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HARMONIZATION OF ADR, RID, AND IMDG REGULATIONS FOR TRANSIT COUNTRIES: AN AZERBAIJAN CASE STUDY

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Resume

In this simulation-based study, a multi-objective mixed-integer linear programming (MOMILP) model is developed for selecting transport modes and modal transfers for hazardous materials (HazMat) along a rail-truck-ferry route of the Middle Corridor, balancing cost, delivery time, and safety risk. The model includes the Caspian ferry crossing, border and ferry waiting times, disruption-adjusted ferry capacity, and hazard-class admissibility under ADR, RID, and the IMDG Code. In an illustrative Khorgos-Vienna case with 32 mode combinations, seven alternatives are non-dominated; the all-rail route minimizes cost and risk at the expense of about 31 h of extra transit time and remains the weighted-sum optimum for every risk weight when cost and time are weighted equally. The Tbilisi-Kars rail link caps throughput until ferry availability falls below about 83%. As the parameters are illustrative, the results are scenario-based insights.

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1 Introduction

The transportation of dangerous goods (DG) is one of the most safety-critical components of global logistics, since a single accident can have catastrophic consequences for people, infrastructure, and the environment [1-2]. The growth of chemical, petrochemical, and fertilizer production in Central Asia and the Caspian basin has expanded the cross-border DG flows, and much of this volume must travel several thousand kilometres through several jurisdictions before reaching European markets. International rules - the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) [3], the Regulations concerning the International Carriage of Dangerous Goods by Rail (RID) [4], and the International Maritime Dangerous Goods (IMDG) Code for sea [5] - govern the classification, packaging, labeling, and carriage of hazardous substances. Although all the three build on the United Nations (UN) Model Regulations, they are developed and amended largely independently for each mode, and the actors responsible for DG transport operate under fragmented institutional and commercial arrangements, which complicates multimodal coordination [6].

In practice, the harmonization problem lies less in the substantive classification of substances, which is largely aligned, than in the points where the modal regimes meet. Documentation requirements, tunnel and route restrictions, segregation rules, approvals of packagings and cargo transport units, and permissible quantities differ between ADR, RID, and IMDG, so a consignment that is fully compliant on one leg may require re-documentation, re-marking, or even re-packing at a transfer terminal. Each such interface adds handling time, costs, and another opportunity for human error. For transit countries such as Azerbaijan and Georgia, located between a rail-dominated Central Asian network, a maritime crossing, and the road- and rail-served markets of Türkiye and Europe, these interfaces are concentrated on their own territory, which makes the efficiency and safety of transfer operations a matter of national transport policy.

Table 1 *Comparison of representative HazMat transportation studies and the proposed framework*

Study	Road	Rail	Maritime/ Ferry	Intermodal	Multi-country regulations	Border delay	Terminal capacity	Cost	Risk	Time
Abkowitz and Cheng [15]	✓	–	–	–	–	–	–	✓	✓	–
Jiang et al. [19]	✓	✓	–	✓	–	–	Partial	✓	–	–
Assadipour et al. [9]	✓	✓	–	✓	–	–	✓	✓	✓	–
Bhavsar et al. [10]	✓	✓	–	✓	–	–	Partial	✓	✓	–
Van Raemdonck et al. [20]	✓	✓	–	Partial	–	–	–	–	✓	–
Present study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

The road transport dominates DG movement and carries the higher accident probability; human factors, infrastructure deficiencies, and poor route selection are consistently identified in accident analyses as leading causes [7]. Rail has a lower accident frequency, but incidents can have larger consequences, particularly through the population exposure to airborne toxins [8]. This asymmetry has motivated rail-truck intermodal solutions that combine the safety and capacity of rail on long hauls with the flexibility of road for collection and delivery [9-10].

The Middle Corridor - the Trans-Caspian International Transport Route linking China, Central Asia, the South Caucasus, and Europe - has gained strategic importance as an alternative to the northern overland routes, and the goal of tripling its freight volumes and halving travel times by 2030 has been set in recent assessments [11-12]. Compared to the most studied corridors, it adds two complications. First, the Baku-Aktau and Baku-Turkmenbashi Caspian ferry lines require successive transshipments between the rail, road, and sea, whereas the IMDG Code was developed mainly for ocean shipping and does not specifically address short ferry crossings in an enclosed sea. Second, a single shipment crosses several jurisdictions - Kazakhstan, Azerbaijan, Georgia, and Türkiye - with differing national implementations of ADR and RID, Transports Internationaux Routiers (TIR) transit procedures, and land border crossings [13]. Existing risk and network-configuration studies are concentrated on corridors in China, Europe, and North America [7, 14], and modelling studies of DG transport along the Middle Corridor remain scarce.

