparative baseline, a reinforcement-learning (RL) benchmark controller was implemented within the SUMO microscopic traffic simulation environment. The controller was designed to emulate adaptive operational decision making under evolving corridor conditions and was employed exclusively for comparative evaluation against the proposed simulation-based decision-support framework. The state representation included bridge operational status, corridor-wide vehicle accumulation, ferry availability, and transportation demand level, while operational actions were selected from a predefined set of feasible bridge–ferry management strategies governing traveler redistribution and ferry utilization. The controller objective was to reduce transportation delay, queue accumulation, and congestion spillback while maintaining efficient utilization of the available crossing capacity. The controller configuration was calibrated through repeated simulation experiments until stable and representative operational performance was achieved under the investigated traffic conditions. Rather than developing an optimized reinforcement-learning policy, the adopted configuration was intended to provide a consistent and representative comparative baseline for evaluating the effectiveness of the proposed framework. Accordingly, the RL controller was used solely as a benchmark and was not integrated into the surrogate-assisted optimization or decision-support framework. The principal configuration and implementation characteristics of the reinforcement-learning (RL) benchmark controller are summarized in Table 12.

Table 12. Reinforcement-learning benchmark controller configuration.

Item	Description
Purpose	Comparative benchmark controller
Simulation environment	SUMO microscopic traffic simulation
State representation	Bridge operational status, corridor-wide vehicle accumulation, ferry availability, transportation demand level
Action space	Predefined traveler redistribution and ferry-utilization strategies
Performance objective	Minimize transportation delay, queue accumulation, and congestion spillback
Configuration strategy	Calibrated through repeated simulation experiments
Role in this study	Comparative benchmark only; not integrated into the proposed framework

The simulation environment further served as the computational engine for surrogate-model development and operational optimization. High-fidelity simulation outputs were used to train and validate the XGBoost surrogate model, which subsequently supported rapid evaluation of operational scenarios during the NSGA-II optimization process. Consequently, the integrated environment enabled efficient investigation of congestion-mitigation strategies, operational adaptations, and transportation decision-support alternatives under varying demand levels and interruption conditions.

Overall, the developed simulation framework provides a realistic and computationally efficient platform for evaluating transportation-system performance, operational resilience, and adaptive management strategies within interruption-sensitive bridge–ferry transportation corridors.

To facilitate interpretation of the reported performance indicators, transportation-delay metrics are reported according to the objective and analytical context of each analysis. The within-sample validation results (Table 7) are expressed as the average corridor-wide cumulative transportation delay observed during the field observation period and used to assess the agreement between observed and simulated corridor operations. Comparative evaluation of alternative operational-control strategies (Table 13 and Figure 7) is based on the mean operational transportation delay obtained for each simulation scenario. The robustness assessment (Table 11) reports the scenario-level mean transportation delay under representative operating conditions. Finally, the event-based analysis (Figure 8) illustrates the temporal evolution of cumulative transportation delay during a representative bridge-interruption event. Consequently, the reported delay values correspond to different temporal and analytical contexts and therefore should not be interpreted as directly comparable.

Table 13. Mean transportation-performance indicators under baseline and proposed operating conditions.

Performance Metric	Baseline/Fixed-Time	Proposed Framework	Improvement (%)
Mean operational transportation delay per simulation scenario (veh·min)	1825	1025	43.8
Peak corridor-wide vehicle accumulation (veh)	1340	457	65.9
Estimated CO ₂ emissions (kg)	1755	1450	17.4

Note: Table 13 reports mean scenario-level performance indicators, whereas validation results represent aggregated corridor-wide conditions over the observation period.

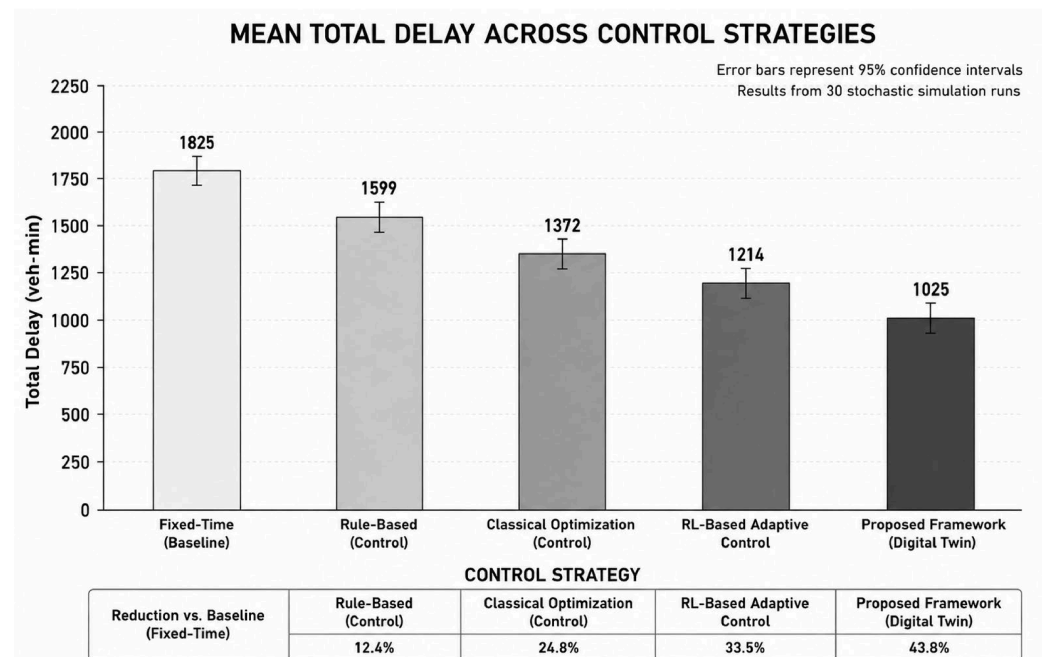


Figure 7. Mean operational transportation delay per simulation scenario under the investigated operational-control strategies.

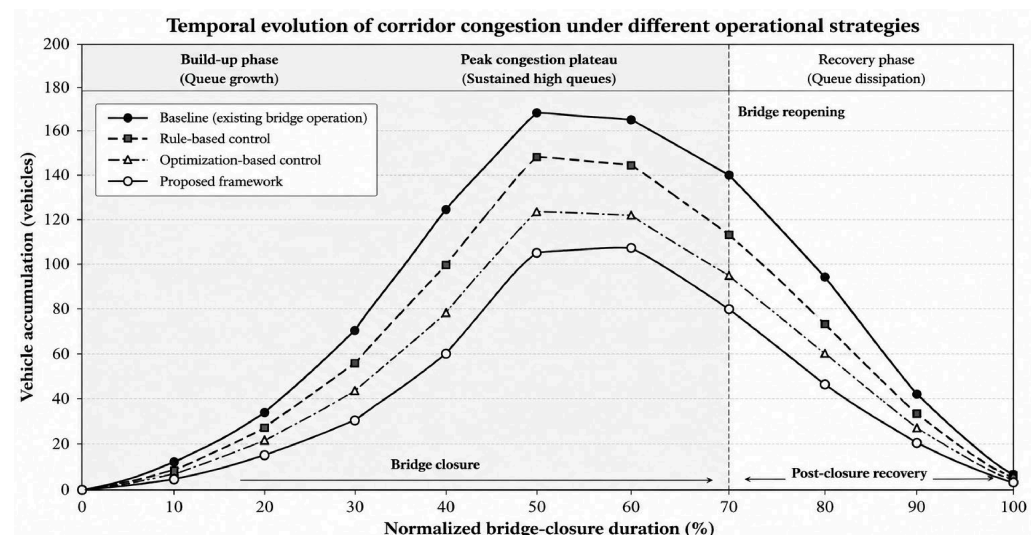


Figure 8. Representative temporal evolution of corridor-wide vehicle accumulation under four operational strategies during bridge closure and post-closure recovery. The trajectories represent the mean behavior from 30 independent stochastic simulation replications, highlighting differences in congestion build-up, peak accumulation, plateau duration, and recovery. The proposed framework consistently achieves the lowest vehicle accumulation and the fastest post-closure recovery among the evaluated strategies.

4. Results and Discussion

4.1. Comparative Evaluation of Operational Control Strategies

The proposed simulation-based decision-support framework was comparatively evaluated against several transportation-management strategies under interruption-sensitive operating conditions within the Port Said–Port Fouad crossing corridor. The investigated strategies included unmanaged baseline operation, rule-based operational control, optimization-based coordination, a reinforcement-learning benchmark controller, and the proposed framework.

The results demonstrate that the proposed framework achieved the most balanced overall operational performance among the transportation-management strategies investigated. While individual benchmark approaches performed well with respect to specific indicators, the proposed framework provided the most favorable trade-off between transportation efficiency, congestion mitigation, environmental performance, and operational resilience. In particular, the framework reduced queue accumulation through adaptive traveler redistribution between bridge and ferry services while simultaneously mitigating congestion spillback within adjacent roadway segments.

While Figure 7 illustrates the comparative delay performance of the investigated strategies, Table 13 provides the corresponding benchmark values for the principal transportation-performance indicators under baseline and proposed operating conditions.

The figure compares the mean operational transportation delay per simulation scenario obtained under unmanaged operation, rule-based control, optimization-based coordination, reinforcement-learning benchmark control, and the proposed framework. Error bars represent variability observed across repeated stochastic simulation replications. The proposed framework achieved the lowest average delay and exhibited the most stable operational performance under varying traffic and interruption conditions.

The values reported in this table provide benchmark indicators supporting the percentage improvements summarized in Table 14.

Table 14. Comparative operational performance of investigated transportation-management strategies.

Control Strategy	Delay Reduction (%)	Queue Reduction (%)	Emissions Reduction (%)	Spillback Mitigation	Recovery Improvement
Rule-Based Control	12.4	18.7	9.5	Moderate	Limited
Optimization-Based Control	24.8	37.2	21.6	Moderate	Moderate
RL Benchmark Controller	33.5	51.4	35.2	Significant	Improved
Proposed Framework	43.8	65.9	17.4	Strong	Significant

Relative to unmanaged operating conditions, the proposed framework reduced mean operational transportation delay by 43.8% (95% CI: 41.2–46.4%), corridor-wide vehicle accumulation by 65.9% (95% CI: 62.9–69.1%), and estimated CO₂ emissions by 17.4%. These improvements were accompanied by reduced spillback occurrence, more efficient utilization of available ferry capacity, and faster recovery following bridge reopening.

Rule-based operational strategies demonstrated limited effectiveness because they were unable to adapt to evolving interruption patterns, fluctuating transportation demand, and changing traveler behavior. Optimization-based approaches provided moderate improvements; however, their effectiveness remained constrained by limited responsiveness to rapidly changing operating conditions. The reinforcement-learning benchmark achieved the largest reduction in CO₂ emissions (35.2%) among the investigated strategies, demonstrating its effectiveness in improving environmental performance. However, this environmental benefit was accompanied by comparatively lower performance in terms of transportation-delay reduction, queue mitigation, spillback control, and post-interruption recovery. In contrast, the proposed framework consistently achieved the greatest improvements in the principal operational-performance indicators related to traffic efficiency and congestion management, including transportation delay reduction, corridor-wide vehicle accumulation, spillback mitigation, and recovery efficiency, while still providing a meaningful reduction in CO₂ emissions (17.4%). Accordingly, the proposed framework is not intended to maximize any single performance indicator; rather, it is designed to achieve the most balanced multi-objective trade-off between operational efficiency, congestion mitigation, environmental sustainability, and transportation-system resilience.

4.2. Congestion Evolution and Queue Dynamics

To evaluate the temporal evolution of congestion under different operational-control strategies, corridor-wide vehicle accumulation was examined throughout a normalized bridge-closure and post-closure recovery cycle. Four operational strategies were compared: the existing bridge operation, rule-based control, optimization-based control, and the proposed simulation-based decision-support framework. The normalized temporal scale enables direct comparison of congestion build-up, peak accumulation, bridge reopening, and queue dissipation among the evaluated strategies.

As illustrated in Figure 8, all strategies exhibit a common congestion-response pattern comprising three principal phases: vehicle accumulation during bridge closure, a peak congestion plateau, and post-closure recovery following bridge reopening. However, substantial differences are observed in both the magnitude and duration of congestion among the investigated operational strategies.

Under the existing bridge operation, vehicle accumulation increases rapidly during the closure period and reaches the highest peak among all evaluated strategies. The baseline condition also exhibits the longest sustained congestion plateau, indicating limited ability to redistribute demand or relieve upstream accumulation while the bridge remains unavailable. Following bridge reopening, accumulated vehicles dissipate gradually, resulting in the slowest recovery profile and the largest residual accumulation during the post-closure phase.

