



Kent Academic Repository

Bayram, Vedat, Ergez, Doruk and Arikanoglu, Ada (2026) *Designing risk-aware mixed-mode evacuation strategies for tsunamis: insights from Istanbul*. Turkish Journal of Electrical Engineering & Computer Sciences, 34 (2). pp. 307-327. ISSN 1300-0632.

Downloaded from

<https://kar.kent.ac.uk/113062/> The University of Kent's Academic Repository KAR

The version of record is available from

<https://doi.org/10.55730/1300-0632.4176>

This document version

Publisher pdf

DOI for this version

Licence for this version

CC BY (Attribution)

Additional information

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in **Title of Journal**, Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our [Take Down policy](https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies) (available from <https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies>).

3-13-2026

Designing risk-aware mixed-mode evacuation strategies for tsunamis: insights from İstanbul

VEDAT BAYRAM

DORUK ERGEZ

ADA ARIKANOĞLU

Follow this and additional works at: <https://journals.tubitak.gov.tr/elektrik>



Part of the [Computer Engineering Commons](#), [Computer Sciences Commons](#), and the [Electrical and Computer Engineering Commons](#)

Recommended Citation

BAYRAM, V, ERGEZ, D, & ARIKANOĞLU, A (2026). Designing risk-aware mixed-mode evacuation strategies for tsunamis: insights from İstanbul. *Turkish Journal of Electrical Engineering and Computer Sciences* 34 (2): 307-327. <https://doi.org/10.55730/1300-0632.4176>



This work is licensed under a [Creative Commons Attribution 4.0 International License](#).

This Research Article is brought to you for free and open access by TÜBİTAK Academic Journals. It has been accepted for inclusion in Turkish Journal of Electrical Engineering and Computer Sciences by an authorized editor of TÜBİTAK Academic Journals. For more information, please contact academic.publications@tubitak.gov.tr

Designing risk-aware mixed-mode evacuation strategies for tsunamis: insights from İstanbul

Vedat BAYRAM^{1,3,*} , Doruk ERGEZ¹ , Ada ARIKANOĞLU^{1,2} 

¹Department of Industrial Engineering, TED University, Ankara, Türkiye

²Department of Industrial Engineering, Koç University, İstanbul, Türkiye

³University of Kent, Kent Business School, Department of Analytics,

Operations and Systems, Centre for Logistics and Sustainability Analytics, Canterbury, United Kingdom

Received: 10.09.2025

Accepted/Published Online: 18.01.2026

Final Version: 13.03.2026

Abstract: Tsunamis pose severe and time-critical risks to densely populated coastal cities, where limited warning times and infrastructure constraints demand carefully coordinated evacuation strategies. This study develops an integrated, risk-aware optimization framework that jointly considers vertical and horizontal sheltering options together with mixed pedestrian-vehicular evacuation dynamics. The proposed mixed-integer second-order cone programming (MISOCP) model simultaneously determines vertical shelter location, evacuee assignment, road-use designation for pedestrians and vehicles, and route selection under congestion, capacity, and budget constraints. Vehicle travel times incorporate congestion effects through a convex flow-dependent function, while pedestrian routing ensures convergent and conflict-free evacuation paths. A risk-minimization objective accounts for tsunami hazard levels, inundation conditions, and spatial exposure, prioritizing safer evacuation routes over purely time-based approaches.

The model is applied to İstanbul's Büyükçekmece district, one of the areas most vulnerable to tsunami impact following a major Marmara Sea earthquake. Using real geographic, demographic, and infrastructure data, we evaluate multiple budget and demand scenarios to examine the model's sensitivity to shelter investment decisions and varying proportions of pedestrian and vehicular evacuees. Results show that opening strategically located vertical shelters substantially reduces total evacuation risk and alleviates congestion in critical zones. Increasing vertical shelter investment provides diminishing returns beyond a moderate budget level, indicating the existence of an efficient investment threshold. Scenario analysis further reveals that mixed-mode evacuations can generate significant congestion on shared road segments; the model mitigates these effects through modal separation and speed adjustments. Overall, the proposed framework offers robust, context-aware decision support for tsunami-prone urban regions.

Key words: Tsunami evacuation, mixed-mode evacuation, vertical shelters, risk-based evacuation planning, convergent routing, mixed-integer second-order cone programming

1. Introduction

The frequency and impact of natural disasters have escalated in recent decades, with an annual average of 369 events recorded between 2003 and 2022, rising to 399 in 2023.¹ Among these, tsunamis—though less frequent than earthquakes or storms—are uniquely devastating, causing catastrophic loss of life and widespread

*Correspondence: v.bayram@kent.ac.uk

¹EM-DAT (2023). Em-dat: The international disaster database [online]. Website <https://www.emdat.be/categories/adsr/> [accessed 29 December 2023].

infrastructure damage in coastal areas.² Tsunamis are typically triggered by large submarine earthquakes, leading to the rapid displacement of water and the formation of powerful waves [1]. The 2004 Indian Ocean tsunami killed over 200,000 people across 14 countries, while the 2011 Tohoku tsunami claimed more than 18,000 lives and destroyed over 400,000 homes [2]. Such events highlight the urgent need for robust risk mitigation strategies [3]. With tsunami risk projected to grow, strengthening preparedness and resilience in vulnerable coastal regions is imperative.

A cornerstone of tsunami preparedness is effective evacuation management, which enables the rapid and safe relocation of populations from high-risk zones to designated shelters. Both the European Commission (EC) and the U.S. National Response Framework emphasize the importance of coordinated evacuation strategies and traffic management to mitigate disaster impacts.^{3,4} In 2022 alone, millions were evacuated due to hurricanes, floods, and wildfires.⁵ Mismanagement of evacuation traffic can lead to chaos, delay escape from hazard zones, and result in significant casualties [4]. Historical evacuations in the U.S., such as during Hurricanes Katrina (2005), Harvey (2017), and Ian (2022), demonstrate how traffic congestion can paralyze entire regions, leaving people exposed to life-threatening conditions.

Tsunami evacuation planning must integrate multimodal traffic management to coordinate pedestrian and vehicle flows. In dense or infrastructure-limited areas, evacuation may rely entirely on pedestrian movement, while well-connected regions can support vehicular traffic [5]. Unlike disasters with longer lead times, tsunamis demand immediate action, often within minutes, to move people to vertical or horizontal shelters via the fastest and safest routes.⁶ The success of such time-sensitive evacuation strategies depends not only on traffic management but also on the availability and accessibility of structurally robust shelters. The U.S. National Tsunami Hazard Mitigation Program emphasizes the importance of vertical and horizontal evacuation plans that direct evacuees to engineered shelters or elevated safe zones.⁷ These strategies are particularly critical in near-field tsunami scenarios, where warning times can be under 20 min. During the 2011 Tohoku tsunami, over 260 buildings in Ishinomaki sheltered about 50,000 people, underscoring their life-saving role.⁸

These global lessons on vertical and horizontal sheltering directly motivate İstanbul's tsunami preparedness efforts, where dense urban form and short warning times make integrated shelter planning essential. The İstanbul Tsunami Action Plan, developed by the İstanbul Metropolitan Municipality (IMM) and Middle East Technical University (METU), addresses the city's high tsunami risk from earthquakes or submarine landslides.⁹

²UNESCO (2019). Tsunami glossary [online]. Website <https://unesdoc.unesco.org/ark:/48223/pf0000188226> [accessed 29 December 2023].

³USDHS (2013). National response framework [online]. Website <https://www.epa.gov/emergency-response/epa-and-national-response-framework> [accessed 27 December 2024].

⁴European Commission: Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO) (2020). Overview of Natural and Man-Made Disaster Risks the European Union May Face – 2020 Edition [online]. Website <https://data.europa.eu/doi/10.2795/1521> [accessed 29 December 2023].

⁵FEMA (2022). 2022 annual report [online]. Website https://www.fema.gov/sites/default/files/documents/fema_tmacc-annual-report-2022.pdf [accessed 27 December 2024].

⁶UNESCO and Intergovernmental Oceanographic Commission IOC (2009). Tsunami risk assessment and mitigation for the indian ocean: knowing your tsunami risk and what to do about it [online]. Website <https://unesdoc.unesco.org/ark:/48223/pf0000184777> [accessed 27 December 2024].

⁷Mintier, J.L., Keller, R., Eisner, R., Jansenson, D., et al., 2001. Designing for Tsunamis: Seven principles for 27 planning and designing for tsunami hazards. Technical Report. National Tsunami Hazard Mitigation Program 28 (NTHMP). Website https://www.preventionweb.net/files/1505_DesigningforTsunamis.pdf?startDownload=true [Accessed 27 March 2024].

⁸FEMA (2019). Guidelines for design of structures for vertical evacuation from tsunamis [online]. Website <https://www.atccouncil.org/files/FEMA%20P-646%20Final.pdf> [accessed 27 December 2024].

⁹Istanbul Metropolitan Municipality (2019). İstanbul province tsunami action plan [online]. Website <https://depremzemin.ibb.istanbul/tr/istanbul-tsunami-eylem-planı> [accessed 27 December 2024].

Hydrodynamic simulations show that tsunami waves could reach İstanbul's coast within 10 min of an earthquake, with peak inundation occurring 60–90 min later, especially in high-risk districts such as the Islands and Eastern Marmara.^{10,11} The plan calls for tsunami-resistant vertical shelters, early warning systems, high-capacity evacuation routes, public education, and retrofitting of critical infrastructure.

Building on these strategies, this study focuses on optimizing evacuation management in İstanbul, where the risk of a tsunami following a major earthquake is significant. Specifically, this study makes several methodological and practical contributions to tsunami evacuation planning:

- **A unified mixed-mode evacuation model.** We develop a new optimization framework that jointly models pedestrian and vehicular evacuation flows on a shared urban network. The model captures congestion effects, flow interactions, and speed reductions on mixed-use road segments, thereby reflecting the operational realities of evacuations where both modes coexist.
- **Integrated vertical and horizontal sheltering.** Unlike existing studies that treat shelter types separately, our approach simultaneously determines the location and activation of vertical shelters while assigning evacuees to both vertical and horizontal shelters based on accessibility, mode of travel, and expected tsunami arrival times. This supports realistic planning in dense urban environments where horizontal evacuation alone is insufficient.
- **Road-segment designation to reduce conflict and confusion.** We introduce a novel mechanism that designates each road segment as either *pedestrian-only*, *vehicle-only*, or *mixed-use*. This feature captures the operational need to prevent pedestrian–vehicle conflicts, reduce congestion, and avoid confusion and hesitation at intersections, critical factors in time-limited tsunami evacuations.
- **A risk-minimizing objective grounded in hazard intensity.** Departing from conventional clearance-time models, our formulation minimizes *total evacuation risk* by incorporating tsunami inundation depths, arrival times, and spatially varying hazard intensities. This ensures that evacuation routes are selected based on safety rather than speed alone, aligning the model with real-world hazard dynamics.
- **A nonlinear optimization problem reformulated as a MISOCP.** The presence of congestion-dependent travel times yields a convex nonlinear objective. We reformulate this problem as a *mixed-integer second-order cone program (MISOCP)* using auxiliary variables and hyperbolic constraints, enabling the model to be solved efficiently by modern optimization solvers with global optimality guarantees.
- **Real-world application to the Büyükçekmece region of İstanbul.** Using detailed geographic, demographic, and hazard data, we apply the model to a tsunami-prone district of İstanbul. Multiple demand and budget scenarios demonstrate the model's effectiveness, reveal key congestion patterns, and highlight vertical shelters critical for reducing risk in near-field tsunami events.

Together, these contributions deliver a comprehensive, risk-aware evacuation planning framework tailored for dense, hazard-prone urban environments and readily adaptable to other coastal cities facing similar tsunami threats. The resulting framework is directly aligned with İstanbul's tsunami preparedness priorities and

¹⁰Istanbul Metropolitan Municipality (2018). Possible Earthquake Loss Estimate District Booklets [online]. Website <https://depremzemin.ibb.istanbul/uploads/prefix-avcilar-666ad4f31841f.pdf> [accessed 11 February 2024].