In this study, that gap is addressed by formulating a multi-objective mixed-integer linear programming (MOMILP) model for selecting transport modes and modal transfers for hazardous materials (HazMat) along a fixed rail-truck-ferry corridor, minimizing cost, risk exposure, and transit time while enforcing capacity and regulatory admissibility. The contribution of the work is threefold: (i) ADR, RID, and IMDG requirements are translated into explicit admissibility constraints that link each hazard class to the arcs and modes on which it may travel; (ii) the Caspian ferry crossing, border-waiting time, and modal transfer costs are treated as first-order model components rather than exogenous adjustments; and (iii) the model is demonstrated on an illustrative, not yet validated, Khorgos-Vienna case, including a multi-commodity extension that shows how capacity and regulation interact. The related literature is reviewed in Section 2, the model is presented in Section 3, the numerical results are reported in Section 4, and the implications, limitations, and conclusions are discussed in Sections 5 and 6. The present study is positioned against representative HazMat transportation models in Table 1.

2 Literature review

Research on HazMat transportation risk originates in the risk/cost routing framework of Abkowitz and Cheng [15], in which the trade-off between the transport cost and population exposure that still underpins routing models was established. Multi-criteria and fuzzy methods have later been applied to bring expert judgment and uncertainty into route risk scoring - for example, in a Pythagorean fuzzy analytic hierarchy process (AHP) assessment of HazMat transport in Istanbul [16], a city that is itself a node on the corridor studied here. Strong but largely retrospective, mode-specific evidence on causation is provided by accident studies: the driver behaviour, vehicle condition, and route choice are identified as dominant factors in road surveys [7], and the frequency and typology of releases on both road and rail are documented in comparative surveys [14]. Population exposure to airborne toxins along rail lines has been modelled in rail-specific studies [8], and the spatial representation of risk on both modes has been improved by geographic information system (GIS)-based analyses [17]. Tunnel restrictions have received particular attention because

ADR assigns road tunnels to categories that prohibit specific hazard classes, which directly constrains route choice [18].

The studies closest to the present problem are intermodal. A multimodal location-routing model based on multi-commodity flows was proposed by Jiang et al. [19], capacity selection and congestion were incorporated into intermodal HazMat planning by Assadipour, Ke and Verma [9], and rail-truck intermodal transport of dangerous goods was addressed directly by Bhavsar, Hassini and Verma [10]. An integrated risk analysis system covering several risk dimensions was proposed by Van Raemdonck, Macharis and Mairesse [20]. Modal transfer decisions and infrastructure capacity are represented in these models, but a bimodal rail-road system operating under a single regulatory regime is assumed in all of them.

The stakeholder networks involved in the land transport of dangerous goods have been examined in governance-oriented work, and it has been shown that responsibilities for classification, documentation, loading, and inspection are dispersed across consignors, carriers, terminal operators, and authorities [6]. The growing methodological diversity of the field, from optimization and GIS to simulation and decision-support systems, as well as its concentration on road transport and single-country settings, has been documented in reviews [1-2]. The corridor-level literature, in turn, is dominated by institutional and economic assessments in which border delays, tariffs, and infrastructure bottlenecks are quantified without DG risk being treated explicitly [11, 12, 21]. In corridor performance monitoring in Central Asia, for example, average border-crossing times ranging from several hours to more than half a day are reported [21], which is material for hazardous cargo but rarely enters HazMat routing models. At the national level, it has been shown in a diagnostic assessment of Azerbaijan based on the Logistics Performance Index that, despite the substantial investment in transport infrastructure, soft-infrastructure constraints - logistics services, data integration, and inter-institutional coordination - continue to limit the use of the country's transit potential [22].

As can be seen in Table 1, the reviewed models are bimodal by construction and formulated within a single regulatory jurisdiction. A maritime ferry transshipment stage, cross-country regulatory heterogeneity, and endogenous border and terminal delay are not represented in any of them, and these features have not been combined in one network-configuration model. A recurring trade-off is thus displayed in the literature between analytical rigor and corridor-level scope: quantitative models are rigorous but narrow, while corridor studies are broad but largely qualitative with respect to safety. In the present study, this trade-off is addressed by embedding Caspian ferry transshipment, multi-jurisdictional admissibility, and border/terminal delay directly in a MOMILP structure.

3 Methodology

The methodology proceeds in five stages: (i) representation of the corridor as a directed multimodal network; (ii) formalization of shipments by origin, destination, quantity, and UN hazard class; (iii) estimation of arc-level costs, time, and risk parameters together with regulatory admissibility indicators; (iv) formulation and solution of the multi-objective mixed-integer linear programming (MOMILP) model; and (v) sensitivity and scenario analysis. This structure makes the trade-offs between economic efficiency and safety explicit and reproducible rather than relying on qualitative corridor comparison.