The rule-based control strategy reduces vehicle accumulation relative to the existing operation through predefined operational responses. Nevertheless, congestion remains comparatively high throughout the closure period, and the reduction in the duration of the congestion plateau is limited. Queue dissipation following bridge reopening is faster than under the baseline condition, although substantial residual vehicle accumulation remains during the recovery phase.

The optimization-based control strategy provides a further reduction in corridor-wide vehicle accumulation. Compared with rule-based control, it lowers the congestion trajectory throughout the build-up and plateau phases and accelerates queue dissipation following bridge reopening. These improvements indicate that coordinated optimization of ferry operation, traveler redistribution, and bridge-management actions can reduce the severity and duration of interruption-induced congestion.

The proposed framework maintains the lowest vehicle-accumulation trajectory throughout the complete bridge-interruption cycle. During the build-up phase, it limits the rate of congestion growth through coordinated traveler redistribution and ferry-side operational adjustments. It also achieves the lowest peak accumulation and the shortest sustained congestion plateau among the investigated strategies. Following bridge reopening, the proposed framework produces the fastest vehicle dissipation and the smallest residual accumulation, indicating improved post-interruption recovery and enhanced corridor resilience.

The temporal comparison demonstrates that the primary advantage of the proposed framework is not limited to reducing peak congestion. It improves the complete congestion-response process by suppressing accumulation growth, limiting the duration of sustained oversaturation, and accelerating the restoration of normal operating conditions. This system-level improvement is particularly important in interruption-sensitive bridge–ferry corridors, where prolonged vehicle accumulation can propagate into adjacent urban roads and generate secondary network-level congestion.

The trajectories presented in Figure 8 represent the mean temporal behavior obtained from 30 independent stochastic simulation replications under the calibrated operating conditions. They are intended to facilitate comparative interpretation of congestion evolution among the evaluated operational strategies rather than to represent a single determinis-

tic bridge-closure event. Overall, the temporal comparison indicates that the proposed simulation-based decision-support framework provides the most favorable congestion-response profile among the investigated strategies, particularly with respect to peak vehicle accumulation, congestion-plateau duration, residual accumulation, and post-closure recovery.

The temporal congestion trajectories illustrated in Figure 8 provide additional insight into the mechanisms governing corridor performance during maritime-induced bridge interruptions. During bridge closure, vehicle arrivals exceed the available crossing capacity, resulting in rapid vehicle accumulation and progressive congestion propagation toward upstream roadway segments and adjacent urban intersections. As the interruption continues, the corridor approaches a temporary congestion plateau, where the limited discharge capacity of the integrated bridge–ferry system balances the continuing arrival demand. Following bridge reopening, accumulated vehicles are gradually discharged and the corridor progressively returns to normal operating conditions.

The lower congestion trajectory achieved by the proposed framework is consistent with the quantitative improvements reported in the preceding sections. The reduced vehicle accumulation corresponds directly to the observed reductions in transportation delay, congestion spillback, and post-closure recovery time. These findings indicate that the proposed framework not only limits peak congestion but also shortens the duration of sustained congestion and accelerates recovery following maritime-induced bridge interruptions, thereby improving both operational efficiency and corridor resilience.

The qualitative congestion patterns shown in Figure 8 are further supported by the quantitative evolution of cumulative transportation delay and queue accumulation presented in Figure 9. Unlike the scenario-level mean delay values reported in Table 13 and Figure 7, the delay values shown in Figure 9 represent the replication-mean cumulative evolution of transportation delay under a representative bridge-interruption condition. The annotated values correspond to the peak cumulative transportation delay obtained from 30 independent stochastic simulation replications.

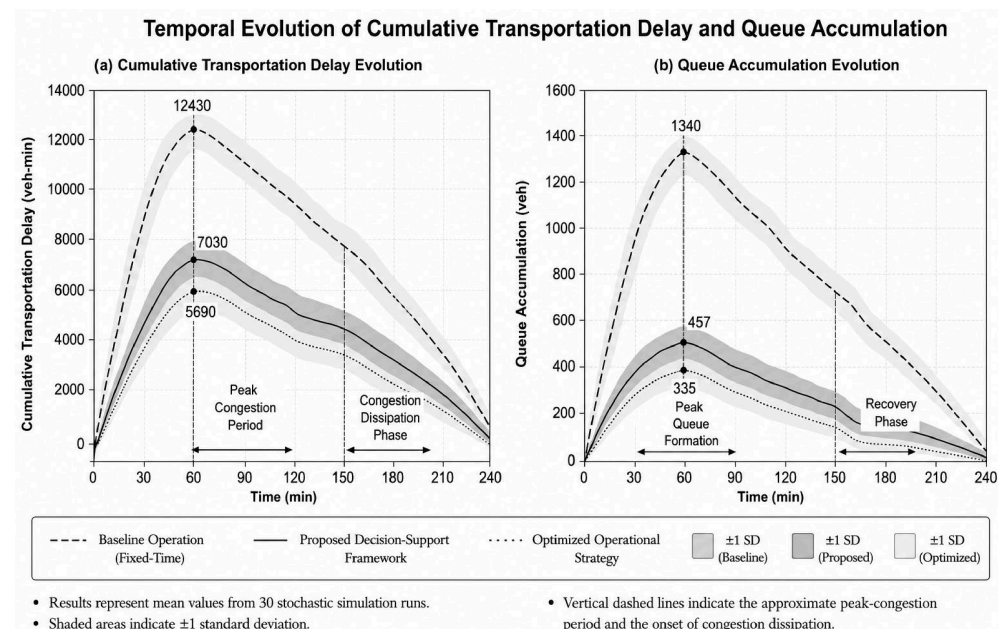


Figure 9. Temporal evolution of cumulative transportation delay and queue accumulation under baseline, proposed, and optimized operational-control strategies during a representative bridge-interruption event. The annotated values denote the peak cumulative transportation delay and peak queue accumulation reached during the simulated event. Shaded regions represent ± 1 standard deviation obtained from 30 stochastic simulation replications, while the vertical dashed lines indicate the approximate peak-congestion period and the onset of congestion dissipation.

The shaded regions in Figure 9 represent variability bounds obtained from 30 independent stochastic simulation replications. Despite uncertainty associated with transportation-demand fluctuations, ferry-service variability, and bridge-interruption duration, the proposed framework exhibited comparatively stable congestion-response characteristics. The relatively narrow variability bounds indicate that the observed performance trends remained consistent across repeated simulation experiments. Collectively, the qualitative and quantitative analyses demonstrate that congestion evolution within the investigated corridor is governed by the combined interaction of bridge-capacity interruptions, ferry-service limitations, storage-area constraints, and traveler-redistribution behavior. Consequently, effective congestion management requires coordinated operation of both bridge and ferry subsystems rather than isolated control actions. These findings provide further evidence that adaptive operational coordination can substantially improve corridor resilience under interruption-sensitive operating conditions.

4.3. Adaptability Assessment Across Representative Cross-Canal Corridor Configurations

To examine the adaptability of the proposed simulation-based decision-support framework beyond the calibrated Port Said–Port Fouad case study, additional comparative analyses were conducted using three representative cross-canal corridor configurations with different operational scales. Rather than representing specific real-world transportation corridors, these configurations were designed to reflect typical urban canal-crossing conditions characterized by different bridge lengths, crossing impedances, and ferry-service capacities. The investigated configurations comprised a compact urban crossing, the calibrated Port Said–Port Fouad baseline corridor, and an extended cross-canal corridor with increased crossing distance and ferry-service capacity.

The representative corridor configurations were evaluated using the same calibrated traffic-demand assumptions, traveler-redistribution model, optimization framework, and operational-control strategies adopted throughout the study. Only representative corridor-scale characteristics, including network geometry, bridge-crossing impedance, and ferry-service capacity, were modified, whereas the traffic-demand model, traveler-behavior assumptions, optimization framework, and overall decision-support architecture remained unchanged. This approach enabled assessment of the framework's adaptability under varying operational environments while preserving the consistency of the underlying computational methodology.

Table 15 summarizes the relative performance improvements achieved by the proposed framework compared with the existing bridge operation for the three representative corridor configurations, while Figure 10 illustrates the corresponding trends across the principal transportation-performance indicators. These standardized adaptability scenarios were evaluated using a common comparative setup; consequently, their percentage improvements describe the adaptability experiment and should not be directly equated with the final calibrated benchmark values reported in Table 13.

As summarized in Table 15 and illustrated in Figure 10, the proposed framework consistently improved transportation performance across all representative corridor configurations. Transportation-delay reduction increased from 29.2% for the compact urban crossing to 32.3% for the extended cross-canal corridor. Similarly, reductions in peak vehicle accumulation and average queue length increased from 36.6% to 39.4%, demonstrating stable congestion-mitigation performance under different corridor scales.

Table 15. Relative performance improvements achieved by the proposed simulation-based decision-support framework compared with the existing bridge operation across representative cross-canal corridor configurations.

Performance Indicator	Compact Urban Crossing	Port Said–Port Fouad (Baseline)	Extended Cross-Canal Corridor
Delay reduction (%)	29.2	30.5	32.3
Peak vehicle accumulation reduction (%)	36.6	37.8	39.4
Average queue length reduction (%)	36.6	37.8	39.4
Congestion spillback reduction (%)	51.2	52.1	53.4
Recovery-time improvement (%)	42.8	43.9	45.3
CO ₂ -emission reduction (%)	16.1	17.4	19.6

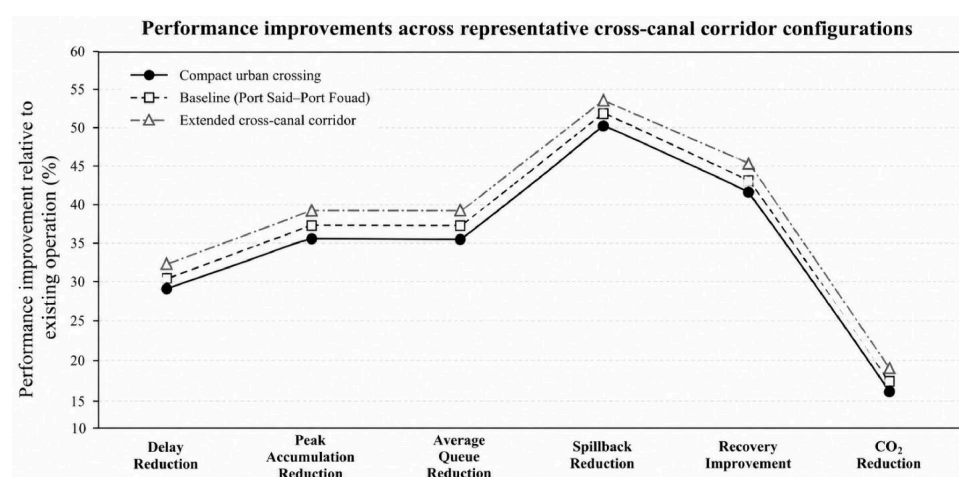


Figure 10. Relative performance improvements of the proposed simulation-based decision-support framework across three representative cross-canal corridor configurations, demonstrating consistent improvements in transportation delay, vehicle accumulation, queue length, congestion spillback, recovery performance, and CO₂ emissions.

The largest improvements were observed for congestion spillback, with reductions ranging from 51.2% to 53.4%, indicating the framework's potential to effectively suppress congestion propagation during bridge-interruption events. Recovery performance also remained consistently robust, with recovery-time improvements between 42.8% and 45.3%, reflecting faster restoration of normal traffic conditions following bridge reopening. Although reductions in CO₂ emissions were comparatively smaller, ranging from 16.1% to 19.6%, the results nevertheless demonstrate consistent environmental benefits associated with improved corridor operation across the investigated representative configurations.

The relatively small variation in performance among the three representative corridor configurations indicates that the proposed framework maintains stable operational effectiveness under different bridge lengths and ferry-service capacities. Although absolute traffic conditions vary according to corridor characteristics, the proposed methodology was found to provide substantial improvements in transportation efficiency, congestion mitigation, and operational resilience within the investigated representative configurations. Nevertheless, these analyses should be interpreted as representative scalability assessments rather than independent external validation, because the investigated configurations were developed by varying representative corridor-scale characteristics while preserving the same calibrated traffic-demand model, traveler-behavior assumptions, optimization framework, and decision-support architecture. Additional validation using independent real-world bridge–ferry transportation corridors would further strengthen

evidence supporting the applicability of the proposed framework to a broader range of operational environments.