¹¹Ocal, N. (2018). Tsunami bilgi notu. Bogazici University, Kandilli Observatory and Earthquake Research Institute, Website http://www.koeri.boun.edu.tr/sismo/2/wp-content/uploads/2015/05/BDTIM_Tsunami_Turkce_Haziran_2021.pdf [accessed 27 December 2024].

contributes to evidence-based urban resilience planning. Aligned with AFAD's National Earthquake Strategy and Action Plan,¹² the UN Sustainable Development Goals,¹³ and the Sendai Framework,¹⁴ the framework supports resilient urban systems in high-risk seismic zones.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on evacuation traffic management. Section 3 introduces the problem setting and presents a nonlinear mixed-integer programming formulation. Section 4 reports and analyzes computational results. Finally, Section 5 concludes the paper and outlines directions for future research.

2. Literature review

This study advances a comprehensive approach to tsunami evacuation planning by integrating critical research domains: tsunami-resilient shelter provision, mixed traffic evacuation management, and evacuation road network design. Each of these areas contributes distinct insights into disaster preparedness and response, yet their integration remains underexplored. In this section, we systematically review the relevant literature within each domain, emphasizing the interdependencies and identifying key research gaps. Particular attention is given to the limited number of studies that address the joint optimization of shelter placement and traffic flow under risk and time constraints, an essential challenge for improving evacuation efficiency in high-risk coastal cities.

To support this discussion, Table 1 presents a structured comparative overview of representative evacuation studies across a unified set of modeling dimensions. The table highlights differences in hazard context, shelter location and assignment decisions, traffic representation, risk treatment, and methodological scope, thereby situating the present study within the broader state of the art.

Table 1. Comparison of evacuation studies across modeling features.

Study	Haz.	Loc.	Asg.	Road seg.	Traffic	Objective	Method	Risk	Data	S/D
[6]	Emerg.	•	•	◦	Vehicle	Min. time/cost	MILP	◦	•	S
[7]	Urban	◦	◦	◦	Vehicle	Compare strat.	ABM	◦	◦	D
[8]	Tsun.	◦	•	◦	Pedestrian	Max evac.	Sim.	◦	•	D
[9]	Tsun.	◦	•	◦	Pedestrian	Behavior real-ism	ABM + social force	•	•	D
[10]	Urban	◦	◦	◦	Vehicle	Min cost	MILP	◦	•	S
[11]	Tsun.	◦	•	◦	Pedestrian	Min risk	Nonlinear opt.	•	•	D
[12]	Freight	◦	◦	◦	Mixed	Impact eval.	Sim.	◦	◦	D
[13]	Urban	◦	◦	◦	Vehicle	Min delay	MILP	◦	•	S
[14, 15]	Tsun.	•	•	◦	Mixed	Reduce risk	MIP + Benders	•	•	D
[16]	Tsun.	•	◦	◦	Pedestrian	Min dist.	GA	◦	◦	S
[17]	Urban	◦	◦	•	Vehicle	Max flow	Tabu	◦	•	S
[18]	Emerg.	◦	◦	◦	Vehicle	Max eff.	Dyn. method	•	•	D
[19]	Emerg.	•	•	◦	Vehicle	Min cost	Fuzzy MILP	•	•	S
[20]	Tsun.	◦	•	◦	Mixed	Perf. eval.	ABM	◦	•	D
[21]	Tsun.	•	◦	◦	Pedestrian	Improve access	GIS	◦	•	S
[22]	Urban	◦	◦	•	Vehicle	Max through-put	LR + Tabu	◦	•	S
[23]	Urban	◦	◦	◦	Pedestrian	Eff. eval.	Sim.	◦	•	D
[24]	Stadium	◦	•	◦	Mixed	Min evac.	CTM + MILP	◦	•	D
[25]	Urban	◦	◦	◦	Mixed	Min clearance time	Sim. + DRL	◦	•	D
This Study	Tsun.	•	•	•	Mixed	Min risk	MISOCP	•	•	S

¹²AFAD (2013). Ulusal deprem stratejisi ve eylem planı (udsep 2012 – 2023) [online]. Website <https://deprem.afad.gov.tr/downloadDocument?id=1643> [accessed 25 August 2025].

¹³UNDESA (2015). Sustainable development goals[online]. Website <https://sdgs.un.org/goals>. [accessed 25 August 2025].

¹⁴UNISDR (2015). Sendai framework for disaster risk reduction 2015–2030 [online]. Website https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf [accessed 25 August 2025]

Specifically, Table 1 reports whether studies explicitly model shelter location and evacuee assignment, incorporate road segment design interventions (e.g., contraflow, lane reversal, corridor designation, or mode-exclusive links), and represent pedestrian, vehicle, or mixed traffic flows. It further summarizes each study's primary objective, solution methodology, treatment of risk arising from hazard exposure, data source (real-world versus synthetic), and whether the modeling framework is static or dynamic. Binary modeling features are denoted using filled and empty bullet symbols for clarity and consistency. A filled bullet ($\bullet$) indicates that the corresponding feature is explicitly modeled, while an empty circle ($\circ$) denotes that it is not considered. This notation is applied uniformly across relevant dimensions, including shelter decisions, road segment design, risk treatment, and data usage.

2.1. Safe shelters for tsunamis

Tsunamis, often triggered by seismic events, can cause rapid and catastrophic destruction, necessitating evacuation strategies that combine horizontal and vertical sheltering. Horizontal evacuation moves people to higher ground,⁷ while vertical evacuation uses tall, tsunami-resistant structures within or near hazard zones, essential when infrastructure is damaged or time is insufficient, especially in dense urban areas. Postdisaster analyses underscore the value of vertical shelters. During the 2011 Great East Japan Earthquake and Tsunami, damaged horizontal routes highlighted their lifesaving role in built-up areas [26]. FEMA similarly advises incorporating vertical evacuation in tsunami-prone regions, such as the U.S. Pacific Northwest, through retrofitting existing buildings and constructing purpose-built shelters for situations with short warning times.⁸ For an extensive review of shelter location modeling in evacuation contexts, see Bayram [3].

Several studies have modeled the strategic placement of vertical shelters. Di Mauro et al. [8] showed that proximity-based assignments improved evacuation in Padang, Indonesia, while Wang et al. [20] used agent-based simulations to assess the combined effects of vertical shelters and transport modes. Park et al. [16] applied a genetic algorithm to minimize shelter travel distance, and Wood et al. [21] used GIS to optimize sites considering geographic and demographic constraints.

Beyond tsunami-specific settings, Amideo et al. [6] investigated the joint optimization of shelter location and evacuation routing under capacity and congestion constraints in a general emergency context, demonstrating both the potential performance benefits and the computational challenges associated with integrated location-routing formulations. Addressing uncertainty in emergency facility planning, Wan et al. [19] proposed a bi-objective model based on trapezoidal fuzzy numbers to balance urgency and cost in distribution center siting decisions, highlighting the value of accounting for imprecise or ambiguous information in disaster response. Extending integrated sheltering strategies to tsunami evacuation, Moslemi et al. [14, 15] developed a framework that jointly optimizes vertical and horizontal shelter location, budget-constrained capacity expansion, and mode-specific evacuee assignment. Moreover, their study introduced a corridor-based evacuation strategy in which selected road segments are exclusively dedicated to vehicular evacuation, offering an operational mechanism to mitigate congestion and improve traffic efficiency under short warning times.

Most studies, aside from Moslemi et al. [14, 15], treat vertical shelter location in isolation, neglecting its interaction with horizontal sheltering. Our work addresses this gap by jointly optimizing both shelter types, improving flexibility and resilience in urban, high-risk coastal areas with short warning times and vulnerable infrastructure.

2.2. Mixed traffic management

In tsunami evacuation planning, the choice between pedestrian and vehicular modes depends on factors such as population density, road infrastructure, geography, and warning time. In dense urban areas, pedestrian evacuation is often more effective due to congestion risks [5]. Cebeci (2023)¹⁵ highlights its suitability in compact cities like İstanbul, where proximity to safe zones and complex layouts hinder vehicle use. Conversely, in sparsely populated regions with developed road networks and sufficient warning, vehicles can expedite evacuation, particularly for vulnerable groups, though congestion remains a challenge, as seen in rural areas during the 2011 Tohoku tsunami [27].

Given environmental, psychological, and behavioral uncertainties [28], mixed traffic evacuations are likely, requiring plans that address pedestrian–vehicle interactions and resulting congestion. Such interactions often cause delays at intersections [29], yet many models overlook these complexities. For example, Zhang and Chang [24] proposed a multimodal plan for Baltimore without fully capturing congestion effects, while Zhang et al. [25] analyzed these interactions but lacked scalability to large networks. Moslemi et al. [30] provide a systematic review of human behavior modeling in large-scale evacuations, emphasizing the need to jointly capture mode choice, and route selection. In the tsunami context, Flores et al. [9] examine stress-dependent pedestrian dynamics using a social-force-based agent model, but their analysis is restricted to pedestrian-only evacuation and does not account for interactions with vehicular traffic or network-level routing.

Modeling congestion in mixed traffic scenarios requires accurate travel time functions that reflect the impact of increased volume. In our work, we employ the BPR function to represent congestion more realistically, and explicitly model the speed reduction experienced by vehicles in the presence of pedestrians, capturing a key dynamic typically overlooked in prior models. This integrated approach provides a more realistic framework for tsunami evacuation under mixed traffic conditions, addressing a significant gap in the current literature.

2.3. Evacuation road network design

Efficient evacuation road network design is crucial for managing mixed pedestrian–vehicle traffic. Strategies include expanding capacity, implementing contraflow to boost outbound flow [13, 17], and optimizing routes by evacuee type [10]. Lane reversal models further enhance flow by reallocating road space in response to demand [22]. In urban areas, differentiating routes by mode—designating “pedestrian-only” and “vehicle-only” roads—reduces congestion, improves safety, and limits pedestrian–vehicle interactions [7, 12, 23, 31]. Micro-simulation and agent-based studies confirm that segregated flows and signal control mitigate conflicts, especially at intersections. In tsunami evacuation, Moslemi et al. [15] proposed a corridor-based strategy dedicating full road segments to vehicles, eliminating pedestrian conflicts. From a network design perspective, Horiai et al. [11] propose a zonal optimization framework for tsunami evacuation that minimizes time-varying risk through a macroscopic fundamental diagram representation of pedestrian flows, demonstrating the effectiveness of large-scale directional guidance. However, the aggregate nature of their formulation precludes explicit modeling of link-level routing decisions, shelter assignment, and multimodal pedestrian–vehicle interactions.

Most models overlook route designation in their optimization. Our framework addresses this gap by explicitly reserving certain segments for exclusive pedestrian or vehicle use, and by adjusting vehicle speeds where mixed traffic is unavoidable, capturing real-world interactions while improving safety and throughput. Overall,

¹⁵Cebeci, O., 2023. Beklenen tsunami tehlikesi ve Önlemler. Denizcilik Sektörü Olası İstanbul Depremine Hazır Mı? Website https://tudav.org/wp-content/uploads/2023/10/Denizcilik_Sektoru_Olasi_Istanbul_Depremine_Hazir_mi_low.pdf [Accessed 25 March 2024].

the comparison reveals that most existing studies address evacuation planning through isolated components, typically focusing on routing, shelter location, or traffic simulation in separation. Fully integrated formulations that jointly consider shelter location, evacuee assignment, and network design remain limited, particularly in contexts involving mixed pedestrian–vehicle traffic. Furthermore, risk associated with hazard exposure is often neglected or treated independently of traffic and shelter decisions. While a small subset of studies accounts for either vertical or horizontal shelters, none simultaneously integrates shelter location, assignment, mixed-mode routing, road segment design, and risk minimization within a single optimization framework. Table 1 therefore highlights a clear methodological gap, which the proposed model addresses by offering a unified, risk-aware optimization framework that captures these interdependent decisions in a coherent and operationally meaningful manner.

Next, we define our problem formally and present its mathematical formulation.