3.1 Network representation

The Middle Corridor is represented as a directed multimodal network

$$G = (N, A), \tag{1}$$

in which the nodes N are railway and road terminals, seaports, border crossings, and intermodal terminals, and the arcs A are transport links indexed by mode $m \in M = \{rail, road, sea\}$. Overland segments offer a rail/road choice and are represented by the two parallel arcs with distinct attributes, whereas the Aktau-Baku Caspian crossing has no overland alternative and is a single arc with m = sea; $M_{ij} \subseteq M$ denotes the modes available on arc (i, j), and decision variables exist only for $m \in M_{ij}$. Each shipment $k \in K$ has origin o_k, destination d_k, quantity q_k, and a UN hazard class; $B \subseteq N$ and $T \subseteq N$ are the border-crossing and transfer-terminal nodes.

Parameters. c_{ijm}, t_{ijm} and p_{ijm} are the unit cost, travel time and accident probability on arc (i, j) with mode m; s_{ij} is a consequence-severity coefficient; cap_{ijm} is the arc capacity; cc_i, ct_i and cr_i are the unit transfer cost, time and risk at terminal $i \in T$; τ_i is the expected border-waiting time at $i \in B$; and δ_{ijm}^{k} equals 1 if the hazard class of k is admissible on (i, j) with mode m under ADR, RID or IMDG rules.

Decision variables. $x_{ijm}^{k} \in \{0,1\}$ equals 1 if k uses arc (i, j) with mode m, and $y_i^{k} \in \{0,1\}$ equals 1 if k changes mode at terminal i.

3.2 Mathematical model formulation

The model minimizes three conflicting objectives: total logistics costs including transfer charges in Equation (2); total expected risk, where the risk of arc (i, j) under mode m is $R_{ijm} = p_{ijm} \cdot s_{ij}$ in Equation (3); and total time including transfer and border-waiting time in Equation (4).

$$\text{Min } Z_1 = \Sigma_{k\in K} \Sigma_{(i,j)\in A} \Sigma_{m\in M} c_{ijm} q_k x_{ijm}^k + \\ + \Sigma_{k\in K} \Sigma_{i\in T} cc_i q_k y_i^k, \quad (2)$$

$$\text{Min } Z_2 = \Sigma_{k\in K} \Sigma_{(i,j)\in A} \Sigma_{m\in M} R_{ijm} q_k x_{ijm}^k + \\ + \Sigma_{k\in K} \Sigma_{i\in T} cr_i q_k y_i^k, \quad (3)$$

$$\text{Min } Z_3 = \Sigma_{k\in K} \Sigma_{(i,j)\in A} \Sigma_{m\in M} t_{ijm} x_{ijm}^k + \\ + \Sigma_{k\in K} \Sigma_{i\in T} ct_i y_i^k + \Sigma_{k\in K} \Sigma_{i\in B} \tau_i \Sigma_{m\in M} \Sigma_{j:(j,i)\in A} x_{jim}^k. \quad (4)$$

When the waiting time before the Caspian crossing is modelled explicitly, the time objective in Equation (4) is extended by a ferry-waiting term:

$$Z'_3 = Z_3 + \Sigma_{k\in K} \Sigma_{(i,j)\in Asea} \omega_{ij} x_{ij,sea}^k, \quad (5)$$

where $A_{sea} \subset A$ is the set of ferry arcs and ω_{ij} is the expected waiting time for berth and vessel before the crossing, an assumed scenario parameter (Section 4.1, Table 3).

In Equation (4), τ_i is charged only when the route enters border node i. The constraints enforce flow conservation for all $k \in K$, $i \in N$ in Equation (6), arc capacity in Equation (7), regulatory admissibility in Equation (9), transfer activation in Equation (10), and integrality in Equation (11):

$$\Sigma_{m\in M} \Sigma_{j:(i,j)\in A} x_{ijm}^k - \Sigma_{m\in M} \Sigma_{j:(j,i)\in A} x_{jim}^k = \\ \{1,\ i = o_k;\ -1,\ i = d_k;\ 0,\ \text{otherwise}\}, \quad (6)$$

$$\Sigma_{k\in K} q_k x_{ijm}^k \le cap_{ijm} \forall\ (i, j) \in A,\ m \in M. \quad (7)$$

When the weather-related closures and vessel shortages on the Caspian crossing are considered, Equation (7) is replaced by the disruption-adjusted capacity constraint

$$\Sigma_{k\in K} q_k x_{ijm}^k \le a_{ijm} \cdot cap_{ijm} \forall\ (i, j) \in A,\ m \in M, \quad (8)$$

where $a_{ijm} = 1$ for rail and road and $a_{ij,sea} \in (0, 1)$ is the availability factor of the Caspian ferry, so that Equation (7) is a special case $a = 1$. A delivery-time limit $Z_3 \le T_{max}$ may also be added in scenario analysis.