4.4. Adaptive Traveler Redistribution Between Bridge and Ferry Systems

The investigated corridor exhibited strong interaction between bridge and ferry transportation modes, particularly during bridge-interruption periods. As bridge availability decreased and queue accumulation intensified, travelers increasingly shifted toward ferry services in an attempt to minimize waiting times and perceived transportation costs.

Under unmanaged operating conditions, this redistribution process frequently generated secondary congestion within ferry terminals because of finite ferry carrying capacity, loading constraints, and batch-service operation. Consequently, congestion was transferred from bridge approaches to ferry facilities rather than being effectively mitigated, resulting in inefficient utilization of available transportation resources.

In contrast, the proposed framework dynamically regulated traveler redistribution according to prevailing congestion conditions, ferry-service availability, queue accumulation, and anticipated waiting times. This adaptive response enabled more balanced utilization of bridge and ferry transportation capacity throughout interruption and recovery periods.

The representative traveler redistribution behavior observed during bridge-interruption and post-reopening recovery phases is illustrated in Figure 11.

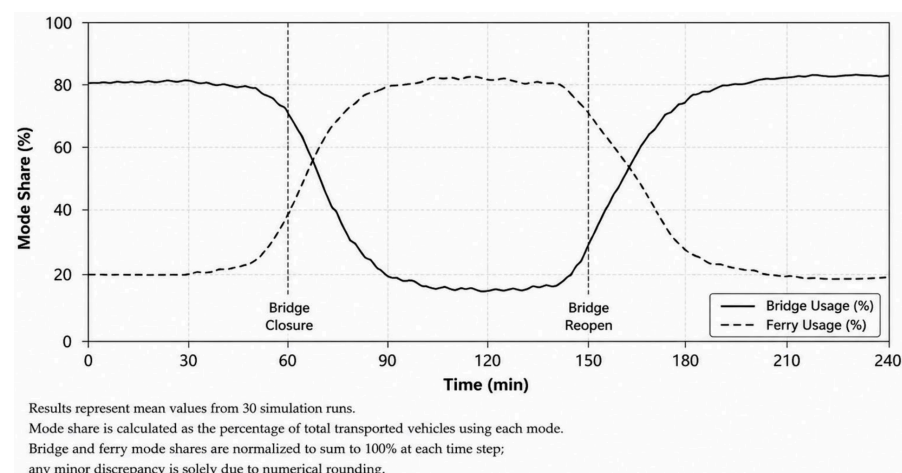


Figure 11. Dynamic redistribution of transportation demand between bridge and ferry systems during bridge-closure and reopening periods. Percentages are normalized such that bridge and ferry shares sum to 100%.

The results indicate that transportation demand shifted progressively toward ferry services immediately following bridge closure, reflecting traveler adaptation to reduced bridge availability. As ferry queues increased, redistribution rates gradually stabilized, preventing excessive oversaturation of ferry-terminal facilities. Following bridge reopening, transportation demand progressively returned toward bridge facilities as travel conditions improved and accumulated congestion dissipated.

These observations demonstrate that traveler behavior constitutes a critical component of corridor performance under interruption-sensitive operating conditions. The effectiveness of the proposed framework therefore arises not only from infrastructure utilization and operational control measures but also from its ability to anticipate and coordinate demand redistribution across available crossing alternatives. The results highlight the importance of incorporating adaptive traveler behavior into transportation-management strategies for integrated bridge–ferry transportation systems.

4.5. Congestion Propagation and Network-Level Traffic Interaction

Congestion spillback represented one of the primary mechanisms governing operational instability within the investigated bridge–ferry corridor. Under high-demand and prolonged interruption conditions, queue accumulation extended beyond bridge approaches and ferry-terminal storage areas into adjacent urban streets and nearby intersections. Consequently, localized congestion evolved into a corridor-wide traffic-management challenge affecting both crossing facilities and surrounding roadway infrastructure.

Figure 12 provides a conceptual illustration of representative congestion-propagation mechanisms under simulated bridge-interruption and high-demand conditions. The figure is intended to facilitate visualization of the progressive evolution of congestion rather than to present quantitative performance results. As illustrated, congestion initially develops near bridge approaches and ferry-terminal access points before progressively extending into upstream roadway segments. As the available storage capacity becomes increasingly constrained, congestion propagates throughout a larger portion of the surrounding transportation network, leading to spillback and reduced operational efficiency. The corresponding quantitative performance evaluation is presented separately in the subsequent tables and figures.

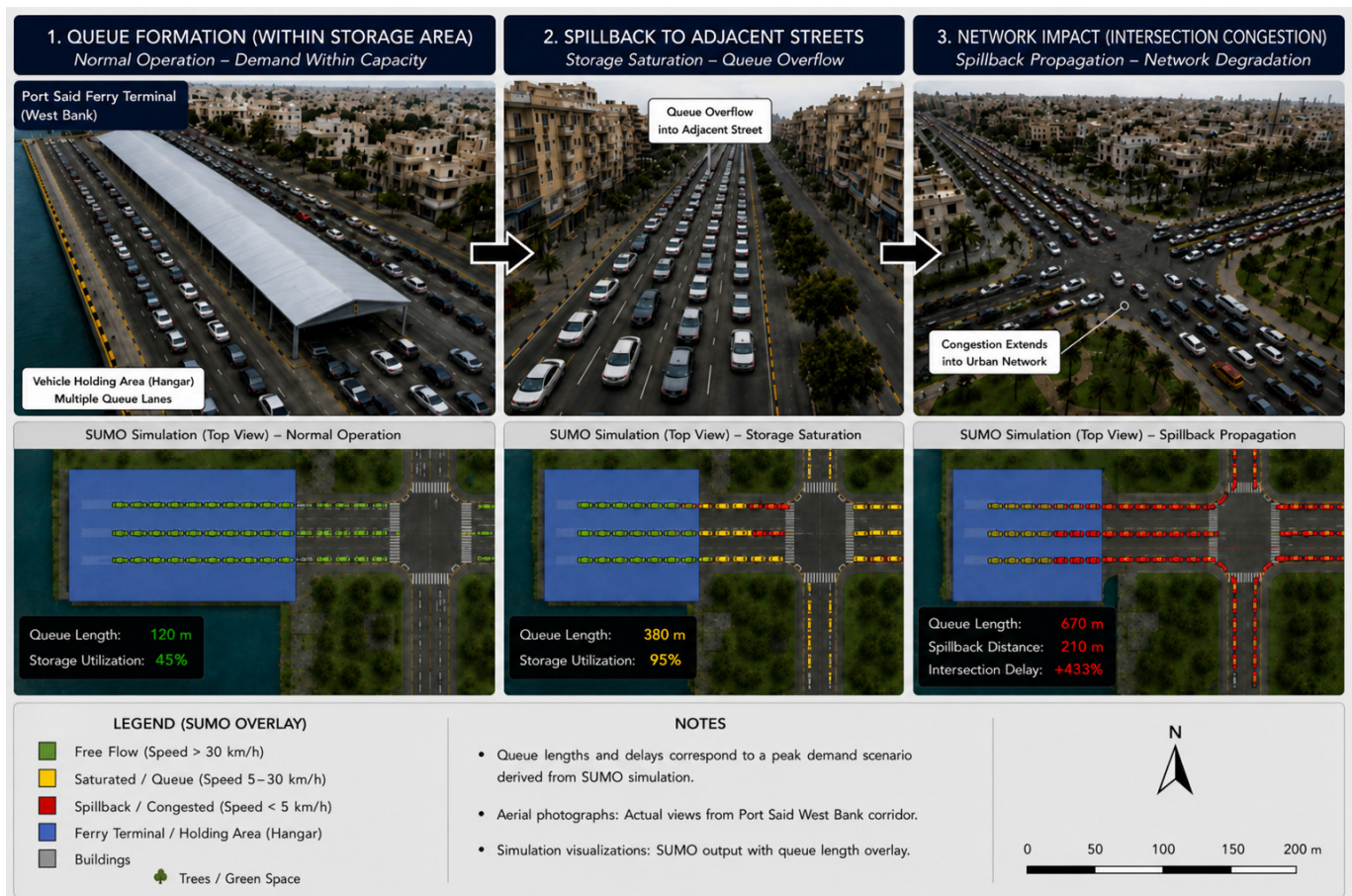


Figure 12. Conceptual illustration of congestion evolution and spillback propagation under representative bridge–ferry operating conditions.

The analysis indicates that spillback severity increased nonlinearly with both interruption duration and transportation-demand intensity. Under prolonged bridge-interruption conditions, congestion propagation followed a cascading pattern in which localized bottlenecks progressively influenced adjacent roadway segments and intersections. This

behavior demonstrates the strong coupling between crossing-facility performance and broader network-level traffic conditions.

The results further highlight the critical role of storage-capacity constraints in governing congestion amplification. Once bridge-approach and ferry-terminal storage areas approached saturation, the ability of the corridor to absorb additional demand decreased substantially. Under such conditions, relatively small increases in transportation demand or interruption duration produced disproportionately large expansions in the spatial extent of congestion.

Compared with unmanaged operating conditions, the proposed framework moderated congestion propagation by improving the distribution of demand between bridge and ferry services and reducing pressure on critical storage locations. Consequently, congestion remained more localized and recovery of upstream roadway conditions occurred more rapidly following restoration of crossing capacity.

These findings demonstrate that interruption-sensitive bridge–ferry systems should be evaluated from a network perspective rather than solely through local performance indicators. Effective corridor management therefore requires not only reducing congestion at individual facilities but also limiting the spatial transmission of congestion throughout the surrounding urban transportation network.

4.6. Multi-Objective Operational Trade-Off Analysis

Transportation-system management within interruption-sensitive bridge–ferry corridors requires balancing multiple competing objectives rather than optimizing a single performance indicator. Consequently, the proposed framework employed NSGA-II multi-objective optimization to investigate trade-offs among transportation delay, queue accumulation, emissions generation, and spillback severity.

The resulting Pareto-optimal solutions revealed that simultaneous minimization of all performance indicators was generally unattainable under highly constrained operating conditions. Strategies aimed at aggressively reducing transportation delay frequently require increased utilization of available crossing capacity and more intensive operational intervention. Conversely, solutions prioritizing environmental performance occasionally accept moderate increases in delay and queue accumulation.

Figure 13 presents the Pareto-optimal solutions generated by the proposed optimization framework.

The Pareto front demonstrates the existence of multiple feasible operational strategies capable of achieving different balances between transportation efficiency and environmental performance. Solutions located at one end of the Pareto front provide maximum congestion mitigation, whereas solutions located at the opposite end prioritize emissions reduction while accepting modest increases in transportation delays.

The analysis further indicates that intermediate Pareto solutions often provided the most balanced overall performance. These solutions simultaneously achieved substantial reductions in transportation delay, queue accumulation, and spillback severity while maintaining acceptable environmental outcomes. Such solutions may therefore represent practical operating strategies for transportation agencies seeking to balance mobility, resilience, and sustainability objectives.

The results highlight the value of multi-objective optimization as a transportation decision-support tool because it enables planners and operators to evaluate competing operational priorities rather than relying on a single performance indicator. Consequently, the framework supports more informed selection of operational strategies under varying demand levels, interruption conditions, and management objectives.

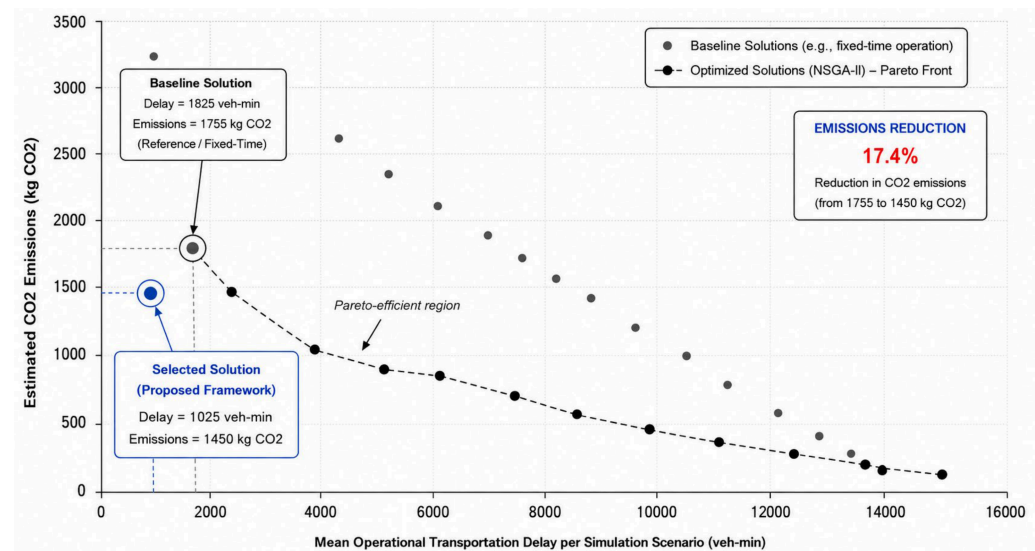


Figure 13. Pareto-optimal trade-off between mean operational transportation delay and estimated CO₂ emissions. The highlighted baseline and selected solutions correspond to the values reported in Table 13. The selected framework reduced delay from 1825 to 1025 veh·min and CO₂ emissions from 1755 to 1450 kg, corresponding to reductions of 43.8% and 17.4%, respectively.