3. Assumptions, problem description and model formulation

This section presents the problem setting and develops the optimization model for tsunami evacuation planning. We first describe the assumptions that define the scope of the analysis and shape the structure of the evacuation system. We then provide a detailed problem description and introduce a nonlinear (convex) mixed-integer formulation that captures congestion effects, multimodal flows, and sheltering decisions. Since the resulting model contains convex nonlinearities, we subsequently show how it can be reformulated as a mixed-integer second-order cone program to ensure computational tractability and global optimality.

3.1. Modeling assumptions

This study relies on several modeling assumptions that align with common practices in evacuation planning and support the tractability of the proposed optimization framework. We assume that all evacuees fully comply with official evacuation directives and begin evacuating immediately after the triggering earthquake, which is treated as a natural warning mechanism for an impending tsunami [3]. Evacuation is carried out either on foot or by personal vehicles; no public transportation or alternative modes are considered. The composition of pedestrian and vehicular evacuees is predetermined at the scenario level, and individuals do not make endogenous mode choices.

Consistent with the operational realities of tsunami response, pedestrians may access both vertical and horizontal shelters, whereas vehicles are restricted to horizontal shelters due to elevation, accessibility, and structural constraints. Pedestrian–vehicle interactions on shared road segments reduce vehicular speeds, while pedestrian speeds are assumed to remain constant. The model adopts a zone-based structure [28] in which each zone receives a single evacuation directive. Zones are defined to be approximately homogeneous in terms of tsunami exposure, and their risk characteristics, such as inundation depth and arrival time, are treated as deterministic inputs within each scenario.

The underlying road network is assumed to remain operational throughout the evacuation period; no road closures, structural failures, or debris-induced blockages are modelled. Road capacities are fixed, and interactions between adjacent segments (e.g., queue spillback) are not explicitly represented [32]. Each road segment may be designated as pedestrian-only, vehicle-only, or mixed-use, and such designations are assumed enforceable during an emergency. Travel times are deterministic and depend on congestion through convex flow–travel time relationships for vehicles on mixed-use roads. Shelter infrastructure is treated as reliable and available throughout the planning horizon. Candidate vertical and horizontal shelters remain structurally functional, and their capacities do not degrade over time.

These assumptions, together with those detailed in Section 4 on data and experimental design, provide a clear and tractable framework while remaining consistent with prior evacuation modeling studies.

3.2. Mixed-mode evacuation problem: definition and formulation

We define the evacuation problem on a directed graph $G = (N, A)$, where N denotes the set of nodes and A represents the set of arcs corresponding to road segments. The subset of origin nodes with evacuation demand is denoted by $O \subseteq N$. Each arc $a \in A$ may be designated for use by pedestrians, vehicles, or both; we define $A^p \subset A$ as the set of pedestrian-accessible arcs and $A^v \subset A$ as the set of vehicle-accessible arcs.

Two categories of shelters are considered: vertical shelters $V \subseteq N$ and horizontal shelters $E \subseteq N$. Vertical shelters $v \in V$ are typically elevated structures located within or near the tsunami inundation zone, whereas horizontal shelters $e \in E$ are situated outside the inundation area. For each origin $o \in O$, subsets $V'_o \subseteq V$ and $E'_o \subseteq E$ represent the vertical and horizontal shelters that are reachable prior to tsunami wave arrival. Each vertical shelter $v \in V$ is associated with a capacity Q_v and an activation cost h_v , representing either the construction cost of new shelters or the reinforcement cost of existing facilities. The total investment in vertical shelters is constrained by a predefined budget B . The total evacuation demand comprises a known number of pedestrians D_p and vehicles D_v originating from specified sub-regions. To consolidate flows reaching safety, each destination node is linked to a super-exit node s_e .

To realistically model pedestrian-vehicle interactions on shared road segments, we incorporate discrete vehicle speed levels indexed by $l \in L$. These levels reflect reduced vehicle speeds on mixed-mode arcs where pedestrian flows are present, capturing the operational trade-offs and safety considerations inherent in shared-use evacuation paths. Each arc $a \in A$ is characterized by a pedestrian travel time t_a^p , a set of vehicular travel times t_a^{vl} for each speed level $l \in L$, pedestrian capacity c_a^p , vehicle capacity c_a^v , and a risk value r_a indicating exposure to tsunami-related hazards. For each node $i \in N$, $\delta(i)^+$ and $\delta(i)^-$ denote the sets of outgoing and incoming arcs, respectively.

The evacuation problem is formulated as a mixed-integer optimization model that jointly determines shelter location, evacuee-shelter assignments, and pedestrian-vehicle traffic flows under congestion, risk, capacity, and budget constraints. The key decision variables include f_a^{op} , representing the pedestrian flow on arc a originating from o , and f_a^{ovl} , denoting the vehicular flow on arc a from origin o when operated at speed level l . Shelter assignment decisions are encoded by the binary variable x_{ov} , which indicates whether origin o is routed to vertical shelter v . The binary variables u_a^{op} and u_a^{ov} specify whether arc a is used by pedestrians or vehicles, respectively. These variables do not impose strict exclusivity; instead, they identify which modes actually occupy each arc so that the model can capture the operational implications of mixed use. When both $u_a^{op} = 1$ and $u_a^{ov} = 1$, arc a becomes a mixed-use segment, and the vehicle speed is automatically reduced through activation of the corresponding speed-level variable z_a^l . This mechanism allows shared roads while internalizing the congestion and safety penalties associated with pedestrian-vehicle interactions.

Pedestrian routing is constrained to be convergent: all pedestrian flow from a given origin follows a single nonbranching path to its assigned shelter. This structure removes ambiguity at intersections and limits on-the-ground decision-making under time pressure, thereby enhancing evacuation reliability. Vertical shelter activation is determined by the binary variable y_v , and the continuous variable q_v captures any excess demand assigned to shelter v , with associated penalties when $q_v > 0$. Collectively, these variables enable an integrated representation of flow dynamics, shelter accessibility, congestion propagation, road-use patterns, and cost-limited investment decisions within a risk-aware tsunami evacuation framework. A complete summary of the model's notation, including all sets, parameters, and decision variables, is provided in Appendix A.

Travel time on each arc is modeled as a positive, monotonically increasing function of traffic flow, reflecting the congestion effect, i.e. as traffic volume increases, speeds decline and travel times rise. To represent this relationship, we adopt the Bureau of Public Roads (BPR) function [33], a widely used convex, nondecreasing, and differentiable form in both transportation and evacuation modeling. In our formulation, the BPR function for vehicular travel time on arc a at speed level l is expressed as:

$$t_a^{vl}(f_a^{vl}) = t_a^{vl0} \left(1 + \alpha \left(\frac{f_a^{vl}}{c_a^v} \right)^\beta \right)$$

where, the parameters α and β represent the sensitivity of travel time to traffic congestion within the BPR function, with commonly used values in the literature being $\alpha = 0.15$ and $\beta = 4$ [3]. The evacuation problem is initially formulated as a Nonlinear Convex Integer Programming (NCIP) model, capturing both the congestion-dependent travel times and the discrete decision variables related to shelter selection, speed level assignment, and route usage. To improve computational tractability, the model is subsequently transformed into a Mixed-Integer Second-Order Cone Programming formulation. The original NCIP model is presented below:

$$\min \sum_{a \in A^p} \sum_{o \in O} t_a^p f_a^{op} r_a + \sum_{a \in A^v} \sum_{l \in L} r_a t_a^{vl0} \left(1 + \alpha \frac{f_a^{vl}}{c_a^v} \right)^\beta f_a^{vl} \quad (1)$$

$$\sum_{o \in O} \sum_{a \in \delta^+(i)} \sum_{l \in L} f_a^{ovl} - \sum_{o \in O} \sum_{a \in \delta^-(i)} \sum_{l \in L} f_a^{ovl} = \begin{cases} D^v, & i = s_o \\ 0, & i \in N \setminus \{s_o, s_e\} \\ -D^v, & i = s_e \end{cases} \quad (2)$$

$$\sum_{a \in \delta^+(i)} f_a^{op} - \sum_{a \in \delta^-(i)} f_a^{op} = \begin{cases} d_o^p x_{ov}, & i = o \\ 0, & i \in N \setminus \{o, v\}, o \in O, v \in V \\ -d_o^p x_{ov}, & i = v \end{cases} \quad (3)$$

$$\sum_{a \in \delta^+(i)} u_a^{op} - \sum_{a \in \delta^-(i)} u_a^{op} = \begin{cases} x_{ov} & \text{if } i = o \\ 0 & \text{if } i \in N \setminus \{o, v\}, o \in O, v \in V \\ -x_{ov} & \text{if } i = v \end{cases} \quad (4)$$

$$f_a^{vl} \leq c_a^v z_a^l \quad \forall \quad a \in A^v; l \in L \quad (5)$$

$$f_a^{vl} = \sum_{o \in O} f_a^{ovl} \quad \forall \quad a \in A; l \in L \quad (6)$$

$$\sum_l f_a^{vl} \leq c_a^v u_a^v \quad \forall \quad a \in A^v \quad (7)$$

$$\sum_{o \in O} f_a^{op} \leq c_a^p u_a^p \quad \forall \quad a \in A^p \quad (8)$$

$$z_a^2 \geq u_a^p \quad \forall \quad a \in A^v \quad (9)$$

$$\sum_l z_a^l = 1 \quad \forall \quad a \in A \quad (10)$$

$$\sum_{o \in O} d_o^p x_{ov} \leq Q_v y_v + q_v \quad \forall \quad v \in V \quad (11)$$

$$\sum_{v \in V} h_v y_v \leq B \quad (12)$$

$$\sum_{v \in V'_o \cup E'_o} x_{ov} = 1 \quad \forall o \in O \quad (13)$$

$$q_v \leq \bar{Q}_v y_v \quad \forall v \in V \quad (14)$$

$$f_a^{op} \geq 0 \quad \forall a \in A^p, o \in O \quad (15)$$

$$f_a^{ovl} \geq 0 \quad \forall a \in A^v, o \in O, l \in L \quad (16)$$

$$x_{ov} \in \{0, 1\} \quad \forall o \in O, v \in V \quad (17)$$

$$u_a^{ov} \in \{0, 1\} \quad \forall a \in A^v, o \in O \quad (18)$$

$$u_a^{op} \in \{0, 1\} \quad \forall a \in A^p, o \in O \quad (19)$$

$$y_v \in \{0, 1\} \quad \forall v \in V \quad (20)$$

$$z_a^l \in \{0, 1\} \quad \forall a \in A, l \in L \quad (21)$$

$$q_v \geq 0 \quad \forall v \in V \quad (22)$$

The objective function in Equation (1) minimizes the total risk-weighted evacuation cost. The first term represents pedestrian travel time on each arc $a \in A^p$, scaled by the tsunami risk value r_a , while the second term models vehicle travel times using the BPR function. This convex function captures congestion effects by increasing travel time nonlinearly as vehicle flow f_a^{vl} approaches arc capacity c_a^v , with each term again weighted by r_a . Constraint (2) enforces *vehicle flow conservation* at each node $i \in N$, ensuring that vehicle flows are balanced from the super source node s_o to the super-exit node s_e . The total inflow and outflow for vehicles across all arcs and speed levels $l \in L$ satisfies the overall vehicle demand D^v . Constraint (3) ensures *pedestrian flow conservation* between each origin $o \in O$ and its assigned vertical shelter $v \in V$, conditional on the assignment variable x_{ov} . This formulation routes pedestrian demand d_o^p along a unique path to a shelter, consistent with a convergent evacuation structure. Constraint (4) governs the *use of pedestrian arcs*, enforcing a convergent path by ensuring that the binary variable u_a^{op} captures whether arc a is used in the path from origin o to shelter v . Constraint (5) restricts the *vehicle flow per arc and speed level*, ensuring that f_a^{vl} does not exceed capacity c_a^v when speed level l is selected via the binary variable z_a^l . Constraint (6) defines *total vehicle flow* on arc a at speed level l as the sum of flows from all origins. Constraint (7) enforces an upper bound on *total vehicle flow* across all speed levels using the capacity c_a^v and binary usage indicator u_a^v , while Constraint (8) applies the same principle to *pedestrian flows*. Constraint (9) ensures that *speed levels reflect pedestrian presence*: if an arc is used by pedestrians (i.e. $u_a^p = 1$), then speed level 2 (reduced speed) must be selected by enforcing $z_a^2 \geq u_a^p$. Constraint (10) enforces that *exactly one speed level is selected* per arc, ensuring well-defined vehicular travel times. Constraint (11) ensures that the *total number of pedestrians assigned to shelter v* does not exceed its base capacity Q_v plus excess capacity q_v , which is only accessible if the shelter is opened (i.e. $y_v = 1$). Constraint (12) imposes a *budget constraint* by limiting the total retrofitting and construction cost of vertical shelters, where h_v denotes the cost of opening shelter v and B is the available budget. Constraint (13) guarantees that each evacuation origin $o \in O$ is *assigned to exactly one shelter*, from the union of reachable vertical and horizontal shelters $V'_o \cup E'_o$. Constraint (14) ensures that *excess capacity q_v* is only available if shelter v is opened, where $\bar{Q}_v$ is the maximum allowable excess capacity. Constraints (15)–(22) define the *domains of the decision variables*.