$$x_{ijm}^k \le \delta_{ijm}^k \forall\ k \in K,\ (i, j) \in A,\ m \in M, \quad (9)$$

$$y_i^k \ge x_{jim}^k + x_{ilm'}^k - 1 \qquad \forall\ k \in K,\ i \in T,\ m \ne m', \quad (10)$$

$$x_{ijm}^k,\ y_i^k \in \{0,1\} \qquad \forall\ i, j, m, k. \quad (11)$$

The constraint in Equation (9) turns hazard-class rules into routing restrictions. A Class 3 flammable liquid (UN 1203) is admissible on every arc, so Equation (9) never binds. A Class 1.1 explosive (UN 0081) is barred by ADR tunnel restrictions from the Tbilisi-Kars road arc and is forced onto the Baku-Tbilisi-Kars (BTK) rail line. A Class 7 radioactive shipment (UN 2916) becomes infeasible on the whole corridor if the Aktau-Baku ferry lacks IMDG radioactive-materials certification, because no overland bypass exists. The constraint in Equation (10) forces $y_i^k = 1$ only when the incoming and outgoing modes at terminal i differ; otherwise minimization drives it to zero, so no spurious transfer charge is incurred.

In operational terms, the indicator δ is compiled for each shipment from three sources: the modal regulation that applies to the arc (ADR for road, RID for rail, IMDG for sea); national deviations and route restrictions notified by the transit state; and the certification of the specific infrastructure or vessel, such as the ADR tunnel category of a road section or the dangerous-goods compliance document held by a ferry. Since the three regulations share the UN numbering and hazard-class system, the same commodity identifier can be used to query every mode, and harmonization gaps appear explicitly as arcs on which $\delta = 0$ for one mode but 1 for its parallel alternative. The model can therefore be used to diagnose where the regulatory differences, rather than physical infrastructure, constrain corridor routing.

3.3 Risk quantification model

The arc risk is the product of accident probability and consequence severity in Equation (12). Severity combines a population-exposure index P_{ij}, an environmental-sensitivity index E_{ij}, and a critical-infrastructure index I_{ij} (tunnels, bridges, urban crossings), each min-max normalized to [0, 1], with weights $\alpha + \beta + \gamma = 1$ in Equation (13). The weights used here are illustrative.

$$R_{ijm} = p_{ijm} \cdot s_{ij}, \quad (12)$$

$$s_{ij} = \alpha \cdot P_{ij} + \beta \cdot E_{ij} + \gamma \cdot I_{ij}. \quad (13)$$

Accident occurrence is treated as a Poisson process over arc length L_{ij} in Equation (14), with the accident rate λ_{ijm} linked to mode, traffic density TD_{ij}, and a hazard-exposure factor HF_{ij} in Equation (15). Where accident registries are too sparse for regression, published mode-specific base rates serve as priors.

$$p_{ijm} = 1 - \exp(-\lambda_{ijm} L_{ij}), \quad (14)$$

$$\ln(\lambda_{ijm}) = \theta_0 + \theta_1 Mode_m + \theta_2 TD_{ij} + \theta_3 HF_{ij}. \quad (15)$$

3.4 Solution method

Since the route, mode, and transfer decisions are discrete while costs, risks, and time accumulate linearly, the model is a MOMILP. Two scalarizations are used: a weighted sum of min-max normalized objectives in Equation (16) and an ε-constraint formulation in Equation (17).

$$\text{Min } Z = w_1 \hat{Z}_1 + w_2 \hat{Z}_2 + w_3 \hat{Z}_3, \quad w_1 + w_2 + w_3 = 1, \tag{16}$$

$$\text{Min } Z_1 \quad \text{s.t.} \quad Z_2 \leq \varepsilon_2, \quad Z_3 \leq \varepsilon_3. \tag{17}$$

The case study has only $2^5 = 32$ feasible mode combinations, so all the alternatives were evaluated by exhaustive enumeration and the Pareto set was identified by pairwise dominance analysis with respect to all three objectives in Equations (2)-(4) simultaneously; the results are therefore exact (0% optimality gap). Larger multi-corridor instances would require a mixed-integer linear programming (MILP) solver (CPLEX, Gurobi) or metaheuristics such as the Non-dominated Sorting Genetic Algorithm II (NSGA-II).

3.5 Model validation, assumptions, and limitations

Stationary costs, time, and accident parameters, time-invariant severity, deterministic demand, independent shipments without consolidation, and a binary admissibility indicator are assumed in the model, whereas the real regulations also allow for the conditional carriage subject to additional documentation, escort, or prior notification. Risk is deterministic: no uncertainty intervals are placed on accident probability or severity, and robustness is examined only through what-if variation of the risk weight, arc capacity, ferry waiting time, and ferry availability. The case-study parameters are illustrative assumptions (Section 4.1, Table 3), and no independent validation against expert elicitation (e.g., a Delphi study) or incident records was performed. The framework should therefore be read as a demonstration of model structure and decision-support capability rather than as a validated representation of corridor risk.