Overall, the obtained results demonstrate that multi-objective optimization provides an effective mechanism for identifying balanced transportation-management strategies within interruption-sensitive bridge–ferry transportation systems. The findings further emphasize the importance of simultaneously considering congestion mitigation, environmental performance, and network resilience when evaluating corridor-management alternatives.

4.7. Nonlinear Congestion Formation Under Increasing Demand

The analysis revealed strongly nonlinear system behavior as transportation demand approached the effective service capacity of the integrated bridge–ferry corridor. Under low- and moderate-demand conditions, increases in transportation demand produced approximately proportional increases in queue accumulation and transportation delay. However, this relationship changed substantially as corridor demand approached critical operating capacity.

Figure 14 illustrates the demand–response behavior observed under progressively increasing transportation-demand conditions. The results indicate the existence of a distinct capacity-transition threshold beyond which congestion growth accelerated disproportionately relative to additional demand increases.

Below the critical capacity threshold, available bridge and ferry resources remained sufficient to accommodate fluctuations in transportation demand, resulting in relatively stable queue behavior and rapid recovery following interruption events. In contrast, once the effective capacity of the corridor was approached, congestion became increasingly sensitive to bridge interruptions, ferry-service limitations, storage-capacity constraints, and operational recovery efficiency.

The observed transition demonstrates the presence of threshold-driven system dynamics in which relatively small increases in transportation demand can trigger disproportionately large increases in queue accumulation, transportation delay, and congestion spillback. This behavior reflects the strong interaction among bridge-capacity interruptions, ferry-service constraints, storage-area saturation, and adaptive traveler responses.

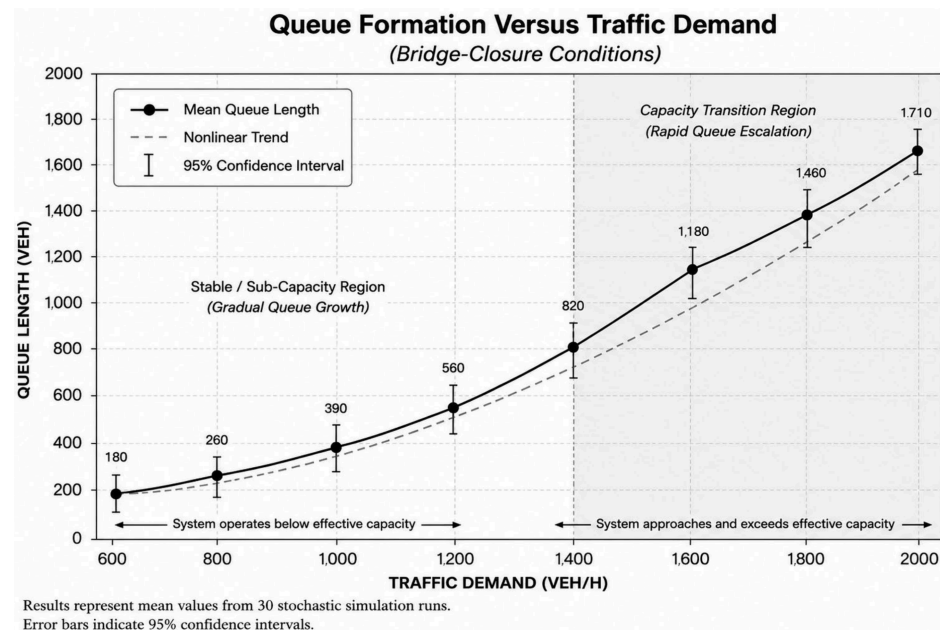


Figure 14. Nonlinear queue formation behavior under increasing traffic-demand conditions and capacity-transition effects within the investigated transportation corridor.

The findings further indicate that congestion-mitigation measures are most effective when implemented before the corridor reaches critical operating conditions. Once the system enters an oversaturated state, recovery becomes progressively more difficult because congestion propagation and storage-capacity limitations reinforce one another, reducing the ability of the corridor to absorb additional demand.

These results demonstrate that transportation-system performance within interruption-sensitive bridge–ferry corridors cannot be adequately represented using linear demand–response assumptions. Instead, corridor behavior is characterized by capacity-transition effects and threshold-driven congestion dynamics that should be explicitly considered when developing operational-management and resilience-enhancement strategies.

4.8. Ferry-Side Sensitivity Analysis

4.8.1. Sensitivity Analysis Under Varying Ferry Capacities

Additional sensitivity analyses were conducted to investigate the influence of ferry-service capacity on transportation-system performance during bridge-interruption conditions. Because ferry operation represents the principal alternative crossing mode during bridge closures, understanding the relationship between ferry capacity and corridor performance is essential for operational planning and congestion-management decision making [37].

Figure 15 illustrates transportation-system sensitivity under varying ferry-capacity conditions. Transportation delay and queue accumulation were selected as the primary performance indicators because they directly reflect the ability of the corridor to accommodate redistributed demand during interruption periods.

The results indicate that transportation delay and queue accumulation decreased substantially as ferry-service capacity increased from low to moderate operating levels. This trend reflects the improved ability of the ferry subsystem to accommodate demand redirected from the bridge during interruption periods, thereby reducing pressure on critical storage areas and limiting congestion accumulation.

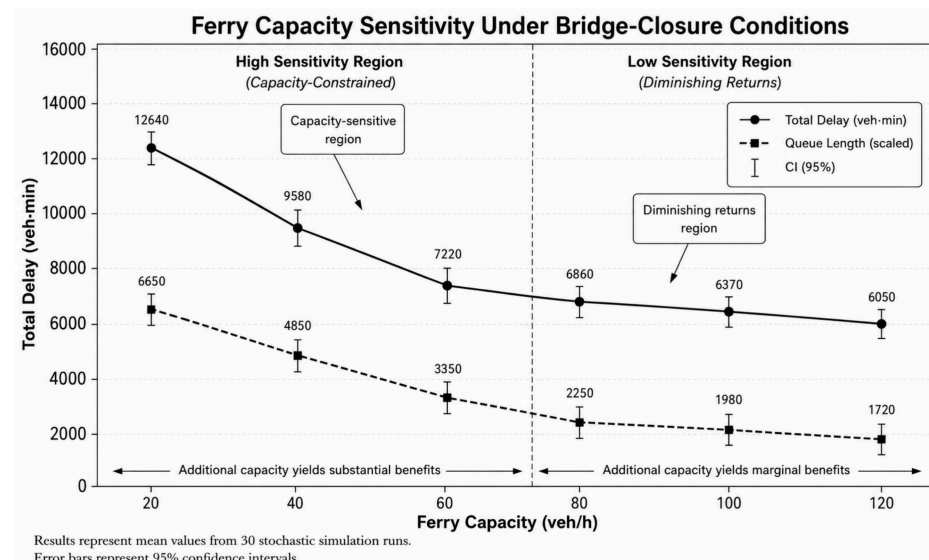


Figure 15. Influence of ferry-service capacity on total transportation delay and queue accumulation during bridge-interruption conditions. Each data point represents the mean value obtained from 30 independent stochastic simulation replications, while the error bars denote the corresponding 95% confidence intervals.

However, the relationship was distinctly nonlinear. Beyond a moderate ferry-capacity threshold, additional capacity increases produced progressively smaller improvements in transportation performance. This behavior indicates the presence of diminishing operational returns, whereby further capacity expansion yields relatively limited benefits compared with the corresponding increase in operational resources.

The analysis suggests that once ferry services become capable of accommodating a substantial proportion of redistributed transportation demand, corridor performance becomes increasingly influenced by other operational constraints. These constraints include bridge-interruption duration, terminal-processing efficiency, storage-area availability, recovery dynamics, and congestion propagation within adjacent roadway segments. Consequently, ferry-capacity expansion alone cannot fully eliminate congestion within crossing systems.

From a transportation-planning perspective, the findings are consistent with ferry-crossing planning principles showing that capacity and service-level decisions strongly influence operational performance [37], whereas excessive capacity expansion may not be economically justified because of diminishing performance gains. Therefore, the most effective corridor-management strategies are likely to combine targeted capacity enhancement with adaptive operational control, traveler redistribution, and congestion-management measures.

Overall, the sensitivity analysis demonstrates that corridor performance is governed by the interaction of multiple operational factors rather than ferry capacity alone. These findings reinforce the importance of system-level transportation management when evaluating improvement strategies for interruption-sensitive maritime–urban transportation corridors.

4.8.2. Representative Ferry-Side Engineering Assessment

The ferry-side assessment presented in this subsection provides a representative engineering interpretation of the expected influence of ferry loading efficiency and active berth availability on effective ferry-service capacity and corridor performance. The investigated parameter levels were not evaluated through independent one-factor-at-a-time SUMO simulation experiments. Accordingly, the reported trends should be interpreted as an analytical engineering assessment supported by the calibrated baseline results, rather than

as an independent quantitative sensitivity analysis. The effective ferry service capacity is expressed as

$$\mu_f^{\text{eff}} = \frac{N_b C_f \eta_L}{T_c}$$

where μ_f^{eff} denotes the effective ferry service rate, N_b is the number of active ferry berths, C_f is the ferry carrying capacity, η_L represents ferry loading efficiency, and T_c is the average ferry operating cycle time. Ferry loading efficiency reflects terminal loading effectiveness, whereas berth availability denotes the number of simultaneously active ferry-service positions.

The representative ferry-side parameter levels considered in this engineering assessment are summarized in Table 16.

Table 16. Representative ferry-side sensitivity scenarios adopted for engineering interpretation.

Parameter	Representative Scenario	Value	Engineering Interpretation
Ferry loading efficiency (η_L)	Reduced	0.70	Reduced loading and unloading efficiency
	Baseline	0.85	Calibrated operating condition
	Improved	1.00	Improved loading coordination
	Optimized	1.15	Highly efficient terminal operation
Active ferry berths (N_b)	Limited	1	Reduced berth availability
	Baseline	2	Calibrated operating configuration
	Expanded	3	Increased parallel ferry operation

The preceding equation indicates that increasing either ferry loading efficiency or berth availability proportionally increases the effective ferry service rate, thereby improving corridor throughput during bridge-interruption periods. The corresponding engineering implications are summarized in Table 17.

Table 17. Representative operational influence of ferry-side sensitivity parameters.

Operational Parameter	Expected Influence on Corridor Performance
Increased ferry loading efficiency (η_L)	Reduced ferry waiting time
	Reduced vehicle accumulation at ferry terminals
	Lower congestion spillback
	Faster post-closure recovery
Increased berth availability (N_b)	Increased effective ferry service capacity
	Higher ferry throughput
	Reduced queue accumulation
	Improved corridor operational resilience

To provide quantitative engineering context for these representative operational trends, the calibrated comparison between the existing bridge operation and the proposed framework is summarized in Table 18. These values correspond to the calibrated baseline analysis presented earlier in the manuscript and are included solely to facilitate engineering interpretation. They should not be interpreted as independent one-factor-at-a-time sensitivity simulation results.

Table 18. Reference calibrated operational improvements associated with the proposed framework.

Performance Indicator	Existing Bridge Operation	Proposed Framework	Improvement
Ferry waiting time (min)	27.90	17.40	37.6%
Queue accumulation (vehicles)	182.21	113.55	37.7%
Approximate physical queue length (km) *	1.37	0.85	37.7%
Spillback index	0.418	0.200	52.2%
Recovery time after bridge reopening (min)	39.84	22.40	43.8%
CO ₂ emissions (kg)	401.01	331.25	17.4%

* Approximate physical queue length was estimated using an average vehicle spacing of 7.5 m per queue. This conversion is provided solely for engineering interpretation and was not used as a primary simulation output.