3.3. Reformulation of the model as a MISOCP

Second-order cone programming (SOCP) is a class of convex optimization problems that extends linear programming (LP) and encompasses certain forms of quadratic programming (QP). Recent advances in conic optimization and the development of efficient interior-point algorithms have established SOCP as a state-of-the-art technique for solving large-scale convex optimization problems [34]. Introductory treatments of SOCP and its modeling capabilities can be found in Ben-Tal and Nemirovski [35] and Alizadeh and Goldfarb [36], who emphasize that well-structured SOCPs can often be solved with computational effort comparable to that of linear programs of similar size. Numerous convex optimization problems across engineering and operations research admit SOCP reformulations (see, e.g., Ben-Tal and Nemirovski [35], Lobo et al. [37]). The effectiveness of mixed-integer SOCP has also been demonstrated in a wide range of applications, including portfolio optimization [38], power distribution reconfiguration [39], stochastic location–inventory design [40], UAV trajectory optimization [41], multiobjective convex polynomial optimization [42], and traffic assignment [43]. These studies collectively illustrate the robustness, scalability, and global optimality guarantees of MISOCP methods, supporting our decision to reformulate the nonlinear evacuation model into a tractable MISOCP framework.

Before presenting the full MISOCP formulation, we remark that the original problem features a convex objective function with linear constraints, and therefore its continuous relaxation is a well-defined convex optimization problem. After reformulation, the model becomes a MISOCP with a linear objective and conic-quadratic constraints. The continuous SOCP relaxation is convex and admits a global optimum over the compact feasible region. Modern conic solvers employ interior-point methods for SOCP relaxations [34–36] within a branch-and-bound or branch-and-cut framework, ensuring finite convergence to a globally optimal solution of the MISOCP. Thus, the existence and computability of an optimal solution are guaranteed by the problem’s convex structure.

To enhance computational tractability, we reformulate the original nonlinear convex integer programming model as a MISOCP problem. The nonlinearity in the objective function (1) arises from the BPR term, which includes the flow variable f_a^{vl} raised to the power $\beta + 1$. This term complicates the solution process and significantly increases computational burden, particularly for large-scale evacuation networks.

Following the approach of Bayram and Yaman [44], we introduce auxiliary continuous variables μ_a^{vl} for each arc-speed pair (a, l) , with $a \in A^v$ and $l \in L$, to decouple the nonlinearity from the objective function. This allows us to shift the nonlinear terms into a set of convex constraints while maintaining a linear objective function. The reformulated objective function becomes:

$$\min \sum_{a \in A^p} \sum_{o \in O} t_a^p f_a^{op} r_a + \sum_{a \in A^v} \sum_{l \in L} \left(r_a t_a^{vl0} f_a^{vl} + \frac{r_a t_a^{vl0} \alpha}{(c_a^v)^\beta} \mu_a^{vl} \right) \quad (23)$$

The nonlinear constraint $f_a^{vl\beta+1} \leq \mu_a^{vl}$ is now modeled via hyperbolic constraints.

We take $\beta = 4$, resulting in $(f_a^{vl})^5 \leq \mu_a^{vl}$. This is decomposed using three nested hyperbolic inequalities:

$$(f_a^{vl})^2 \leq \theta_a^l h_a^l, \quad (24)$$

$$(\theta_a^l)^2 \leq u_a^l f_a^{vl}, \quad (25)$$

$$(u_a^l)^2 \leq \mu_a^l f_a^{vl}, \quad (26)$$

where θ_a^l , u_a^l , and μ_a^l are auxiliary nonnegative variables, and $h_a^l = 1$.

Combining the objective function (23) with the original model constraints (2)–(22) and the hyperbolic inequalities (24)–(26), we obtain the final MISOCP formulation:

$$\min \quad \sum_{a \in A^p} \sum_{o \in O} t_a^p f_a^{op} r_a + \sum_{a \in A^v} \sum_{l \in L} \left(r_a t_a^{vl0} f_a^{vl} + \frac{r_a t_a^{vl0} \alpha}{(c_a^v)^\beta} \mu_a^{vl} \right) \quad (27)$$

s.t. Constraints (2)–(22),

$$(f_a^{vl})^2 \leq \theta_a^l h_a^l, \quad \forall a \in A^v, l \in L \quad (28)$$

$$(\theta_a^l)^2 \leq u_a^l f_a^{vl}, \quad \forall a \in A^v, l \in L \quad (29)$$

$$(u_a^l)^2 \leq \mu_a^l f_a^{vl}, \quad \forall a \in A^v, l \in L \quad (30)$$

$$\theta_a^l, u_a^l, \mu_a^l, f_a^{vl} \geq 0, \quad \forall a \in A^v, l \in L \quad (31)$$

This conic reformulation enables the use of modern MISOCP solvers, improving numerical tractability and solution times while preserving the accuracy and richness of the original nonlinear evacuation model. Building on the formulation and methodological framework presented, next section applies the proposed evacuation model to a real-world case study in the Büyükçekmece District of İstanbul.

4. Evacuation planning for a potential tsunami in İstanbul: a case study

This section presents a comprehensive case study conducted in the Büyükçekmece District, one of İstanbul's most tsunami-prone coastal areas, to evaluate the applicability and effectiveness of the proposed evacuation planning model. The analysis integrates a rich set of real-world data, including (i) tsunami hazard and risk outputs generated using the NAMI DANCE simulation tool and the MeTHuVA risk methodology [45, 46]; (ii) a detailed road network of 964 nodes and 3,635 arcs extracted from OpenStreetMap¹⁶ and classified into potential pedestrian-only, vehicle-only, and mixed-use segments; (iii) an inventory of 93 vertical shelters and 185 horizontal shelters; (iv) population distribution estimates calibrated at the evacuation-zone level using TÜİK census data¹⁷; and (v) cost parameters for reinforcing or constructing shelters based on official 2023 Turkish unit rates. These datasets collectively support a realistic and operationally relevant representation of Büyükçekmece's evacuation setting. The model is tested under varying budget levels and evacuation demand configurations, allowing for an in-depth analysis of investment decisions, pedestrian-vehicle dynamics, and their effects on evacuation performance metrics such as congestion levels, shelter utilization, and population-at-risk. A complete description of the data, preprocessing steps, and parameter derivations is provided in Appendix B. We also refer the reader to Bayram et al. (2025),¹⁸ Moslemi et al. [14, 15] and IMM¹⁹ for more details on the data prepared.

¹⁶OpenStreetMap (2025). Open Street Map [online]. Website <https://www.openstreetmap.org> [accessed 27 December 2024].

¹⁷TÜİK (2021). Population Census [online]. Website <https://veriportali.tuik.gov.tr/en/press/45866> [accessed 14 December 2024].

¹⁸Bayram, V., Yildiz, B., Dogulu, C., Yalciner, A.C., Moslemi, S., Arıkanoglu, A., Ergülen, I., Bingöl, G.G.D., Mamouri, L., Barlas, E.A., Din, N., Ergez, D., Kulkarni, O., Luo, M., 2025b. Tsunami Tehdidine Karşı İstanbul İli Marmara Denizi Kıyıları Tahliye Planlaması ve Yönetimi. Araştırma Projesi Raporu. TUBİTAK 1001 Projesi, Proje No: 221M165. Ankara. Proje Yürütücüsü: Dr. Ogr. Uyesi Vedat Bayram [in Turkish].

¹⁹İstanbul Metropolitan Municipality (2018). İstanbul İli Marmara Kıyıları için Tsunami Modelleme, Hasar Görebilirlik ve Tehlike Analizi Projesi [online]. Website <https://depremzemin.ibb.istanbul/uploads/prefix-istanbul-ili-marmara-kıyılarında-tsunami-kaynakli-risk-arastirmasi-sonuc-raporu-66866e4d3981a.pdf> [accessed 27 December 2024].

4.1. Experimental design

This section presents computational experiments to evaluate the proposed evacuation optimization model using real-world data and to assess sensitivity to key design parameters. Two parameters were analyzed: budget allocation to explore trade-offs between investment in vertical shelters and coverage and evacuation demand composition to assess how varying vehicle–pedestrian splits affect congestion, efficiency, and risk.

Eleven scenarios were tested: one base case and ten experiments. The budget experiments comprise five scenarios with budgets ranging from 0% to 100%, keeping demand at a 50–50 vehicle–pedestrian split. The demand experiments include five scenarios with varying mode splits, while the budget remains fixed at 60% of the calibrated maximum.

4.2. Computational efficiency and managerial insights

This section presents the results of the computational experiments and discusses key managerial insights derived from the model outputs. All experiments were conducted on a laptop equipped with a 2.3 GHz Intel i7-11800H CPU and 32.0 GB RAM. The model was implemented in Python and solved using Gurobi version 11.0.2. The network output has been visualized with the open-source online tool Kepler.gl version 3.1.8.²⁰ Table 2 summarizes the performance of the model across different scenarios based on the following key performance indicators: (i) the number of vertical evacuation shelters opened, (ii) total risk incurred during the evacuation, (iii) number of mixed-use arcs defined as road segments used by both vehicular and pedestrian traffic and (iv) solution time in seconds.

Table 2. Combined scenario setup and performance indicators.

	Scenario Name	Budget Level	% Pedestrian Demand	# Vert. Shelters Opened	Total Risk	# Mixed Arcs	Sol.Time (Seconds)
Baseline Experiment	<i>Base Case</i>	60%	50%	48	1,007,509.41	12	230,760
Budget Experiments	<i>Scenario 0B</i>	0%	50%	0	1,555,898.92	155	5,400
	<i>Scenario 20B</i>	20%	50%	29	1,125,861.05	12	58,320
	<i>Scenario 40B</i>	40%	50%	37	1,015,492.22	13	54,000
	<i>Scenario 80B</i>	80%	50%	55	1,007,509.14	122	12,240
	<i>Scenario 100B</i>	100%	50%	59	1,007,509.14	135	7,200
Evacuation Demand Experiments	<i>Scenario 0P</i>	60%	0%	0	914,324.63	0	8,727
	<i>Scenario 10P</i>	60%	10%	46	1,584,189.00	44	83,501
	<i>Scenario 30P</i>	60%	30%	46	1,263,334.20	27	192,600
	<i>Scenario 70P</i>	60%	70%	48	824,595.19	123	45,000
	<i>Scenario 100P</i>	60%	100%	48	656,519.42	0	71,280

All instances were solved to optimality. The solution times exhibit significant variation across scenarios, with the base case being the most computationally challenging. This is attributed to the moderate levels of both vehicular and pedestrian demand, which result in a larger feasible space and increased complexity in traffic assignment and shelter location decisions.

Scenarios with 0% budget (Scenario 0B) are solved quickly due to the absence of shelter location decisions, effectively reducing the problem to a traffic assignment under constrained conditions. Similarly, the pure-mode demand scenarios 0P and 100P are computationally less intensive since they avoid mixed traffic interactions, thereby eliminating the need to designate road segments for shared use.