4 Numerical results and case study application

In this section, the model is applied to the illustrative Khorgos-Vienna case. The case-study network and the parameters used are described in Section 4.1, the Pareto-optimal route alternatives for a single shipment are identified in Section 4.2, the analysis is extended to several shipments competing for capacity in Section 4.3, and the response of the results to the objective weights, arc capacity, ferry waiting time, and ferry availability is examined in Section 4.4.

4.1 Case-study network and illustrative parameters

The corridor is represented as a six-link route: Khorgos (China-Kazakhstan (CN-KZ) border) - Aktau - Baku - Tbilisi - Kars - Istanbul - Vienna. The Aktau-Baku segment is a fixed ferry crossing and the other five offer a rail/road choice, giving $2^5 = 32$ mode combinations for a representative UN Class 3 shipment of $q = 50$ twenty-foot equivalent units (TEU). Arc parameters are listed in Table 2. Each modal interchange adds 80 USD/TEU, 6 h, and 0.00002 risk, and the border-waiting time at Khorgos is set to 24 h, a value between the 12.5 h (2023) and 34.8 h (2022) averages observed for rail at Khorgos and below the 29.3 h regional rail average reported in the Central Asia Regional Economic Cooperation (CAREC) corridor monitoring data [21, p. 15 and 20]. Costs, distances, and capacities are assumed values of a plausible order of magnitude informed by corridor reports [11-12] rather than taken from a published tariff. Accident probabilities and severities are set directly rather than estimated from Equations (14)-(15), with rail values uniformly below road following [8, 14, 17]; since the rail and road alternatives of a segment follow different alignments, the severity coefficient is

Table 2 *Illustrative arc-level parameters used in the numerical example*

Segment	Mode	Dist. (km)	Cost (USD/TEU)	Time (h)	p (accident prob.)	s (severity)	Cap. (TEU/wk)
Khorgos - Aktau	rail	3300	900	96	0.00008	0.35	500
Khorgos - Aktau	road	3190	1400	130	0.00025	0.65	150
Aktau - Baku (Caspian Sea)	sea	450	600	40	0.00015	0.30	300
Baku - Tbilisi	rail	580	250	18	0.00003	0.35	400
Baku - Tbilisi	road	572	320	12	0.00012	0.65	200
Tbilisi - Kars (BTK line)	rail	313	200	14	0.00004	0.35	250
Tbilisi - Kars	road	380	260	9	0.00018	0.65	180
Kars - Istanbul	rail	1164	480	30	0.00006	0.35	300
Kars - Istanbul	road	1429	700	22	0.00022	0.65	200
Istanbul - Vienna	rail	1277	620	40	0.00005	0.35	350
Istanbul - Vienna	road	1560	900	28	0.00020	0.65	220

Table 3 *Provenance of the parameters used in the case study*

Parameter	Value used	Basis	Source
Khorgos rail border time	24 h base; 12.5 h and 34.8 h as scenarios	Observed means, 2023 and 2022 (pp. 15, 20)	[21]
Ferry waiting ω	0, 48, 120, 288 h	Assumed scenario; long Caspian dwell noted qualitatively in [11]	[11]
Ferry availability a	1, 0.8, 0.7, 0.5	Assumed scenario	-
Tbilisi-Kars DG capacity	250 TEU/week (varied)	Assumed DG allocation (not the physical line capacity)	[23]
Accident probability p, severity s	As in Table 2	Assumed from published base rates	[8, 14, 17]