The calibrated reference values indicate that improved ferry-terminal operation is associated with substantial reductions in ferry waiting time (37.6%), queue accumulation (37.7%), congestion spillback (52.2%), post-closure recovery time (43.8%), and CO₂ emissions (17.4%). The comparatively smaller reduction in emissions reflects the influence of additional factors, including total travel activity, vehicle operating conditions, and engine-load characteristics.

Overall, this representative assessment identifies ferry loading efficiency and berth availability as two important operational parameters governing the resilience of integrated bridge–ferry transportation corridors. Improved loading efficiency increases the effective ferry service rate by reducing loading and unloading losses, whereas additional active berths increase simultaneous ferry throughput. Together, these mechanisms are expected to reduce ferry waiting, vehicle accumulation, congestion spillback, and post-closure recovery time. The present assessment provides an engineering interpretation based on the calibrated decision-support framework and should not be interpreted as an independent one-factor-at-a-time sensitivity analysis. Future investigations incorporating dedicated ferry-operation experiments or scenario-specific simulations would enable fully quantitative characterization of individual ferry-side operational parameters.

4.9. Operational Behavior Under Prolonged Bridge Closure

Bridge interruptions represent one of the most influential operational disturbances affecting performance within the Port Said–Port Fouad crossing corridor. To evaluate the resilience of the proposed framework under increasingly adverse operating conditions, additional analyses were conducted considering progressively longer bridge-interruption durations.

Figure 16 illustrates the influence of bridge-closure duration on transportation-system performance under baseline and adaptive operational-management conditions.

The results indicate that transportation performance deteriorated progressively as bridge-interruption duration increased. Under baseline operating conditions, transportation delay exhibited a strongly nonlinear response to prolonged closures, reflecting the growing inability of the corridor to accommodate arriving demand during extended capacity interruptions. As closure duration increased, the transportation system became increasingly vulnerable to congestion amplification and delayed recovery.

In contrast, the proposed framework maintained comparatively stable performance across the investigated range of interruption durations. Although transportation delay increased under more severe disruption conditions, the rate of performance deterioration remained substantially lower than that observed under unmanaged operation. This behavior indicates that coordinated bridge–ferry management can improve the ability of the corridor to absorb and recover from prolonged operational disturbances.

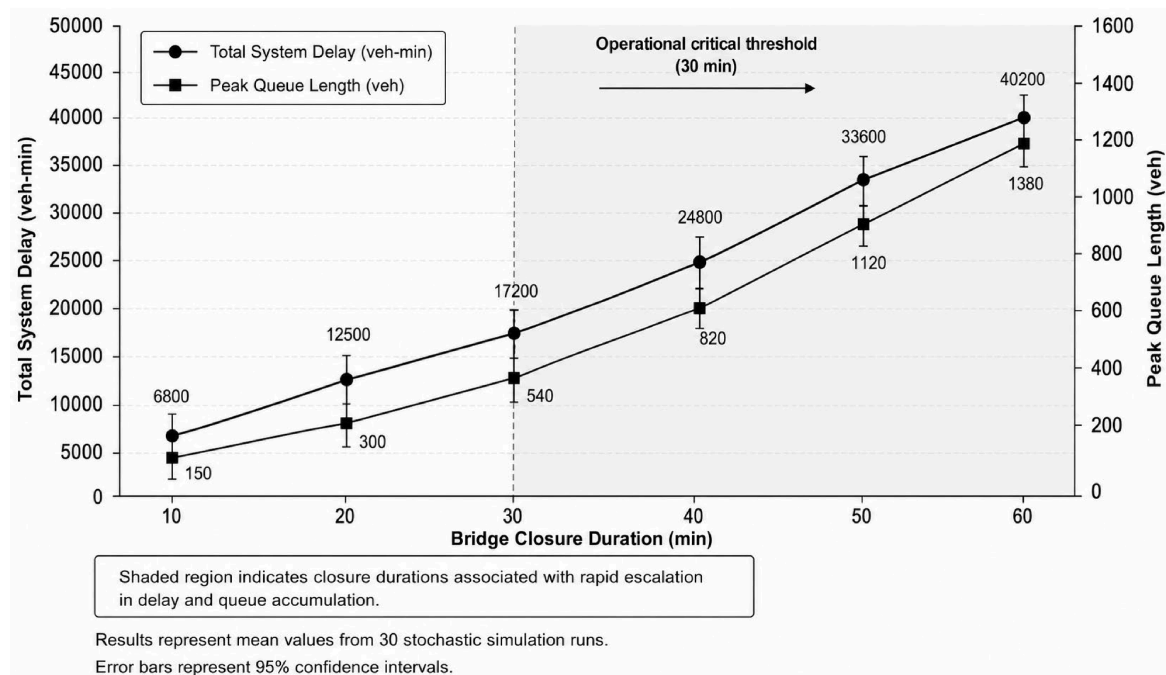


Figure 16. Influence of bridge-closure duration on total system delay and peak queue length under representative bridge-interruption conditions. Each data point represents the mean value obtained from 30 independent stochastic simulation replications, while the annotated values denote the corresponding mean total system delay and peak queue length for each investigated bridge-closure duration.

The difference between baseline and adaptive operating conditions became increasingly pronounced as interruption duration increased. Under relatively short interruptions, performance differences remained moderate because the available transportation infrastructure retained sufficient residual capacity to accommodate accumulated demand. However, under prolonged interruption conditions, adaptive traveler redistribution and coordinated ferry utilization became increasingly important for maintaining corridor functionality.

From a transportation-resilience perspective, the findings demonstrate that the effectiveness of adaptive operational management increases with disruption severity. The proposed framework therefore provides a practical decision-support mechanism for reducing vulnerability to maritime-navigation disturbances and enhancing the ability of interruption-sensitive bridge-ferry transportation systems to maintain acceptable performance during extended bridge closures.

Overall, the results highlight the importance of resilience-oriented operational planning within maritime-urban transportation environments, where disruption duration can exert a dominant influence on corridor performance and recovery behavior.

4.10. Spillback Escalation Under Prolonged Bridge-Closure Conditions

To further evaluate corridor resilience under prolonged disruption conditions, additional analyses were conducted to examine spillback escalation behavior as bridge-closure duration progressively increased. Particular attention was given to the ability of different operational-control strategies to delay the onset of severe spillback propagation and maintain stable corridor operation during extended bridge interruptions.

Figure 17 illustrates spillback-severity trends under increasing bridge-closure durations for unmanaged operation, rule-based coordination, and the proposed framework.

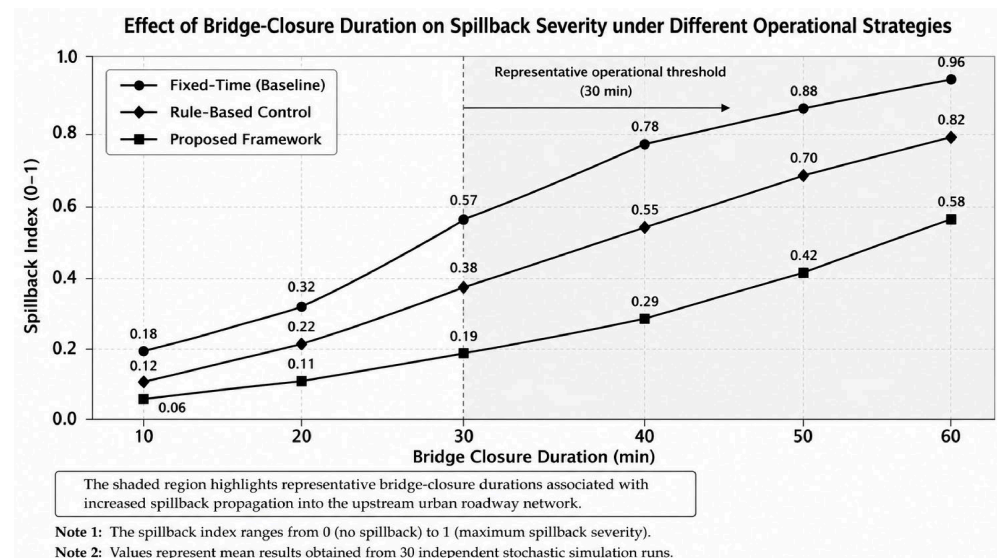


Figure 17. Effect of bridge-closure duration on spillback severity under different operational strategies. The proposed framework consistently maintains the lowest spillback index across the investigated bridge-closure duration range, indicating improved operational resilience under prolonged interruption conditions. Values represent mean results obtained from 30 independent stochastic simulation runs.

The results indicate that all investigated strategies experienced increasing spillback severity as bridge-closure duration increased. Longer interruption periods reduced the effective corridor capacity, resulting in progressively greater queue accumulation and upstream spillback propagation. However, substantial differences were observed in the rate at which overflow conditions developed. Under unmanaged operation, spillback intensity increased rapidly once bridge-closure duration exceeded approximately 30 min, indicating the onset of critical operational conditions.

The rule-based strategy provided moderate improvements by delaying congestion escalation under intermediate demand levels. Nevertheless, its effectiveness diminished under heavily oversaturated conditions because of its limited responsiveness to evolving congestion patterns and changing transportation-system states.

In contrast, the proposed framework consistently maintained lower spillback intensity across the entire bridge-closure duration range. The adaptive redistribution of transportation demand between bridge and ferry services enabled more balanced utilization of available crossing capacity and reduced pressure on critical storage areas. Consequently, the onset of severe overflow conditions occurred at substantially longer interruption durations compared with unmanaged operations.

The results further demonstrate that the primary benefit of adaptive operational management is not the complete elimination of congestion under prolonged bridge-closure conditions, but rather the postponement of critical system transitions associated with congestion amplification and network-wide spillback propagation. This behavior effectively increases the operational tolerance of the corridor and improves its ability to accommodate temporary demand surges without experiencing rapid performance degradation.

These findings highlight the importance of spillback-aware operational strategies for interruption-sensitive bridge–ferry transportation systems. From a transportation-management perspective, delaying the onset of oversaturated conditions may be as important as reducing congestion itself because it enhances corridor resilience and provides operators with additional flexibility during periods of elevated demand and prolonged operational disruptions.

4.11. Integrated Sensitivity Summary

The sensitivity and scenario-based analyses presented in Sections 4.7–4.9 collectively demonstrate that transportation-system performance within the Port Said–Port Fouad corridor is governed by the interaction among bridge-interruption duration, transportation-demand intensity, ferry-service capability, and traveler-redistribution behavior.

Among the investigated parameters, bridge-interruption duration exhibited the strongest influence on corridor performance. Prolonged interruptions produced substantial increases in transportation delay, queue accumulation, congestion spillback, and recovery duration because of the sustained loss of crossing capacity. Transportation-demand escalation represented the second most influential factor, particularly under oversaturated operating conditions where congestion amplification accelerated rapidly once critical capacity thresholds were approached.

Ferry-service capability played an important moderating role by providing alternative crossing capacity during interruption periods. The sensitivity analyses showed that moderate increases in ferry capacity generated significant reductions in transportation delay and queue accumulation. However, the associated benefits gradually diminished at higher capacity levels, indicating that ferry-capacity expansion alone cannot fully eliminate congestion under interruption-sensitive operating conditions.

The analyses further demonstrated the importance of adaptive traveler redistribution. Coordinated demand allocation between bridge and ferry services improved utilization of available transportation resources, reduced pressure on critical storage areas, and delayed the onset of severe congestion conditions. Consequently, traveler behavioral adaptation emerged as an important contributor to corridor resilience and operational stability.

Table 19 summarizes the combined influence of the principal operational disturbances investigated throughout the study and provides a consolidated overview of their effects on corridor performance.

Table 19. Sensitivity robustness matrix for major operational parameters.

Parameter Variation	Total Delay Change (%)	Queue-Length Change (%)	Overflow Severity Change (%)	Operational Stability
+10% Traffic Demand	+14.2	+18.5	+21.3	Moderate
+20% Traffic Demand	+28.7	+35.1	+41.6	Reduced
+20% Bridge-Closure Duration	+26.8	+33.7	+38.4	Reduced
+40% Bridge-Closure Duration	+51.2	+67.9	+74.5	Critical
−15% Ferry Capacity	+19.5	+24.1	+29.7	Moderate
−25% Ferry Capacity	+34.6	+42.8	+48.3	Reduced
+15% Ferry Loading Time	+12.7	+16.9	+18.2	Moderate
+25% Incident-Related Delay	+31.4	+39.5	+46.8	Reduced
+20% Traveler Redistribution to Ferry	−11.3	−14.7	−17.9	Improved

The sensitivity matrix confirms that bridge-interruption duration remains the dominant operational factor governing congestion escalation and spillback propagation within the investigated corridor. A 40% increase in bridge-closure duration generated the largest deterioration across all performance indicators, highlighting the critical influence of maritime-navigation disruptions on corridor operation. In contrast, increased traveler redistribution toward ferry services consistently improved transportation performance and reduced congestion severity.