²⁰Kepler.gl (2025). Kepler.gl [online]. Website <https://kepler.gl> [accessed 17 May 2024].

In contrast, scenarios involving a mixture of pedestrian and vehicular demand, especially near the 50-50 ratio (e.g., Base Case and Scenario 30P), show higher computational times due to the complexity introduced by mode interactions, congestion propagation, and competing road usage. This highlights the critical role of traffic heterogeneity and its impact on optimization complexity.

From a managerial perspective, the results suggest a nonlinear relationship between investment in shelters and risk reduction. Notably, a substantial reduction in risk is achieved even with partial budget allocations (e.g., Scenario 40B), whereas additional investments beyond 60% yield diminishing returns. Likewise, the risk profile under mixed demand scenarios emphasizes the importance of demand management strategies. Promoting pedestrian evacuation, where feasible, not only reduces overall risk but also simplifies traffic dynamics, leading to more tractable and efficient evacuation plans.

4.2.1. Budget experiments

This subsection evaluates the effect of varying budget levels on two primary performance indicators: (i) the number of vertical shelters opened and (ii) the total risk incurred. Results are summarized in Figure 1, which depicts the trade-off between these indicators.

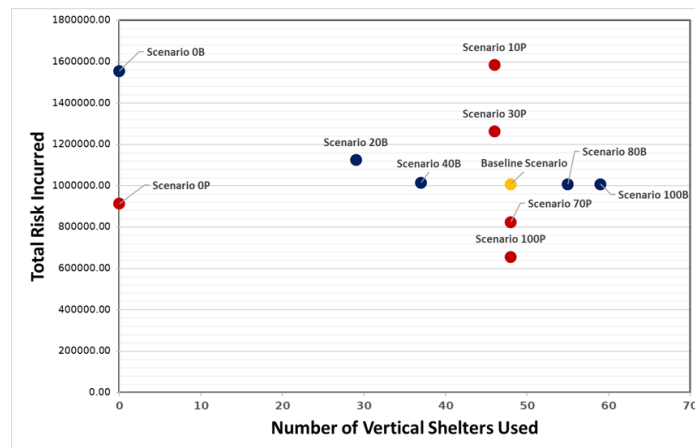


Figure 1. Pareto frontier illustrating the trade-off between total risk incurred and the number of vertical shelters opened across different budget scenarios.

In the 0B scenario, with no budget for vertical shelters, all evacuees are routed to horizontal shelters, causing severe congestion, especially on arcs leading to peripheral shelters and exits and yielding the highest total risk. As the budget increases, additional vertical shelters are activated, alleviating congestion and reducing overall risk. The number of open shelters rises with budget up to Scenario 80B, beyond which further openings yield negligible marginal benefit, indicating an effectively optimal configuration. In Scenario 100B, additional shelters are opened without further risk reduction, as surplus capacity does not alter evacuation flows or assignments. Overall, except for Scenario 0B, the budget scenarios result in comparable total risk values. This suggests that once a critical subset of strategically located vertical shelters is activated, particularly within

high-density zones, major congestion bottlenecks are largely mitigated. Beyond this threshold, evacuation performance is primarily constrained by network characteristics, including tsunami arrival times, fixed path geometries, and spatial concentration of demand, rather than shelter capacity. This pattern is reflected in Figure 1, where higher-budget scenarios cluster horizontally in the Pareto diagram, indicating limited sensitivity of total risk to additional shelter investment beyond the critical level.

Figure 2 illustrates distinct spatial usage patterns across shelter types. Of the 93 candidate vertical shelters, 23 are consistently selected, primarily within densely populated neighborhoods where congestion risk is most pronounced, underscoring their role in redistributing evacuees and mitigating network bottlenecks. In contrast, horizontal shelters exhibit higher utilization near the periphery of the network, serving origins located closer to coastal exits and boundary nodes. This divergence highlights the strong spatial dependence of shelter selection and the influence of network topology on evacuation dynamics. From a policy and emergency planning perspective, this finding has important implications. The subset of frequently selected vertical shelters represents a set of critical assets for effective evacuation in the studied region and should be prioritized in preparedness, structural reinforcement, and accessibility improvement efforts. Moreover, these facilities may be viewed as critical infrastructure nodes when evaluating the resilience and vulnerability of the evacuation network, informing both investment decisions and contingency planning.

Scenario 0B offers insight into evacuation performance under extreme constraints. In the absence of vertical shelters, all pedestrian evacuees are directed to horizontal shelters. While vehicular evacuees successfully evacuate from all 275 origins, only 41% of pedestrian evacuees succeed. Specifically, evacuees from 161 origins fail to reach safety before the tsunami arrives. Figure 3 shows that successful evacuations are concentrated near the periphery, where proximity to horizontal shelters is greater. This outcome highlights the essential role of vertical shelters in enabling timely evacuations, particularly in dense interior regions.



Figure 2. Frequency of usage for vertical and horizontal shelters across all budget scenarios (darker colors indicate higher usage). **Figure 3.** Evacuation performance in Scenario 0B: Green indicates safe evacuation, red indicates failure of evacuation.

The distribution of vertical versus horizontal shelter usage among successfully evacuated pedestrians reveals that the proportion assigned to vertical shelters increases slightly with budget—rising from 76.24% in Scenario 20B to 79.01% in Scenario 100B—suggesting that budget has a limited effect on shelter assignment. This modest change implies that factors such as network topology, demand distribution, and congestion patterns play a more significant role.

This observation is reinforced by the shelter assignment networks depicted in Figure 4. Although the number of opened vertical shelters increases from 29 in Scenario 20B to 37 in Scenario 40B, the pedestrian

evacuation patterns remain largely unchanged. Most assignment adjustments involve reallocation between shelters of the same type, rather than switching between vertical and horizontal shelters.

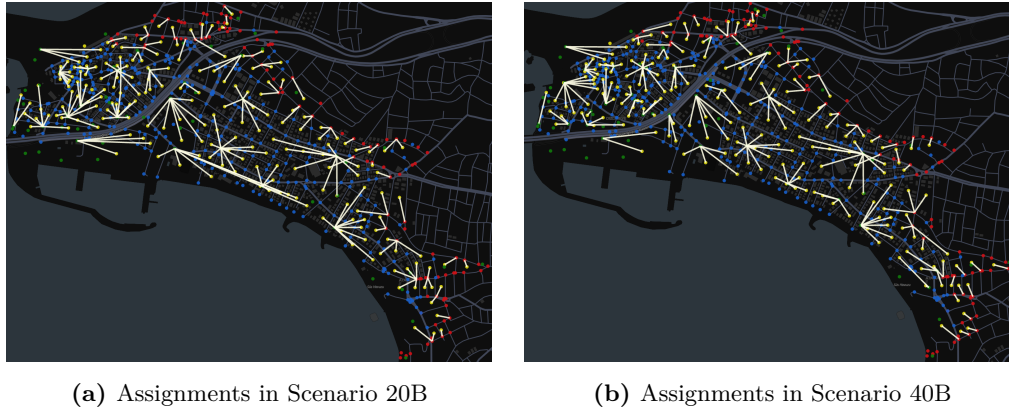


Figure 4. Pedestrian origin-shelter assignments

In summary, the budget parameter plays a critical role in enhancing the model's ability to distribute evacuees efficiently throughout the network, which is the primary driver of risk reduction as the budget increases. While a budget level corresponding to Scenario 20B is sufficient to ensure the complete evacuation of the region, it does so at a comparatively higher risk. Beyond Scenario 80B, further budget increments yield negligible marginal improvements in risk mitigation, indicating a point of diminishing returns and underscoring the optimality of the 80B budget level in balancing effectiveness and resource efficiency.

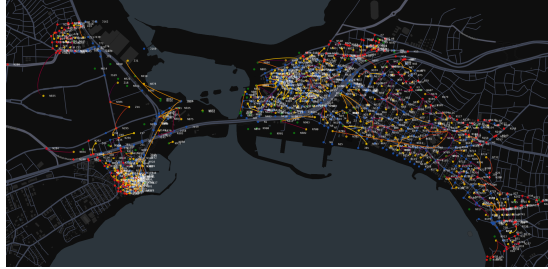
4.2.2. Evacuation demand experiments

This set of experiments evaluates how varying the proportion of pedestrian and vehicle evacuees affects overall evacuation performance. The analysis demonstrates a nonlinear relationship between evacuee composition and total evacuation risk. Due to their slower speeds and increased exposure times, pedestrians are more vulnerable than vehicle users. However, the presence of both pedestrian and vehicle evacuees leads to greater interaction and road congestion, increasing the total incurred risk.

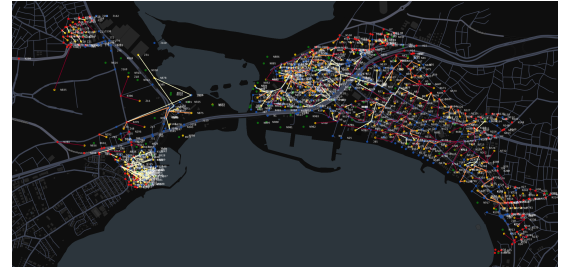
Table 2 shows that the extreme scenarios, 0P (all vehicular) and 100P (all pedestrian), yield lower total risk than mixed cases, with the 100P scenario achieving the minimum risk due to the absence of intermodal congestion and the effective use of vertical shelters. Beyond a certain pedestrian share, total risk decreases monotonically, reflecting nontrivial interactions among evacuee type, network usage, and congestion dynamics. The observed nonlinear relationship between evacuee composition and evacuation risk underscores the dominant influence of intermodal interactions rather than evacuee type in isolation. Although pedestrians are individually more exposed due to lower travel speeds and longer evacuation times, mixed pedestrian-vehicle scenarios incur higher aggregate risk because of interference and congestion on shared road segments. This interaction-driven mechanism explains why extreme scenarios outperform mixed cases, with the all-pedestrian configuration benefiting from the elimination of vehicular bottlenecks and exclusive reliance on vertically oriented sheltering.

Figures 5a and 5b illustrate spatial flows in the Base Case, revealing how evacuee type shapes network utilization and congestion hotspots. As shown in Figure 1, the number of vertical shelters remains stable (46–48) across scenarios under the fixed budget, with slight increases driven by pedestrian demand, since only vertical

shelters serve them. Even with low pedestrian proportions, their dispersed origins necessitate multiple shelters across the network.



(a) Pedestrian flow



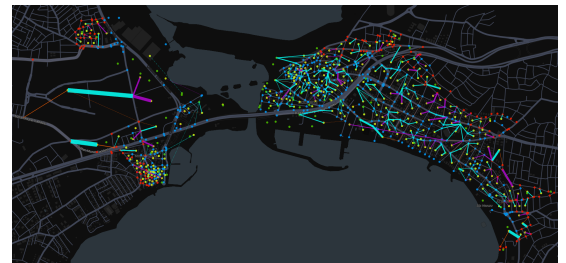
(b) Vehicle flow

Figure 5. Pedestrian and Vehicle Flows in the network for the base case scenario. Darker arcs indicate higher flow.

A critical finding concerns the role of mixed arcs, road segments used by both pedestrians and vehicles, which act as congestion hotspots. Figures 6a and 6b illustrate arc usage by evacuee type in Scenarios 30P and 70P, respectively. In Scenario 30P, vehicle-only arcs dominate, whereas pedestrian-only arcs prevail in Scenario 70P. Mixed arcs remain limited in number and are typically located in densely populated areas or near the network periphery, where modal interactions are most pronounced. Their spatial concentration highlights the importance of targeted congestion mitigation in evacuation planning. Despite substantial variation in evacuee composition across scenarios, the number of activated vertical shelters remains nearly unchanged. This indicates that shelter placement is driven primarily by spatial coverage and accessibility requirements rather than aggregate demand levels. Even scenarios with low pedestrian shares require multiple vertical shelters to ensure feasible access for geographically dispersed pedestrian origins.