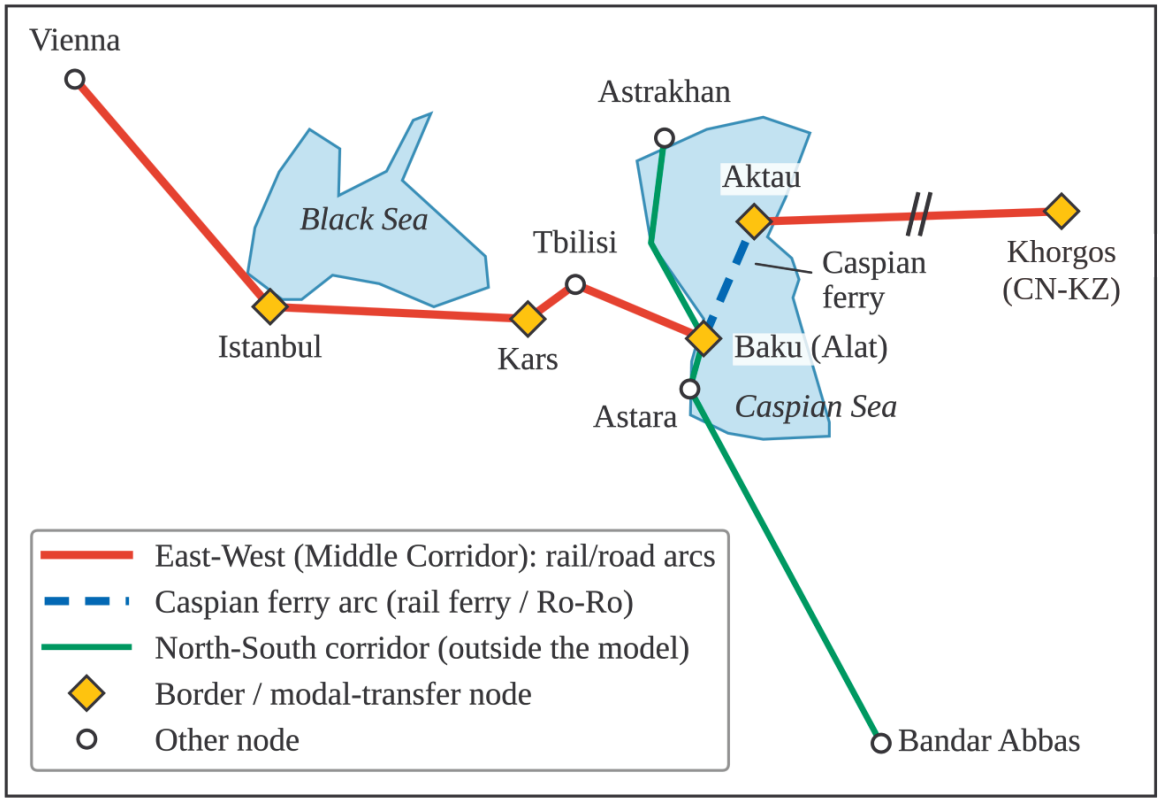


Figure 1 *Schematic of the East-West (Middle Corridor) and North-South corridors and the border and modal-transfer nodes used in the model (simplified coastlines; not to scale)*

specified separately for each parallel arc. The 250 TEU/week on the Tbilisi-Kars rail arc is an assumed weekly allocation for dangerous goods, not the physical capacity of the BTK line [23]. Ferry waiting time ω and ferry availability a are the scenario parameters: in the World Bank corridor study [11], it is reported that the longest delays on the corridor occur at the Caspian Sea crossing and that Caspian ports have relatively long cargo dwell times, but no port-specific dwell figure is given; the 120 h and 288 h values (5 and 12 days) are therefore assumed upper-range scenarios rather than measured ferry waiting times. The provenance of each parameter is given in Table 3.

The East-West route modelled here, the Caspian ferry arc, the North-South corridor for context, and the border and modal-transfer nodes are shown in Figure 1.

4.2 Pareto-optimal route alternatives

Objectives in Equations (2)-(4) were evaluated for all 32 combinations; the seven non-dominated alternatives (R1-R7) are reported in Table 4, with cost and risk per TEU and time as shipment totals. For the all-rail route (R1), arc costs sum to 3,050 USD/TEU and two transfers (at Aktau and Baku) add 160, giving 3,210 USD/TEU; arc risk of 0.000136 plus 0.00004 transfer risk gives 0.000176; and 238 h of travel, 12 h of transfer, and 24 h of border waiting give 274 h.

The other 25 enumerated combinations, including every combination that uses road on the Khorgos-Aktau segment, are dominated. The all-rail route (R1) minimizes both cost and risk but is the slowest of the seven; replacing rail legs with road progressively

Table 4 *Non-dominated alternatives (R1-R7) among the 32 enumerated mode combinations (segments: Khorgos-Aktau, Aktau-Baku, Baku-Tbilisi, Tbilisi-Kars, Kars-Istanbul, Istanbul-Vienna)*

No.	Route name	Mode sequence by segment	Transfers	Cost Z_1 (USD/TEU)	Time Z_2 (h)	Risk Z_3
R1	All-Rail Route	Rail-Sea-Rail-Rail-Rail-Rail	2	3210	274	0.000176
R2	Caucasus Road Bypass	Rail-Sea-Road-Road-Rail-Rail	3	3420	269	0.000367
R3	Vienna Road Final-Leg	Rail-Sea-Rail-Rail-Rail-Road	3	3570	268	0.000309
R4	Extended Road Corridor to Kars	Rail-Sea-Road-Road-Road-Rail	3	3640	261	0.000489
R5	Türkiye-Europe Road Corridor	Rail-Sea-Rail-Rail-Road-Road	3	3790	260	0.000431
R6	All-Road Corridor	Rail-Sea-Road-Road-Road-Road	2	3840	243	0.000581
R7	Georgia-Onward Road Corridor	Rail-Sea-Rail-Road-Road-Road	3	3850	255	0.000534