Overall, the combined sensitivity analyses confirm that the proposed framework remains operationally stable across a broad range of disturbance conditions while providing effective support for congestion mitigation, spillback control, and resilience enhancement within interruption-sensitive bridge–ferry transportation systems.

4.12. Robustness Assessment, Uncertainty Characterization, and Model Limitations

To further evaluate the robustness of the proposed decision-support framework under uncertain operating conditions, a scenario-based robustness assessment was performed using 30 independent stochastic simulation replications for each investigated operating condition. Four representative operating scenarios were considered, namely low-demand, normal-demand, high-demand, and prolonged bridge-interruption conditions. The objective was to quantify the variability of the principal vehicle-oriented performance indicators and to characterize the uncertainty associated with representative operational variations within the scope of the adopted simulation framework.

Figure 18 presents the scenario-based uncertainty assessment by reporting the percentage changes in mean transportation delay and mean queue accumulation relative to the calibrated normal-demand scenario, whereas Table 20 summarizes the corresponding statistical performance indicators. Under low-demand conditions, the mean transportation delay decreased from 6980 to 4280 veh·min, accompanied by a reduction in mean queue accumulation from 470 to 185 vehicles, corresponding to reductions of 38.7% and 60.6%, respectively. Conversely, increasing traffic demand substantially intensified congestion, increasing transportation delay to 11,420 veh·min and mean queue accumulation to 1020 vehicles, representing increases of 63.6% and 117.0%, respectively. The prolonged bridge-interruption scenario produced the most severe operating condition, increasing transportation delay to 16,830 veh·min and mean queue accumulation to 1480 vehicles, corresponding to increases of 141.1% and 214.9%, respectively.

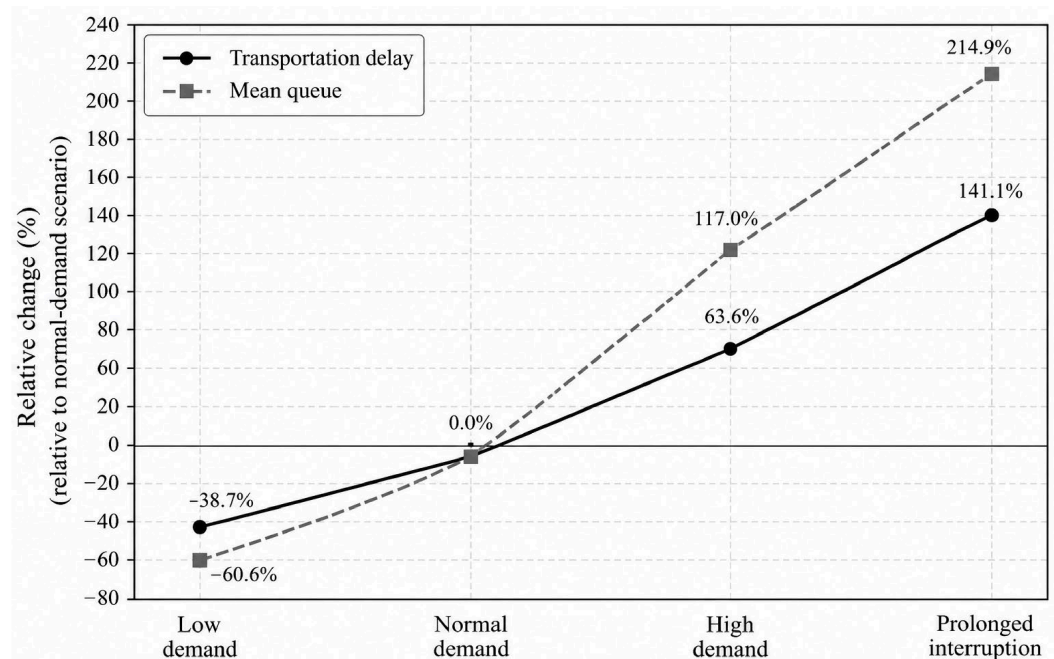


Figure 18. Scenario-based uncertainty assessment of the proposed framework under representative operating conditions. Percentage changes in mean transportation delay and mean queue accumulation are reported relative to the calibrated normal-demand scenario. Values represent the mean results obtained from 30 independent stochastic simulation replications for each investigated operating scenario. Positive values indicate an increase relative to the baseline scenario, whereas negative values indicate a reduction.

Table 20. Robustness assessment of the proposed decision-support framework under representative operating conditions based on 30 independent stochastic simulation replications.

Operating Scenario	Mean Transportation Delay (veh·min)	SD	COV (%)	Mean Queue (Vehicles)	Delay Change Relative to Normal (%)	Queue Change Relative to Normal (%)
Low-demand conditions	4280	215	5.0	185	−38.7	−60.6
Normal-demand conditions (baseline)	6980	340	4.9	470	0.0	0.0
High-demand conditions	11,420	690	6.0	1020	+63.6	+117.0
Prolonged bridge-interruption conditions	16,830	1120	6.7	1480	+141.1	+214.9

Across all investigated scenarios, the coefficient of variation remained below approximately 7%, indicating that the stochastic simulation results remained statistically stable despite variations in traffic demand, bridge-interruption duration, ferry operation, and traveler response. These results demonstrate that the proposed framework provides statistically stable predictions of the investigated vehicle-oriented performance indicators while also highlighting the strongly nonlinear nature of congestion evolution. Once the corridor approaches its storage-capacity limit, relatively moderate increases in traffic demand or interruption duration produce disproportionately large increases in transportation delay and queue accumulation because of spillback propagation and network saturation effects.

The uncertainty associated with the baseline simulation outputs was further quantified using the relative half-width of the 95% confidence interval obtained from the 30 stochastic simulation replications. As illustrated in Figure 19, the estimated uncertainty envelope remained below approximately 5.1% for all principal vehicle-performance indicators. Transportation delay exhibited the smallest relative uncertainty (2.1%), followed by spillback (3.5%) and queue accumulation (3.9%), whereas recovery performance showed the largest uncertainty (5.1%). Nevertheless, the uncertainty associated with all investigated indicators remained comparatively small, indicating that the calibrated simulation framework provides consistent and statistically reliable predictions under the adopted operating assumptions.

Because an independent multimodal reference model incorporating explicit pedestrian and bicycle interactions was not available, the influence of the adopted simplifying assumptions could not be quantified directly as an independent simulation-error component. Instead, the presented robustness assessment and uncertainty characterization provide a quantitative uncertainty envelope for the principal vehicle-oriented performance indicators under representative operational variations, thereby defining the practical range of variability associated with the adopted modeling assumptions rather than a direct estimate of model error.

The present simulation framework was developed primarily to evaluate vehicle-oriented operational performance. Accordingly, several simplifying assumptions were adopted to maintain computational efficiency while preserving the principal traffic dynamics of the investigated bridge–ferry corridor. These assumptions include generalized traveler route-choice behavior, aggregated ferry operational characteristics, representative weather conditions, and the exclusion of explicit pedestrian and bicycle interactions from the microscopic traffic model.

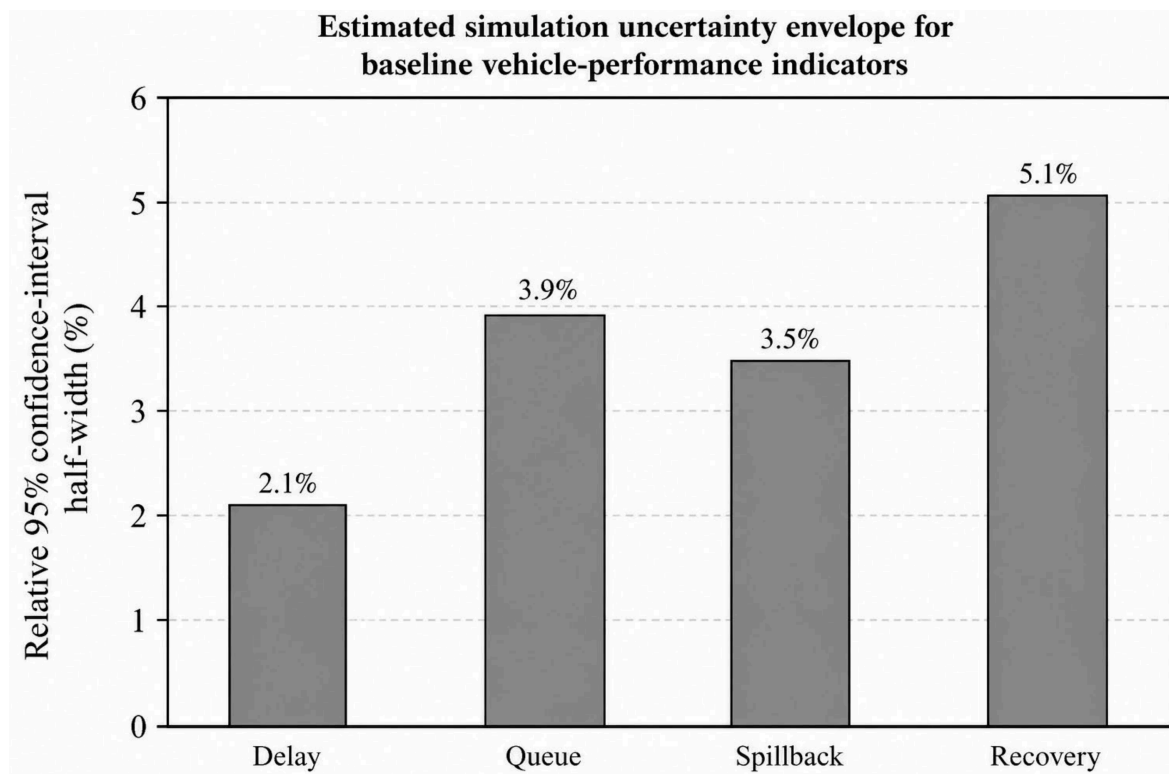


Figure 19. Estimated simulation uncertainty envelope for the principal baseline vehicle-performance indicators. Uncertainty is expressed as the relative half-width of the 95% confidence interval obtained from 30 independent stochastic simulation replications. The relatively small confidence-interval widths indicate statistically consistent baseline simulation results under the adopted operating assumptions.

The exclusion of non-motorized users is expected to have only a limited influence on the reported vehicle-performance indicators because pedestrian and bicycle movements are physically separated from vehicular operations within the Port Said–Port Fouad crossing system. Pedestrians are accommodated in dedicated seating and standing areas on both sides of the ferry vehicle decks, while several ferries also provide additional upper-deck passenger seating. Consequently, pedestrian demand is not expected to materially reduce the effective vehicle-carrying capacity of the ferries under the investigated operating conditions. Similarly, the floating bridge incorporates a dedicated lateral lane for pedestrians and cyclists that is physically separated from the vehicular carriageway. Therefore, pedestrian and bicycle movements are not expected to directly influence vehicle delays, queue accumulation, congestion spillback, or post-closure recovery within the scope of the adopted vehicle-oriented simulation framework.

Although these simplifying assumptions are expected to have only a limited influence on the vehicle-oriented performance indicators investigated in the present study, they may affect broader multimodal service-quality aspects, including pedestrian comfort, accessibility, passenger waiting conditions, and safety. Future developments of the proposed framework should therefore integrate explicit pedestrian and bicycle demand models, weather-responsive traveler behavior, ferry passenger-flow interactions, and multimodal coordination mechanisms to support comprehensive corridor management under diverse operating conditions.

Overall, the combined robustness assessment and uncertainty characterization demonstrate that the proposed framework provides statistically stable and reproducible predictions of the investigated vehicle-oriented performance indicators across a wide range of representative operating conditions. At the same time, the identified modeling assump-

tions clearly define the current scope of applicability while providing a practical roadmap for future developments toward fully integrated multimodal Digital Twin transportation systems.

4.13. Engineering Interpretation and Practical Implications

The results obtained throughout the comparative evaluation, sensitivity investigations, and optimization analyses provide several important engineering insights regarding the operation of interruption-sensitive bridge–ferry transportation systems.