(a) Scenario 30P



(b) Scenario 70P

Figure 6. Arc usage by evacuee type in Scenarios 30P and 70P. Blue: pedestrian-only, orange: vehicle-only, purple: mixed usage. Thicker arcs indicate higher flow.

Despite the presence of mixed demand, evacuation performance remains robust: approximately 95% of arcs are exclusively used by one evacuee type across all scenarios. Of the remaining arcs, 116 experience congestion in only one scenario, and just 28 in two scenarios. Notably, all congested arcs originate from evacuation zone nodes, confirming that primary bottlenecks arise at the origin points. This also reflects the model's inherent capacity to separate pedestrian and vehicle flows to minimize interactions and congestion.

5. Conclusion

This study develops a comprehensive, risk-aware tsunami evacuation model tailored to İstanbul's urban context, integrating mixed pedestrian–vehicle dynamics, vertical and horizontal shelter structures, congestion effects, and mode-specific road designations. By minimizing total evacuation risk rather than travel time alone, the model supports safer evacuation planning under stringent time constraints and resource limitations.

Applied to the tsunami-prone Büyükçekmece district, the model demonstrates that strategically placed vertical shelters significantly enhance performance, especially for pedestrians with limited mobility, by reducing both risk and congestion. Budget analyses reveal diminishing returns beyond certain investment thresholds, while mixed-mode scenarios increase congestion due to shared road interactions, reinforcing the value of spatial and modal segregation. Network-level results highlight the effectiveness of pedestrian-only and vehicle-only routes, with shelter allocation driven primarily by spatial accessibility rather than demand volume.

For policymakers, the model offers a practical decision-support tool that can guide predisaster investment in vertical shelters and the design of mode-specific evacuation corridors. Its risk-based orientation provides a more resilient alternative to traditional time-focused evacuation strategies.

The modeling and solution framework presented in this study can be extended in several directions. Incorporating uncertainty in evacuation demand and road network availability, arising from earthquake-induced debris or partial infrastructure failure, would support robust or stochastic variants of the model. Integrating behavioral factors, such as partial compliance with evacuation directives, would enhance realism in demand estimation and route choice. Addressing these extensions will likely require more advanced optimization approaches, including decomposition methods, hyperheuristics, polyploid or island-based metaheuristics, and other adaptive search techniques that have demonstrated effectiveness in complex decision environments [47, 48]. These enhancements represent promising avenues for future research.

6. Author contributions

Vedat Bayram (Conceptualization: lead; formal analysis: lead; funding acquisition: lead; investigation: lead; methodology: lead; project administration: lead; resources: lead; supervision: lead; validation: lead; writing–original draft: equal; writing–review & editing: lead). Doruk Ergez (Software: lead; visualization: lead; writing–original draft: supporting). Ada Arikanoglu (Data curation: equal; software: supporting; writing–original draft: equal)

Acknowledgment/disclaimers/conflict of interest

The authors thank the Scientific and Technological Research Council of Türkiye (TÜBİTAK) who provided financial support for this work (ARDEB 1001 Grant No: 221M165).

References

- [1] McKnight DS, Macdonald JA, Pelton J, Kunstadter C, Martinez P, Arora R, Jenniges JV. The global risk continuum (GRC). *Journal of Space Safety Engineering* 2020; 7 (1): 38–43. <https://doi.org/10.1016/j.jsse.2020.01.002>.
- [2] Maly E, Suppasri A. The Sendai framework for disaster risk reduction at five: Lessons from the 2011 Great East Japan earthquake and tsunami. *International Journal of Disaster Risk Science* 2020; 11 (2): 167–178. <https://doi.org/10.1007/s13753-020-00268-9>.

- [3] Bayram V. Optimization models for large scale network evacuation planning and management: A literature review. *Surveys in Operations Research and Management Science* 2016; 21 (2): 63–84. <https://doi.org/10.1016/j.sorms.2016.11.001>.
- [4] Thompson RR, Garfin DR, Silver RC. Evacuation from natural disasters: a systematic review of the literature. *Risk Analysis* 2017; 37 (4): 812–839. <https://doi.org/10.1111/risa.12654>.
- [5] Scheer S, Gardi A, Guillaude R, Eftichidis G, Varela V, de Vanssay B, Colbeau-Justin L. Handbook of Tsunami Evacuation Planning. Publications Office of the European Union 2011. <https://doi.org/10.2788/34292>.
- [6] Amideo AE, Scaparra MP, Kotiadis K. Optimising shelter location and evacuation routing operations: The critical issues. *European Journal of Operational Research* 2019; 279 (2): 279–295. <https://doi.org/10.1016/j.ejor.2018.12.009>.
- [7] Chen X, Zhan FB. Agent-based modelling and simulation of urban evacuation: relative effectiveness of simultaneous and staged evacuation strategies. *Journal of the Operational Research Society* 2008; 59 (1): 25–33. <https://doi.org/10.1057/palgrave.jors.2602330>.
- [8] Di Mauro M, Megawati K, Cedillos V, Tucker B. Tsunami risk reduction for densely populated Southeast Asian cities: analysis of vehicular and pedestrian evacuation for the city of Padang, Indonesia, and assessment of interventions. *Natural Hazards* 2013; 68: 373–404. <https://doi.org/10.1007/s11069-013-0632-z>.
- [9] Flores C, Lee HS, Mas E. Understanding Tsunami Evacuation via a Social Force Model While Considering Stress Levels Using Agent-Based Modelling. *Sustainability* 2024; 16 (10): 4307. <https://doi.org/10.3390/su16104307>.
- [10] Hadas Y, Laor A. Network design model with evacuation constraints. *Transportation Research Part A: Policy and Practice* 2013; 47: 1–9. <https://doi.org/10.1016/j.tra.2012.10.027>.
- [11] Horiai S, Okumura M, Sato K. The necessity of macroscopic directional guidance in pedestrian tsunami evacuation: a zonal MFD-based optimization approach. *Frontiers in Physics* 2025; 13: 1644312. <https://doi.org/10.3389/fphy.2025.1644312>.
- [12] Ishaque MM, Noland RB. Trade-offs between vehicular and pedestrian traffic using micro-simulation methods. *Transport Policy* 2007; 14 (2): 124–138. <https://doi.org/10.1016/j.tranpol.2006.09.001>.
- [13] Konstantinidou MA, Kepaptsoglou KL, Karlaftis MG, Stathopoulos A. Joint evacuation and emergency traffic management model with consideration of emergency response needs. *Transportation Research Record* 2015; 2532 (1): 107–117. <https://doi.org/10.3141/2532-12>.
- [14] Moslemi S, Bayram V, Yildiz B. Behaviorally Informed Planning for Retrofitting, Sheltering, and Mixed-Mode Evacuation in Urban Tsunami Preparedness: Toward a Tsunami-Resilient Istanbul. Available at Optimization Online 2025. <https://optimization-online.org/?p=32332>.
- [15] Moslemi S, Bayram V, Yildiz B, Murray-Tuite PM. Multi-Modal Tsunami Evacuation Zoning and Corridor Management for Mixed Traffic Control: Istanbul Case Study. Available at SSRN 5323721 2025. <https://doi.org/10.2139/ssrn.5323721>.
- [16] Park S, van de Lindt JW, Gupta R, Cox D. Method to determine the locations of tsunami vertical evacuation shelters. *Natural Hazards* 2012; 63 (2): 891–908. <https://doi.org/10.1007/s11069-012-0196-3>.
- [17] Tuydes H, Ziliaskopoulos A. Tabu-based heuristic approach for optimization of network evacuation contraflow. *Transportation Research Record* 2006; 1964 (1): 157–168. <https://doi.org/10.3141/1964-18>.
- [18] Wan S, Chen Z, Dong J. An efficiency-based interactive dynamic technique with interval-valued hesitant fuzzy constraint cone for rescue route planning. *Expert Systems with Applications* 2023; 231: 120648. <https://doi.org/10.1016/j.eswa.2023.120648>.
- [19] Wan SP, Chen ZH, Dong JY. Bi-objective trapezoidal fuzzy mixed integer linear program-based distribution center location decision for large-scale emergencies. *Applied Soft Computing* 2021; 110: 107757. <https://doi.org/10.1016/j.asoc.2021.107757>.

- [20] Wang H, Mostafizi A, Cramer LA, Cox D, Park H. An agent-based model of a multimodal near-field tsunami evacuation: Decision-making and life safety. *Transportation Research Part C: Emerging Technologies* 2016; 64: 86–100. <https://doi.org/10.1016/j.trc.2015.11.010>.
- [21] Wood N, Jones J, Schelling J, Schmidtlein M. Tsunami vertical-evacuation planning in the U.S. Pacific Northwest as a geospatial, multi-criteria decision problem. *International Journal of Disaster Risk Reduction* 2014; 9: 68–83. <https://doi.org/10.1016/j.ijdr.2014.04.009>.
- [22] Xie C, Turnquist MA. Lane-based evacuation network optimization: An integrated Lagrangian relaxation and tabu search approach. *Transportation Research Part C: Emerging Technologies* 2011; 19 (1): 40–63. <https://doi.org/10.1016/j.trc.2010.03.003>.
- [23] Yang G, Zhou T, Peng M, Wang Z, Wang D. Synergy of Road Network Planning Indices on Central Retail District Pedestrian Evacuation Efficiency. *ISPRS International Journal of Geo-Information* 2023; 12 (6): 239. <https://doi.org/10.3390/ijgi12060239>.
- [24] Zhang X, Chang GL. The multi-modal evacuation system (MES) for Baltimore metropolitan region. In: 2012 15th International IEEE Conference on Intelligent Transportation Systems, IEEE 2012; 1250–1257. <https://doi.org/10.1109/ITSC.2012.6338592>.
- [25] Zhang Z, Fei Y, Fu D. A Deep Reinforcement Learning Traffic Control Model for Pedestrian and Vehicle Evacuation in the Parking Lot. *Physica A: Statistical Mechanics and its Applications* 2024; 646: 129876. <https://doi.org/10.1016/j.physa.2024.129876>.
- [26] Suppasri A, Shuto N, Imamura F, Koshimura S, Mas E, Calciner AC. Lessons learned from the 2011 Great East Japan tsunami: performance of tsunami countermeasures, coastal buildings, and tsunami evacuation in Japan. *Pure and Applied Geophysics* 2013; 170 (6-8): 993–1018. <https://doi.org/10.1007/s00024-012-0511-7>.
- [27] Lindell MK. Planning for flood evacuation: analysis, modeling and management. In: *Research Handbook on Flood Risk Management*, Edward Elgar Publishing 2024; 226–238. <https://doi.org/10.4337/9781839102981.00025>.
- [28] Lindell MK, Murray-Tuite P, Wolshon B, Baker EJ. Large-scale evacuation: The analysis, modeling, and management of emergency relocation from hazardous areas. CRC Press 2018. <https://doi.org/10.4324/9781315119045>.
- [29] Zhang X, Chang GL. A dynamic evacuation model for pedestrian–vehicle mixed-flow networks. *Transportation Research Part C: Emerging Technologies* 2014; 40: 75–92. <https://doi.org/10.1016/j.trc.2014.01.003>.
- [30] Moslemi S, Dogulu C, Bayram V, Yildiz B. Survey-Based Statistical and Predictive Modeling of Decision-Making and Compliance Behavior in Tsunami Evacuation: The Istanbul Case. Available at SSRN 2025. <https://doi.org/10.2139/ssrn.5924904>.
- [31] Pel AJ, Bliemer MCJ, Hoogendoorn SP. A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation* 2012; 39: 97–123. <https://doi.org/10.1007/s11116-011-9320-6>.
- [32] Sheffi Y, Mahmassani H, Powell WB. A transportation network evacuation model. *Transportation Research Part A: General* 1982; 16 (3): 209–218. [https://doi.org/10.1016/0191-2607\(82\)90013-X](https://doi.org/10.1016/0191-2607(82)90013-X).
- [33] U.S. Department of Commerce, Bureau of Public Roads. Traffic Assignment Manual for Application with a Large, High-Speed Computer. U.S. Department of Commerce, Bureau of Public Roads, Office of Planning, Urban Planning Division 1964. <https://books.google.com.tr/books?id=gkNZAAAAMAAJ>.
- [34] Nesterov Y, Nemirovskii AS, Ye Y. Interior-point polynomial algorithms in convex programming. SIAM 1994. <https://doi.org/10.1137/1.9781611970791>.
- [35] Ben-Tal A, Nemirovski A. Lectures on modern convex optimization: Analysis, algorithms, and engineering applications. MPS-SIAM Series on Optimization, SIAM 2001. <https://doi.org/10.1137/1.9780898718829>.
- [36] Alizadeh F, Goldfarb D. Second-order cone programming. *Mathematical Programming* 2003; 95 (1): 3–51. <https://doi.org/10.1007/s10107-002-0339-5>.