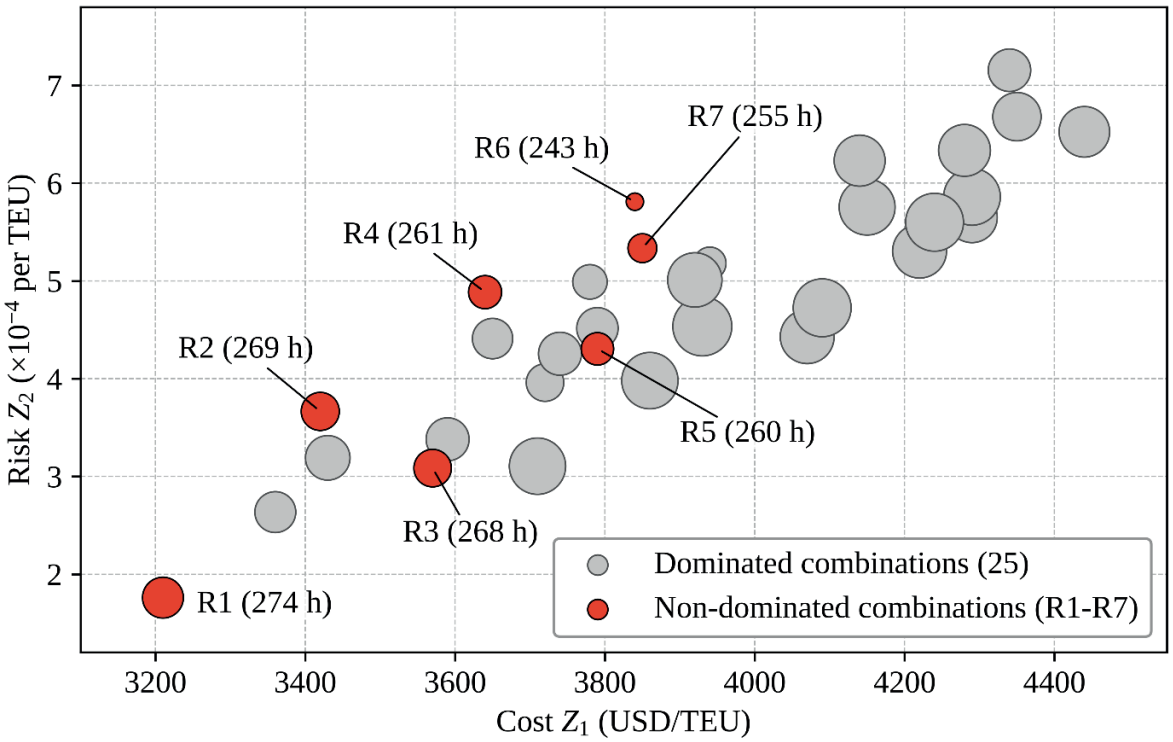


Figure 2 *Costs and risks of the 32 enumerated mode combinations; bubble size and labels denote the transit time. Red points (R1-R7) are non-dominated with respect to cost, risk and time jointly; grey points are dominated*

shortens transit time at higher cost and risk, down to 243 h for the all-road configuration (R6). Each of R2-R7 is retained because no other alternative is at least as good in all three objectives; for example, R7 costs slightly more than R6 and takes 12 h longer but carries lower risk (0.000534 vs. 0.000581). In the two-dimensional cost-risk plane of Figure 2, R1 alone is non-dominated, so the trade-off exists only through the transit time.

The trade-off along the frontier can be expressed in marginal terms. Moving from R1 to R3 saves 6 h at an extra 360 USD/TEU and raises risk by about 76%; moving from R1 to the all-road configuration R6 saves 31 h (about 11% of transit time) at an extra 630 USD/TEU (about 20%) while more than tripling risk (0.000581 vs. 0.000176). Each hour saved on the way to R6 thus costs roughly 20 USD/TEU and adds about 1.3×10^{-5} risk units per TEU. For a HazMat consignor, speed is bought mainly with safety rather than with money - precisely the trade-off that single-objective routing conceals.

4.3 Multi-commodity, multi-origin-destination extension

To exercise capacity competition and the constraint in Equation (9), four shipments were routed

simultaneously: k_1 (UN 1203, 110 TEU/wk) and k_2 (UN 0081, 70 TEU/wk) and k_3 (UN 2916, 25 TEU/wk) from Khorgos to Vienna, and k_4 (UN 1203, 90 TEU/wk) from Baku to Vienna. Downstream of Baku, k_1, k_2, and k_4 compete for the Tbilisi-Kars rail arc (250 TEU/wk). Since k_2 is barred from the road alternative, it pre-empts 70 TEU/wk, leaving 180 TEU/wk for k_1 and k_4, whose combined 200 TEU/wk exceeds it. Diverting k_4 to road costs 19,800 USD/wk against 24,200 USD/wk for k_1, so the model diverts k_4, while k_1 and k_2 stay on rail (3,210 USD/TEU, 274 h). Shipment k_3 has no admissible Aktau-Baku arc and is reported as infeasible. Overall, 270 TEU/wk are served at 737,100 USD with a combined risk of 0.05022, while 25 TEU/wk of Class 7 demand cannot be served under current ferry certification.