A primary observation is that corridor performance is governed by the coupled interaction among bridge interruptions, ferry-service capability, traveler redistribution, storage-capacity constraints, and congestion-spillback propagation. Rather than being controlled by a single operational factor, transportation-system behavior emerges from the dynamic interaction of these mechanisms. Consequently, effective corridor management requires coordinated operation of both bridge and ferry subsystems rather than isolated interventions targeting individual components.

The sensitivity analyses further revealed the existence of threshold-driven congestion behavior. Under low- and moderate-demand conditions, the corridor maintained relatively stable operation, with available crossing capacity sufficient to accommodate fluctuations in transportation demand. However, as demand approached the effective service capacity of the system, congestion growth became increasingly nonlinear. Under such conditions, relatively small increases in transportation demand or bridge-closure duration generated disproportionately large increases in queue accumulation, transportation delay, and spillback severity. These findings highlight the importance of proactive operational management before critical congestion thresholds are reached.

The results also indicate that infrastructure-capacity expansion alone cannot fully eliminate congestion within interruption-sensitive bridge–ferry systems. Although increased ferry-service capability improved transportation performance, the associated benefits gradually diminished at higher capacity levels. Once ferry services became capable of accommodating a substantial proportion of redistributed demand, other constraints—including bridge-interruption duration, terminal-processing efficiency, storage availability, and recovery dynamics—became increasingly dominant. Consequently, long-term performance improvement requires a combination of capacity enhancement, operational coordination, and adaptive demand management rather than reliance on infrastructure expansion alone.

Another important finding concerns the role of traveler behavior. The adaptive redistribution mechanism demonstrated that congestion mitigation depends not only on infrastructure capacity but also on how transportation demand is allocated between available crossing alternatives. Coordinated utilization of bridge and ferry services improved resource allocation, reduced pressure on critical storage areas, and delayed the onset of oversaturated operating conditions. These observations emphasize the importance of incorporating behavioral adaptation into transportation-management strategies for multimodal transportation corridors.

From a practical perspective, the proposed framework can support congestion mitigation, disruption-response planning, multimodal transportation coordination, and resilience-oriented transportation management [27]. Transportation agencies may use the framework to evaluate alternative operational strategies, identify critical performance thresholds, and assess the likely consequences of operational disruptions before implementing management actions in the field.

Overall, the findings demonstrate that interruption-sensitive transportation systems should be managed using an integrated and system-level perspective that simultaneously considers infrastructure availability, traveler behavior, operational flexibility, and network-level congestion interactions. The proposed framework provides a practical decision-support tool for improving transportation efficiency, operational resilience, and sustainability within complex bridge–ferry transportation environments.

4.14. Towards Digital Mapping and Digital Twin-Oriented Transportation Management

Beyond the operational improvements demonstrated in this study, the proposed framework establishes an important step toward future digital mapping and Digital Twin-oriented transportation management of interruption-sensitive bridge–ferry transportation systems. Although the present methodology does not constitute a fully synchronized real-time Digital Twin, it provides several of the fundamental analytical components required for future digital transportation environments [18,38,40].

The developed framework integrates operational-state characterization, microscopic traffic simulation, adaptive traveler behavior, congestion-propagation analysis, surrogate-assisted prediction, and optimization-based decision support within a unified analytical environment. Together, these capabilities enable comprehensive representation of the interactions among bridge availability, ferry operations, transportation demand, queue accumulation, and network-level congestion dynamics.

From a transportation-management perspective, the framework may serve as the analytical core of a future corridor-wide digital mapping platform capable of continuously representing operational conditions and evaluating alternative management strategies. By combining transportation-state estimation with predictive analytics and optimization tools, transportation agencies can move beyond reactive congestion management toward more proactive and evidence-based operational decision making.

Future implementation pathways may incorporate automated data acquisition from traffic sensors, AIS vessel-monitoring systems, ferry-operation databases, and intelligent transportation infrastructure [27,28]. The integration of such data streams would enable continuous updating of transportation-system states, improving the realism and responsiveness of operational forecasting and decision-support processes.

In the longer term, Digital Twin-oriented transportation systems could combine real-time monitoring, simulation-based forecasting, predictive analytics, and optimization-assisted control within a unified management environment. Such capabilities would allow transportation operators to anticipate congestion formation, evaluate operational alternatives before implementation, and improve resilience during bridge interruptions, demand surges, and other disruptive events.

Therefore, the present study should be viewed not only as an operational optimization framework but also as a foundational step toward future digital transportation-management ecosystems capable of supporting adaptive, predictive, and resilience-oriented management of interruption-sensitive maritime–urban mobility systems.

Figure 20 illustrates the envisioned evolution pathway of the proposed framework from a field-calibrated simulation-based decision-support environment toward future Digital Mapping and Digital Twin-oriented transportation management. The current implementation focuses on operational-state characterization, simulation, surrogate-assisted prediction, and optimization, whereas future developments may incorporate automated data acquisition, continuous monitoring, predictive analytics, and adaptive operational control.

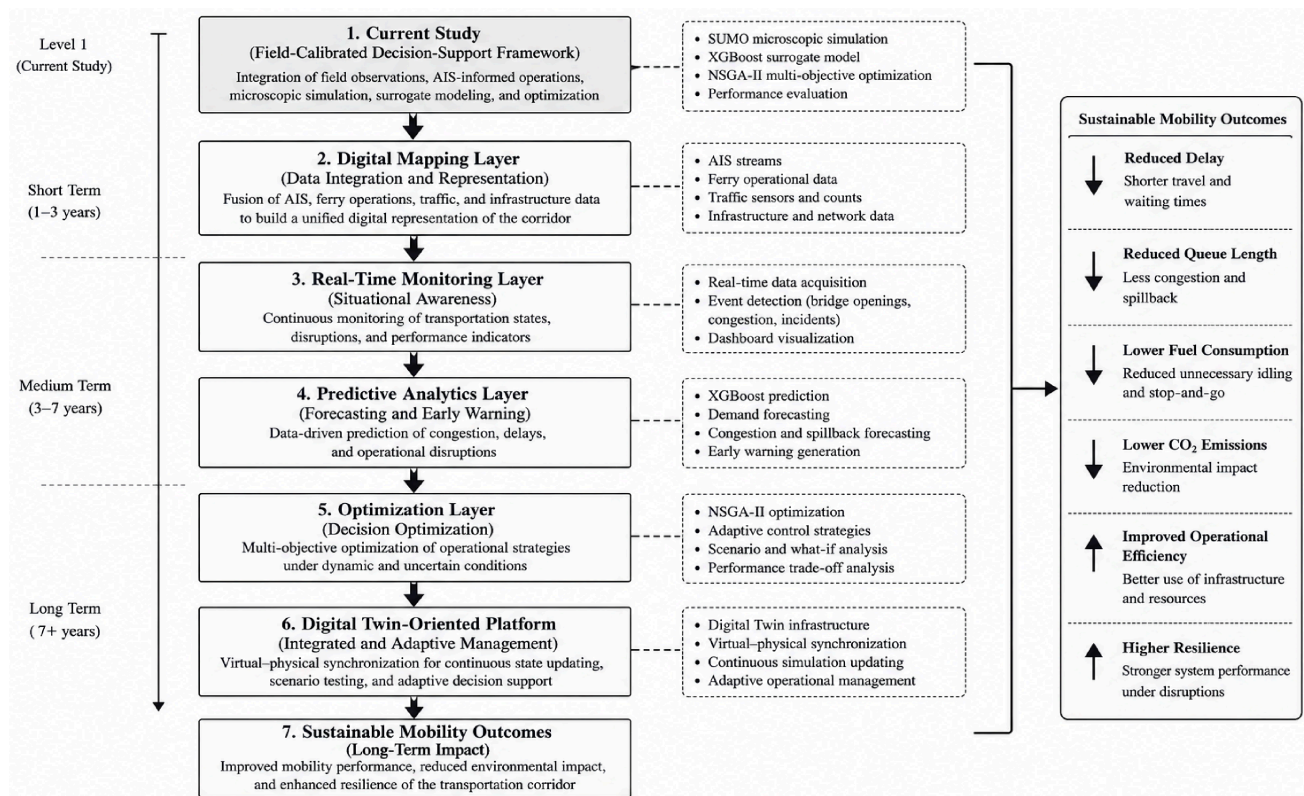


Figure 20. Evolution of the proposed framework from field-calibrated decision support toward future Digital Twin-oriented transportation management. Upward arrows (↑) indicate improvements in desirable operational performance, whereas downward arrows (↓) indicate reductions in undesirable operational impacts.

5. Practical Limitations and Deployment Considerations

Despite the promising performance demonstrated by the proposed framework, several practical limitations should be acknowledged when interpreting the results and considering future deployment.

First, the developed methodology relies on simplified representations of certain operational processes, including traveler behavioral adaptation, transportation-demand uncertainty, and ferry-operational variability. Although these assumptions improve model tractability and computational efficiency, actual transportation systems may exhibit additional behavioral and operational complexities that are not explicitly represented in the current implementation.

Second, the proposed framework was developed using field-informed observations and calibrated simulation conditions rather than continuous real-time synchronization with live operational data. Consequently, the methodology should be interpreted as a field-calibrated simulation-based decision-support framework rather than an operational real-time management platform.

Another limitation relates to traveler redistribution behavior. The implemented mode-shift mechanism was primarily governed by congestion conditions and waiting times, whereas actual traveler decisions may additionally be influenced by trip purpose, socioeconomic characteristics, route familiarity, weather conditions, and individual preferences.

From a computational perspective, the XGBoost surrogate model substantially reduced the computational burden associated with repeated microscopic simulation evaluations. Nevertheless, large-scale deployment involving continuous optimization, network-wide analysis, and near-real-time operational support may require additional computational resources and scalable implementation architectures.

An additional methodological consideration is that the proposed framework was not designed to maximize a single performance objective, such as CO₂ emissions reduction. Instead, the adopted multi-objective optimization strategy was developed to achieve a balanced compromise among transportation delay, congestion mitigation, operational resilience, and environmental performance. Consequently, alternative control strategies, such as the reinforcement-learning benchmark, may outperform the proposed framework with respect to specific individual objectives while providing a less balanced overall operational performance across multiple transportation-performance indicators.

Although long-term external operational datasets were not available for independent external validation, obtaining such datasets within strategic bridge–ferry transportation corridors is inherently challenging because of restricted data accessibility and continuously changing operational conditions. Consequently, the adopted field-calibration and within-sample validation procedure was designed to ensure consistency between observed and simulated behavior under representative corridor conditions. Therefore, the validation presented in this study should be interpreted as within-sample validation demonstrating internal consistency between the calibrated simulation environment and the observed operational behavior rather than as a fully independent external validation.

Despite these limitations, the developed framework provides a practical and computationally efficient basis for evaluating congestion evolution, spillback propagation, traveler redistribution, operational resilience, and transportation-system performance within complex bridge–ferry transportation environments operating under uncertain conditions.

6. Conclusions

This study developed a field-calibrated simulation-based decision-support framework for analyzing and improving the performance of interruption-sensitive bridge–ferry transportation systems subjected to maritime-induced capacity disruptions. The framework was applied to the Port Said–Port Fouad crossing corridor, where bridge interruptions, ferry operations, and multimodal traveler behavior interact to influence overall corridor performance.

The results demonstrated that coordinated management of bridge and ferry operations can substantially improve transportation efficiency and system resilience. Relative to unmanaged operating conditions, the proposed framework reduced transportation delay by 43.8%, corridor-wide vehicle accumulation by 65.9%, and estimated CO₂ emissions by 17.4%. Furthermore, the robustness assessment demonstrated statistically stable performance under representative operating conditions, including increased traffic demand and prolonged bridge-interruption scenarios, supporting the reliability of the proposed framework within the investigated operational domain.

By integrating microscopic traffic simulation, surrogate-assisted prediction, and multi-objective optimization, the proposed methodology enables efficient evaluation of alternative operational strategies while preserving realistic representation of congestion evolution, traveler redistribution, and bridge–ferry interactions. The obtained results indicate that adaptive operational coordination can effectively accommodate demand fluctuations, mitigate congestion propagation, shorten post-interruption recovery, and enhance the operational resilience of interruption-sensitive transportation corridors.

Although the framework was field-calibrated using representative observations from the investigated corridor, additional developments would further improve its applicability and predictive capability. Future research may be organized into three complementary directions.

Near-term research should focus on enhancing model realism through continuously updated operational datasets, improved traveler-behavior representation, weather-

responsive ferry operations, and the incorporation of additional operational variables, including ferry loading efficiency, berth availability, and dynamic traffic-demand estimation.