- [37] Lobo MS, Vandenberghe L, Boyd S, Lebret H. Applications of second-order cone programming. *Linear Algebra and Its Applications* 1998; 284 (1-3): 193–228. [https://doi.org/10.1016/S0024-3795\(98\)10032-0](https://doi.org/10.1016/S0024-3795(98)10032-0).
- [38] Bonami P, Lejeune MA. An exact solution approach for portfolio optimization problems under stochastic and integer constraints. *Operations Research* 2009; 57 (3): 650–670. <https://doi.org/10.1287/opre.1080.0599>.
- [39] Taylor JA, Hover FS. Convex models of distribution system reconfiguration. *IEEE Transactions on Power Systems* 2012; 27 (3): 1407–1413. <https://doi.org/10.1109/TPWRS.2012.2184307>.
- [40] Atamtürk A, Berenguer G, Shen ZJ. A conic integer programming approach to stochastic joint location-inventory problems. *Operations Research* 2012; 60 (2): 366–381. <https://doi.org/10.1287/opre.1110.1037>.
- [41] Sun X, Zhang B, Chai R, Tsourdos A, Chai S. UAV trajectory optimization using chance-constrained second-order cone programming. *Aerospace Science and Technology* 2022; 121: 107283. <https://doi.org/10.1016/j.ast.2021.107283>.
- [42] Chuong TD. Second-order cone programming relaxations for a class of multiobjective convex polynomial problems. *Annals of Operations Research* 2022; 311 (2): 1017–1033. <https://doi.org/10.1007/s10479-020-03577-w>.
- [43] Bayram V. An exact second order cone programming approach for traffic assignment problems. *RAIRO-Operations Research* 2024; 58 (1): 847–864. <https://doi.org/10.1051/ro/2023172>.
- [44] Bayram V, Yaman H. Shelter location and evacuation route assignment under uncertainty: A Benders decomposition approach. *Transportation Science* 2018; 52 (2): 416–436. <https://doi.org/10.1287/trsc.2017.0762>.
- [45] Çankaya ZC, Süzen ML, Yalçiner AC, Kolat C, Zaytsev A, Aytöre B. A new GIS-based tsunami risk evaluation: MeTHuVA (METU tsunami human vulnerability assessment) at Yenikapi, Istanbul. *Earth, Planets and Space* 2016; 68 (1): 1–13. <https://doi.org/10.1186/s40623-016-0507-0>.
- [46] Tufekci D, Suzen ML, Yalciner AC, Zaytsev A Revised MeTHuVA method for assessment of tsunami human vulnerability of Bakirkoy district, Istanbul. *Natural Hazards* 2018; 90 (2): 943–974. <https://doi.org/10.1007/s11069-017-3082-1>.
- [47] Dulebenets MA. An Adaptive Polyploid Memetic Algorithm for scheduling trucks at a cross-docking terminal. *Information Sciences* 2021; 565: 390–421. <https://doi.org/10.1016/j.ins.2021.02.039>.
- [48] Li B, Afkhami P, Khayamim R, Borowska-Stefańska M, Wiśniewski S, Fathollahi-Fard AM, Ozkul S, Dulebenets MA. An intelligent hyperheuristic algorithm for the berth allocation and scheduling problem at marine container terminals. *Transportation Research Part E: Logistics and Transportation Review* 2025; 198: 104104. <https://doi.org/10.1016/j.tre.2025.104104>.
- [49] Helbing D, Molnár P. Social force model for pedestrian dynamics. *Physical Review E* 1995; 51 (5): 4282–4286. <https://doi.org/10.1103/PhysRevE.51.4282>.
- [50] Wilmot CG, Meduri N. Methodology to establish hurricane evacuation zones. *Transportation Research Record* 2005; 1922 (1): 129–137. <https://doi.org/10.1177/0361198105192200117>.
- [51] Lim GJ, Zangeneh S, Kim SJ. Clustering approach for defining hurricane evacuation zones. *Journal of Urban Planning and Development* 2016; 142 (4): 04016008. [https://doi.org/10.1061/\(ASCE\)UP.1943-5444.0000323](https://doi.org/10.1061/(ASCE)UP.1943-5444.0000323).

Appendix

A. Notation Used

Table S1. Description of the notation used.

Sets	
A	Set of all road segments
A^p	Set of potential pedestrian road segments ($A^p \subset A$)
A^v	Set of potential vehicle road segments ($A^v \subset A$)
N	Set of nodes
O	Set of evacuation zones
V	Set of vertical shelters ($V \subset N$)
E	Set of horizontal shelters ($E \subset N$)
V'_o	Set of vertical shelters accessible from source node o
E'_o	Set of horizontal shelters accessible from source node o
L	Set of vehicle speed levels
Parameters	
t_a^p	Travel time of pedestrians on road segment $a \in A^p$
t_a^{vl0}	Free flow travel time of a vehicle with speed level $l \in L$ on road segment $a \in A^v$
t_a^{vl}	Congestion adjusted travel time of a vehicle with speed level $l \in L$ on road segment $a \in A^v$
c_a^v	Saturation rate (capacity) of road segment $a \in A^v$ for vehicles
c_a^p	Pedestrian capacity of road segment $a \in A^p$
r_a	Risk level of road segment $a \in A$
$\delta(i)^+$	Outgoing road segments from node $i \in N$
$\delta(i)^-$	Incoming road segments to node $i \in N$
D^p	Total pedestrian demand
D^v	Total vehicle demand
d_o^p	Pedestrian demand originating from evacuation zone $o \in O$
s_e	Super exit node
s_o	Super origin node
Q_v	Capacity of vertical shelter $v \in V$
$\bar{Q}_v$	Theoretical upperbound on the additional capacity for vertical shelter $v \in V$
h_v	Cost of constructing/retrofitting vertical shelter $v \in V$
P	Penalty of increasing vertical shelter's capacity
B	Total budget of opening a vertical shelter
α	BPR function parameter
β	BPR function parameter
Decision Variables	
f_a^{op}	Pedestrian flows on road segment $a \in A^p$ originating from evacuation zone $o \in O$
f_a^{ovl}	Vehicular flows on road segment $a \in A^v$ originating from evacuation zone $o \in O$ using speed level l
f_a^{vl}	Total Vehicular flow on road segment $a \in A^v$ using speed level l
x_{ov}	Binary decision variable indicating whether there is an assignment from an evacuation zone $o \in O$ to vertical shelter $v \in V$
u_a^{ov}	Binary decision variable indicating whether road segment $a \in A^v$ is used by vehicles from an evacuation zone $o \in O$
u_a^v	Binary decision variable indicating whether road segment $a \in A^v$ is used by vehicles
u_a^{op}	Binary decision variable indicating whether road segment $a \in A^p$ is used by pedestrians originating from evacuation zone $o \in O$
u_a^p	Binary decision variable indicating whether road segment $a \in A^p$ is used by pedestrians
y_v	Binary decision variable indicating whether vertical shelter $v \in V$ is opened
z_a^l	Binary decision variable indicating whether speed level $l \in L$ is used on road segment $a \in A$
q_v	Decision on extra capacity usage of vertical shelter $v \in V$

B. Data

We refer the reader to Bayram et al. (2025)¹⁸ and Moslemi et al. [14, 15] for more details on the data prepared.

B.1. Disaster Context and Study Area: Büyükçekmece, Istanbul

The Istanbul Tsunami Action Plan,⁹ developed jointly by the Istanbul Metropolitan Municipality (IMM) and Middle East Technical University (METU), addresses the city's acute vulnerability to tsunamis triggered by seismic activity or submarine landslides. This plan builds upon earlier initiatives such as the IMM-JICA disaster prevention and mitigation project,²¹ launched in the aftermath of the 1999 Marmara earthquake, a catastrophic event that devastated Sakarya, Izmit, and Yalova and exposed critical gaps in Istanbul's preparedness for both primary and secondary hazards. The IMM-JICA technical report underscored the urgent need for a comprehensive emergency evacuation system, particularly to mitigate fatalities arising from cascading events like tsunamis, floods, and fires.

Hydrodynamic simulations conducted as part of the Istanbul Tsunami Action Plan reveal that tsunami waves could strike Istanbul's coastline within 10 minutes of an initiating earthquake, with maximum inundation occurring 60 to 90 minutes later in districts such as the Islands and Eastern Marmara.^{9,22} These narrow time windows demand optimized and coordinated evacuation operations. Accordingly, the plan outlines a comprehensive resilience strategy, including the development of tsunami-resistant vertical shelters, deployment of early warning systems, designation of high-capacity evacuation routes, enhancement of public awareness campaigns, and retrofitting of critical infrastructure. The current case study is designed in alignment with these priorities, focusing on a tsunami-driven emergency evacuation scenario to evaluate the effectiveness of the proposed evacuation model under real-world constraints.

The case study focuses on the Büyükçekmece District, situated on the European side of Istanbul, Türkiye, along the Marmara Sea coastline. This region was selected as a pilot area due to its high tsunami exposure, significant evacuation complexity, and large at-risk population. According to TUIK,¹⁷ Büyükçekmece has a population of 269,160 and encompasses one of the largest anticipated inundation zones in Istanbul, characterized by considerable flow depths. Figure S1 provides visual context using Google Maps imagery: the left panel locates Büyükçekmece within the broader Istanbul area, while the right panel shows a close-up of the tsunami hazard zone described by the municipality. The inundation area comprises six densely populated neighborhoods identified as high-risk due to their susceptibility to flooding. Insights derived from this study are intended to support evacuation planning efforts across similarly vulnerable coastal districts.

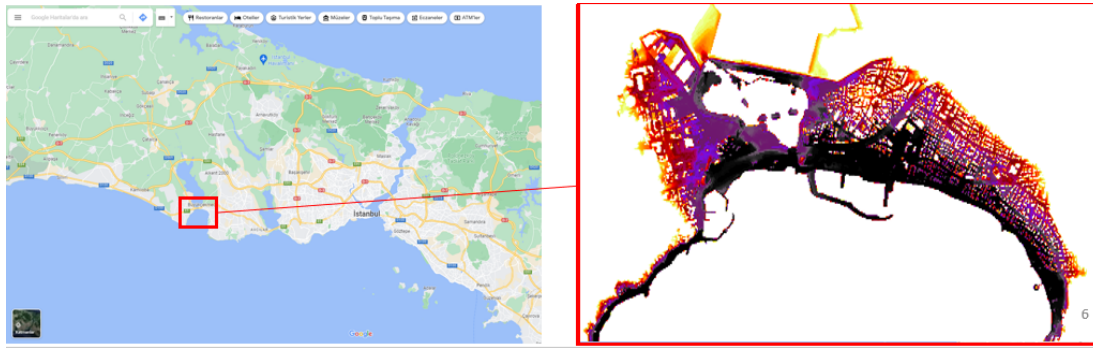


Figure S1. Büyükçekmece Region²³ and Tsunami Inundation Map⁹

²¹Istanbul Metropolitan Municipality and Japan International Cooperation Agency (2022).The study on a disaster prevention/mitigation basic plan in istanbul including seismic microzonation in the republic of turkey [online]. Website <https://openjicareport.jica.go.jp/pdf/11707825.pdf> [accessed 27 December 2024].

²²Ocal, N. (2018). Tsunami bilgi notu. Bogazici University, Kandilli Observatory and Earthquake Research Institute, Website http://www.koeri.boun.edu.tr/sismo/2/wp-content/uploads/2015/05/BDTIM_Tsunami_Subat_2018.pdf [accessed 27 December 2024].

B.1.1. Risk Data

Tsunami risk in the evacuation model is calculated at the coordinate level, encompassing evacuation zones, road segments, intersection points, and vertical shelters. This static risk assessment, determined prior to an event, supports strategic evacuation planning by identifying locations of heightened exposure and fragility. The required data were generated using the NAMÍ DANCE tsunami simulation software [45], which accurately models wave generation, propagation, and coastal impact.

Risk values at each coordinate are computed using a formulation adapted from the MeTHuVA methodology [45, 46], which defines risk r as a product of hazard and vulnerability components:

$$r = \left[\frac{VL}{EE \times n} \right] \times H$$

In this equation, H denotes the hazard level obtained from simulations; VL represents local vulnerability; and EE is the evacuation elasticity. The parameter n reflects community preparedness and awareness, ranging from 1 (low preparedness) to 10 (high preparedness). This formulation allows dynamic risk quantification across all spatial elements of the evacuation network.

The hazard data underlying these calculations are scenario-dependent and incorporate key earthquake and tsunami generation parameters such as fault location, magnitude, rupture length, and the potential for submarine landslides. Specifically, 14 tsunami scenarios were analyzed in the⁹ report (see Table S2). Scenario 13, which models a submarine landslide near the Büyükçekmece coast, was selected as the worst-case scenario due to its severe inundation footprint and rapid wave arrival times.

No	Tsunami Scenario	Description
1	PI	Princes' Islands Fault (Oblique/Reverse/Normal)
2	PIN	Princes' Islands Fault (Normal)
3	GA	Ganos Fault (Oblique/Reverse/Normal and Reverse)
4	PI+GA	Princes' Islands Fault (Oblique/Reverse/Normal) and Ganos Fault
5	YAN	Yalova Fault (Oblique/Reverse/Normal and Normal)
6	YM	Central Marmara Fault (Normal)
7	SN06	Marsite Project Tsunami Source (Scenario 06)
8	SN08	Marsite Project Tsunami Source (Scenario 08)
9	SN10	Marsite Project Tsunami Source (Scenario 10)
10	SN23	Marsite Project Tsunami Source (Scenario 23)
11	SN29-30	Marsite Project Tsunami Source (Scenario 29-30)
12	LSY	Submarine Landslide Source (Yenikapı Offshore)
13	LSBC	Submarine Landslide Source (Büyükçekmece Offshore)
14	LST	Submarine Landslide Source (Tuzla Offshore)

Table S2. Tsunami Scenarios and Descriptions

Using this scenario, spatiotemporal risk distributions are mapped across the transportation and shelter network. Outputs from NAMÍ DANCE simulations provide critical parameters including wave arrival times, inundation extents, water depths, flow velocities, and momentum forces. These outputs, combined with vulnerability and preparedness indicators, enable a detailed and spatially resolved risk assessment essential for optimizing evacuation strategies.

²³Google (2025).Google Maps [online]. Website <https://www.google.com/maps> [accessed 23 December 2024].

B.1.2. Road Network Data

The Büyükçekmece study area comprises a high-risk coastal zone consisting of six neighborhoods. The road network for this area was extracted from OpenStreetMap¹⁶ an open-source geospatial database. The resulting network includes 964 nodes and 3,635 arcs. Nodes represent evacuation zones (origins), vertical shelters, safe horizontal shelters (exits), and road intersections. Specifically, the network comprises 275 evacuation zones, 93 vertical shelters, 185 horizontal shelters, and 411 intersection nodes. The spatial distribution of these nodes is visualized in Figure S2, where yellow dots denote origins, green dots represent vertical shelters, red dots indicate horizontal shelters, and blue dots show intersections. The map was generated using ArcMap.

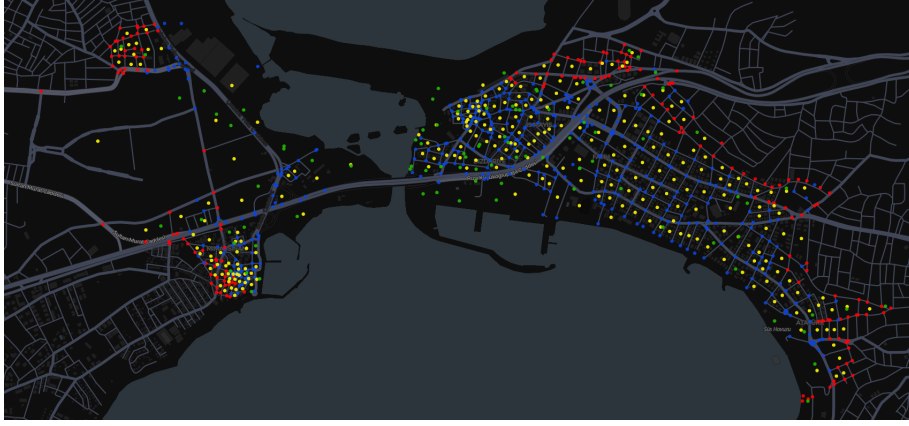


Figure S2. Büyükçekmece Road Network

The arcs are categorized into two types: pedestrian-only arcs (A^p), where vehicle access is prohibited (81 arcs), and mixed-use arcs (A^v), accessible to both pedestrians and vehicles. Mixing of traffic elevates congestion and associated risk. To account for the increased congestion and safety concerns on shared roads, vehicle speeds are categorized into two levels: Level 1 for vehicle-only roads operating at standard speed limits, and Level 2 for mixed-use roads (shared with pedestrians), where vehicle speeds are systematically reduced by 50% to reflect the presence of pedestrian traffic.

Arc-level attributes such as the number of lanes were derived from OpenStreetMap¹⁶ and used to determine capacity. For vehicular traffic, a per-lane capacity (flow rate) of 900 vehicles is assumed. Pedestrian arc capacity (c_a^p) is computed by assuming one person per square meter of usable width. Road segments are further classified into three categories based on functional class and speed limits: local streets (50 km/h), arterial roads (110 km/h), and freeways (130 km/h).²⁴ Pedestrian speed is assumed to be 4 km/h, consistent with values in the literature [49]. Given arc lengths and speed values, travel times for both pedestrians (t_a^p) and vehicles ($t_a^{v|0}$) are computed as the ratio of arc length to speed.

²⁴KGM (2025). Türkiye’de araçların uyması gereken yasal hız sınırları [online]. Website <https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Trafik/HizSinirlari.aspx> [accessed 21 May 2024].

Some road segments and associated shelters may become inundated before evacuees arrive, rendering them inaccessible. Thus, for each evacuation zone, we determine the subset of reachable shelters denoted by V'_o and E'_o that can be safely accessed before wave arrival. Shelter assignments are restricted to this subset, ensuring that evacuees are not exposed to tsunami impact en route.

Finally, each arc is associated with a static tsunami risk value (r_a), calculated based on outputs from the NAMI DANCE tsunami simulation model. This risk value is integrated into the model to support risk-aware evacuation planning.

B.1.3. Vertical and Horizontal Shelter Locations and Vertical Shelter Capacities

The dataset incorporates both vertical and horizontal shelters to support evacuation planning under tsunami risk. Vertical shelters ($v \in V$) include structurally resilient facilities, such as government buildings, educational institutions, hospitals, and municipal service centers, capable of accommodating evacuees above the expected inundation levels. These shelters are classified into two categories: (i) existing buildings, which require structural assessment and, where necessary, retrofitting to withstand tsunami loads; and (ii) prospective new constructions on available open areas, including parks and vacant lots. In the Büyükçekmece region, a total of 93 vertical shelter locations have been identified. Among these, 42 correspond to existing buildings, while the remaining 51 are unoccupied land parcels designated as candidate sites for new shelter construction.

The capacity of each vertical shelter is determined by excluding floors projected to be submerged based on tsunami inundation levels calculated using the MeTHuVA risk assessment methodology. Only the floors situated above the estimated wave height are considered usable, and shelter capacity is computed based on the available area on these safe levels.

Horizontal shelters are defined as road intersection points located just outside the inundation zone boundary. These serve as exit points from the at-risk area, with the objective of ensuring evacuees reach these safe zones before the arrival of tsunami waves.

B.1.4. Evacuation Zones and Demand Data

Evacuation origin nodes ($o \in O$) represent the starting points of evacuation and are located at the geometric centers of predefined evacuation zones. These zones are defined as rectangular blocks bounded by intersecting streets, consistent with methodologies used by Wilmot and Meduri [50] and Lim et al. [51], who partitioned urban areas into smaller subregions based on major road networks or evacuation corridors.

Population demand data for each evacuation zone were estimated using a multi-step process. First, the total number of buildings in each of the six neighborhoods was obtained from the Istanbul Metropolitan Municipality database.²⁵ Population figures were sourced from the 2021 address-based population census.¹⁷ For each neighborhood, the average population per building was computed by dividing the total population by the number of buildings.

To assign population to each evacuation zone, building counts were manually verified using high-resolution satellite and street imagery from Google Maps²⁶ and Yandex Maps.²⁷ The number of buildings within each zone was then multiplied by the average population per building to estimate the evacuee demand. This process resulted in a total of 39,180 individuals identified for evacuation from the high-risk coastal area of Büyükçekmece.

²⁵Istanbul Metropolitan Municipality Database(2023).Istanbul Metropolitan Municipality [online]. Website <https://data.ibb.gov.tr/en/> [accessed 12 April 2024].

²⁶Google (2025).Google Maps [online]. Website <https://www.google.com/maps> [accessed 17 April 2024].

²⁷Yandex (2025).Yandex Maps [online]. Website <https://www.yandex.com/maps> [accessed 21 April 2024].

B.1.5. Cost Data

The cost parameters for reinforcing existing vertical shelters and constructing new ones were derived from 2023 unit rates published in the Official Gazette of the Republic of Türkiye.²⁸ The reinforcement cost per unit area was set at 7,500 TL/m², while relocation and temporary accommodation costs were set at 6,000 TL per household and 85 TL/m², respectively. These unit costs were incorporated into the model's budget framework to evaluate various reinforcement strategies for existing buildings.

To address shelter capacity deficiencies within the six neighborhoods and their sub-regions, additional candidate locations for vertical shelters were identified. Priority was given to publicly owned open spaces, such as parks, vacant land, and parking areas, to avoid complications related to land acquisition. The construction cost for new tsunami-resilient vertical shelters was set at 22,500 TL/m², and this figure was also included in the model's cost structure.

The full budget was defined as the total cost required to reinforce all existing shelter candidates and to construct new vertical shelters at all feasible locations. To establish an appropriate upper bound for the budget parameter, a sensitivity analysis was performed. The model was initially solved under the full budget condition, enabling unrestricted selection of shelter locations. In this scenario, 59 out of the 93 candidate shelters were selected to accommodate evacuees. The cumulative cost of these 59 shelters was then designated as the calibrated maximum budget for subsequent analyses. This value served as a realistic upper limit for generating a range of constrained budget scenarios, allowing systematic evaluation of trade-offs in the allocation of financial resources across shelter options.

C. Abbreviations Used

Table S3. The abbreviations used in the paper and the corresponding long-form explanations.

AFAD	Disaster and Emergency Management Presidency
BPR	Bureau of Public Roads
EC	European Commission
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
IMM	Istanbul Metropolitan Municipality
JICA	Japan International Cooperation Agency
LP	Linear Programming
METU	Middle East Technical University
MISOCP	Mixed-Integer Second-Order Cone Programming
NCIP	Non-linear Convex Integer Programming
QP	Quadratic Programming
TUIK	Turkish Statistical Institute
UN	United Nations
US	United States

²⁸Official Gazette (2023).Design supervision and control of special buildings amendment in the regulation of services regulation on its construction [online]. Website <https://www.resmigazete.gov.tr/eskiler/2023/12/20231201.pdf>.