Medium-term research should investigate advanced intelligent transportation technologies, including reinforcement-learning-based traffic control, multi-agent transportation-management architectures, Graph Neural Network-based congestion prediction, connected-vehicle information, and real-time vessel-arrival forecasting to further improve adaptive operational decision making.

Long-term research may extend the proposed methodology toward Digital Twin-oriented transportation-management ecosystems capable of supporting coordinated operation across multiple bridge–ferry corridors. Future developments may incorporate multimodal passenger and freight interactions, infrastructure resilience assessment, sustainability-oriented performance indicators, lifecycle operational optimization, autonomous ferry operations, and regional transportation coordination to support increasingly adaptive and resilient transportation management.

Overall, the proposed methodology provides transportation agencies with a practical and computationally efficient decision-support tool for evaluating operational alternatives, mitigating congestion impacts, and improving resilience within interruption-sensitive bridge–ferry transportation systems. Furthermore, the developed methodology establishes a practical foundation for the progressive evolution toward digital mapping and Digital Twin-oriented transportation-management applications through the integration of automated data acquisition, predictive analytics, and adaptive operational decision support.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request. Certain operational observations used in the study are subject to practical accessibility limitations associated with the investigated transportation corridor.

Acknowledgments: The author would like to acknowledge the support provided by the Arab Academy for Science, Technology and Maritime Transport (AASTMT), Port Said Branch, during the development of this research. The author also gratefully acknowledges Israa M. Salah Eldin for her valuable comments during the review of the manuscript. The author used ChatGPT (OpenAI, GPT-5.5) as an AI-assisted writing support tool during manuscript preparation to improve language quality, grammar, readability, and academic presentation. ChatGPT was also used only to assist with the formatting and visual arrangement of the Graphical Abstract. The scientific content, data, concepts, and interpretation presented in the Graphical Abstract were prepared and developed by the author. No AI tool was used to generate research data, perform simulations, conduct statistical analyses, interpret results, or formulate the scientific conclusions of this study. All technical content, methodology, analyses, and conclusions were independently developed, verified, and approved by the author.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

AI	Artificial Intelligence
AIS	Automatic Identification System
CO ₂	Carbon Dioxide
KPI	Key Performance Indicator
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
ML	Machine Learning

NSGA-II	Non-dominated Sorting Genetic Algorithm II
PM	Polynomial Mutation
R ²	Coefficient of Determination
RL	Reinforcement Learning
RMSE	Root Mean Square Error
SBX	Simulated Binary Crossover
SUMO	Simulation of Urban Mobility
XGBoost	Extreme Gradient Boosting

References

- Rodrigue, J.P. *The Geography of Transport Systems*, 5th ed.; Routledge: New York, NY, USA, 2020.
- Sunitiyoso, Y.; Nuraeni, S.; Pambudi, N.F.; Inayati, T.; Nurdayat, I.F.; Hadiansyah, F.; Tiara, A.R. Port Performance Factors and Their Interactions: A Systems Thinking Approach. *Asian J. Shipp. Logist.* **2022**, *38*, 107–123. [\[CrossRef\]](#)
- Zhao, Q.; Xu, H.; Wall, R.S.; Stavropoulos, S. Building a Bridge Between Port and City: Improving the Urban Competitiveness of Port Cities. *J. Transp. Geogr.* **2017**, *59*, 120–133. [\[CrossRef\]](#)
- Afrin, T.; Yodo, N. A Survey of Road Traffic Congestion Measures Towards a Sustainable and Resilient Transportation System. *Sustainability* **2020**, *12*, 4660. [\[CrossRef\]](#)
- Treiber, M.; Kesting, A. *Traffic Flow Dynamics: Data, Models and Simulation*; Springer: Berlin/Heidelberg, Germany, 2013. [\[CrossRef\]](#)
- Daganzo, C.F. *Fundamentals of Transportation and Traffic Operations*; Pergamon: Oxford, UK, 1997.
- Newell, G.F. A Simplified Theory of Kinematic Waves in Highway Traffic. *Transp. Res. Part B* **1993**, *27*, 281–287. [\[CrossRef\]](#)
- Dehghani, Y.; Arnold, P.B.; Pereira, R.L. Estimation of Delays to Boats and Vehicular Traffic Caused by Moveable Bridge Openings: An Empirical Analysis. *Transp. Res. Rec.* **1993**, *1404*, 38–46.
- Birnstiel, C.; Parke, G.; Hewson, N. *Movable Bridges*; ICE Publishing: London, UK, 2015.
- Behrisch, M.; Bieker, L.; Erdmann, J.; Krajzewicz, D. SUMO—Simulation of Urban Mobility: An Overview. In Proceedings of the Third International Conference on Advances in System Simulation (SIMUL 2011), Barcelona, Spain, 23–29 October 2011; pp. 63–68.
- Lopez, P.A.; Behrisch, M.; Bieker-Walz, L.; Erdmann, J.; Flötteröd, Y.; Hilbrich, R.; Lucken, L.; Rummel, J.; Wagner, P.; Wießner, E. Microscopic Traffic Simulation Using SUMO. In Proceedings of the 21st IEEE International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4–7 November 2018; pp. 2575–2582.
- Ben-Akiva, M.; Bierlaire, M.; Burton, D.; Koutsopoulos, H.N.; Mishalani, R. Network State Estimation and Prediction for Real-Time Transportation Management Applications. In Proceedings of the 81st Annual Meeting of the Transportation Research Board, Washington, DC, USA, 13–17 January 2002; Paper No. 02-3659. 36p.
- Zhou, X.; Mahmassani, H.S.; Zhang, K. Dynamic Micro-Assignment Modeling Approach for Integrated Multimodal Urban Corridor Management. *Transp. Res. Part C* **2008**, *16*, 167–186. [\[CrossRef\]](#)
- Gomez, C.; Baker, J.W. An Optimization-Based Decision Support Framework for Coupled Pre- and Post-Earthquake Infrastructure Risk Management. *Struct. Saf.* **2019**, *77*, 1–9. [\[CrossRef\]](#)
- Fuller, A.; Fan, Z.; Day, C.; Barlow, C. Digital Twin: Enabling Technologies, Challenges, and Open Research. *IEEE Access* **2020**, *8*, 108952–108971. [\[CrossRef\]](#)
- Dilek, E.; Dener, M. Computer Vision Applications in Intelligent Transportation Systems: A Survey. *Sensors* **2023**, *23*, 2938. [\[CrossRef\]](#) [\[PubMed\]](#)
- Tao, F.; Xiao, B.; Qi, Q.; Cheng, J.; Ji, P. Digital Twins and Cyber-Physical Systems Toward Smart Manufacturing and Intelligent Infrastructure. *Engineering* **2023**, *20*, 41–56.
- Werbińska-Wojciechowska, S.; Giel, R.; Winiarska, K. Digital Twin Approach for Operation and Maintenance of Transportation System—Systematic Review. *Sensors* **2024**, *24*, 6069. [\[CrossRef\]](#) [\[PubMed\]](#)
- Haydari, A.; Yilmaz, Y. Deep Reinforcement Learning for Intelligent Transportation Systems: A Survey. *IEEE Trans. Intell. Transp. Syst.* **2022**, *23*, 11–32. [\[CrossRef\]](#)
- Behrooz, H.; Hayeri, Y.M. Machine Learning Applications in Surface Transportation Systems: A Literature Review. *Appl. Sci.* **2022**, *12*, 9156. [\[CrossRef\]](#)
- Kumar, S.; Metya, S.; Sinha, A.; Simon, M.; Yadav, A. XGBoost-Based Surrogate Technique for System Reliability Analysis of Foundation Over Cavity Aided with Bootstrapping. *Sci. Rep.* **2026**, *16*, 7113. [\[CrossRef\]](#) [\[PubMed\]](#)
- Liang, Y.; Ren, Z.; Wang, L.; Liu, H.; Du, W. Surrogate-Assisted Cooperative Signal Optimization for Large-Scale Traffic Networks. *Knowl.-Based Syst.* **2021**, *234*, 107542. [\[CrossRef\]](#)
- Chen, T.; Guestrin, C. XGBoost: A Scalable Tree Boosting System. In Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, San Francisco, CA, USA, 13–17 August 2016; pp. 785–794.

24. Ma, X.; Li, Y.; Chen, J. Data-Driven Traffic Prediction Using XGBoost Machine Learning Framework. *J. Adv. Transp.* **2021**, *2021*, 8879321. [[CrossRef](#)]
25. Deb, K.; Agrawal, S.; Pratap, A.; Meyarivan, T. A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197. [[CrossRef](#)]
26. Deb, K.; Jain, H. An Evolutionary Many-Objective Optimization Algorithm Using Reference-Point-Based Nondominated Sorting Approach. *IEEE Trans. Evol. Comput.* **2014**, *18*, 577–601. [[CrossRef](#)]
27. Lamei, T.; Elsayed, A.; Ibrahim, A.; Abdel-Rahim, A. Modeling the Resilience of Multimodal Freight Networks Under Disruptions: A Systematic Review. *Infrastructures* **2026**, *11*, 130. [[CrossRef](#)]
28. Wu, Y.; Chen, S. Resilience Modeling and Pre-Hazard Mitigation Planning of Transportation Network to Support Post-Earthquake Emergency Medical Response. *Reliab. Eng. Syst. Saf.* **2023**, *230*, 108918. [[CrossRef](#)]
29. Segovia, P.; Puig, V.; Negenborn, R.R.; Reppa, V. Dynamic Coordination of Multiple Movable Bridges and Vessels for Time-Efficient Inland Waterway Navigation. *IEEE Trans. Intell. Transp. Syst.* **2025**, *26*, 5481–5493. [[CrossRef](#)]
30. Segovia, P.; Puig, V.; Reppa, V. A Model Predictive Scheduling Strategy for Coordinated Inland Vessel Navigation and Bridge Operation. In Proceedings of the IEEE Conference on Control Technology and Applications (CCTA 2023), Bridgetown, Barbados, 16–18 August 2023.
31. Mooij, M.J.; Dominguez Frejo, J.R.; Reppa, V. Automatic Drawbridge Scheduling by Integrating Highway and Waterway Traffic Flow Information. *IFAC-PapersOnLine* **2024**, *58*, 290–295. [[CrossRef](#)]
32. Pu, Y.; Liu, H.; Wang, J.; Xu, Y.; Anvari-Moghaddam, A. Cooperative Dispatching of Port Integrated Energy and Ferry Logistics Systems under Interrelated Cross-Domain Uncertainties. *Energy* **2025**, *337*, 138507. [[CrossRef](#)]
33. Magryta-Mut, B.; Torbicki, M. Impact of Weather Variability on the Operational Costs of a Maritime Ferry. *Water* **2025**, *17*, 3146. [[CrossRef](#)]
34. Klar, R.; Svensson, N.; Stelling, P.; Angelakis, V. Fuel Efficiency in Ferry Services: GPS-Based Clustering and Explainable AI. *Transp. Res. Part D Transp. Environ.* **2026**, *157*, 105403. [[CrossRef](#)]
35. Saragani, C.; Garrido, J.; Sauri, S. Digital Twin Adoption in Port Authorities: A Structured Framework for Use Case Assessment. *J. Shipp. Trade* **2026**, *11*, 12. [[CrossRef](#)]
36. Khanmohamadi, M.; Guerrieri, M. Towards Transportation Metaverse: A Conceptual Perspective on Future Road, Railway, Maritime, and Aviation Systems. *Infrastructures* **2026**, *11*, 181. [[CrossRef](#)]
37. Jørgensen, F.; Solvoll, G. Designing Capacity and Service Level at Ferry Crossings. *Transp. Res. Procedia* **2017**, *26*, 215–223. [[CrossRef](#)]
38. Ge, C.; Qin, S. Digital Twin Intelligent Transportation System (DT-ITS): A Systematic Review. *IET Intell. Transp. Syst.* **2024**, *18*, 2325–2358. [[CrossRef](#)]
39. Ortúzar, J.D.; Willumsen, L.G. *Modelling Transport*, 5th ed.; Wiley: Chichester, UK, 2019.
40. Llagostera-Brugarola, E.; Corpas-Marco, E.; Victorio-Vergel, C.; Lopez-Aguilera, E.; Vázquez-Gallego, F.; Alonso-Zarate, J. A Digital Twin for Intelligent Transportation Systems in Interurban Scenarios. *Appl. Sci.* **2025**, *15*, 7454. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.