Two features of this result deserve emphasis. First, the allocation is driven by regulation as much as by costs: because the explosive shipment k_2 has no admissible road alternative on Tbilisi-Kars, it acquires de facto priority on the scarce rail arc, and the capacity burden shifts to the flammable-liquid flows that may legally use either mode. Second, the infeasibility of k_3 is caused not by capacity but by the absence of a certified maritime arc, so no rail or road investment could make this shipment routable. For a transit country, extending ferry certification to additional hazard classes in line with the IMDG Code may therefore enlarge the set of servable cargo more than incremental capacity expansion would.

4.4 Sensitivity analysis

With $w_1 = w_3 = (1 - w_2)/2$, objectives min-max normalized over the 32 enumerated alternatives, and w_2 varied from 0 to 1 in steps of 0.01, the all-rail route (R1) is the weighted-sum optimum for every value of w_2, including $w_2 = 0$. The R1 is simultaneously the cheapest and the safest alternative, and its normalized cost advantage over the fastest route R6 (0.51) exceeds its normalized time disadvantage (0.43), so in this weighting scheme the risk weight does not change the solution. A risk-weight threshold appears only when cost is excluded and risk is traded against time alone ($w_1 = 0$, $w_3 = 1 - w_2$): the all-road route R6 is then selected for w_2 below about 0.36 and R1 above it, and no intermediate route is selected at any weight, because a weighted sum cannot reach the non-convex part of the frontier. This threshold depends on the normalization range: if the objectives are normalized over the seven non-dominated routes only, it moves to $w_2 = 0.50$. For capacity, the minimum-cost feasible route was recomputed for weekly demand from 10 to 600 TEU at full ferry availability ($a = 1$). The all-rail route stays feasible up to 250 TEU/week, the dangerous-goods allocation on the Tbilisi-Kars rail arc, which is the corridor's binding link: its road alternative carries only 180 TEU/week, and the Aktau-Baku ferry independently caps flow at 300 TEU/week. Since a single shipment cannot be split between parallel arcs (the routing variables are binary), above 250 TEU/week no mode combination satisfies the capacity constraint in Equation (7), so capacity determines whether a feasible solution exists at all, not merely its costs; when demand consists of several shipments, part of it can be diverted to the road arc (Section 4.3).

When the two analyses are taken together, preference-driven outcomes can be separated from infrastructure-driven ones. It follows from the risk-weight analysis that the rail-dominant solution is not an artefact of one particular weighting. It follows from the capacity analysis that, for a single shipment above 250 TEU/week, no weighting can restore feasibility; only physical expansion of the Tbilisi-Kars rail link - followed, beyond 300 TEU/week, by additional Aktau-Baku ferry capacity - can do so. Weight selection and capacity planning should therefore be treated as distinct policy levers.

Ferry waiting time and disruption. The waiting time ω and the availability factor a enter the model through Equations (5) and (8). Since the crossing is unavoidable, a route-independent ω shifts all 32 alternatives equally: the set of seven non-dominated routes is unchanged, while the all-rail route lengthens from 274 h to 322, 394 and 562 h for ω = 48, 120 and 288 h, and the 31 h saved by the all-road route falls from 11.3% to 9.6%, 7.9% and 5.5% of transit time. The availability factor matters for capacity: at $a = 0.8$ the effective ferry capacity (240 TEU/week) is below the 250 TEU/week DG allocation on the Tbilisi-Kars arc, so the ferry becomes the binding link (the switch occurs once a falls below $250/300 \approx 0.83$), and at $a = 0.5$ it falls to 150 TEU/week. A mode-dependent ferry wait (rail ferry versus roll-on/roll-off (Ro-Ro)) would be needed to change the ranking of routes, and open data to parameterise it were not found.

5 Discussion

Within the illustrative parameterization, the rail-dominant configurations consistently outperform the road-intensive ones on risk, in line with evidence that rail has lower accident frequency and population exposure [2, 8]. The all-rail configuration remains preferred across risk weights unless cost is disregarded (Section 4.4). Capacity, however, is decisive: since the Tbilisi-Kars road alternative has less capacity than rail, a single shipment above 250 TEU/week cannot be absorbed by modal substitution, and if ferry availability falls below about 83% the Aktau-Baku crossing becomes the binding link, suggesting that expanding BTK rail or Aktau-Baku ferry capacity may yield safety benefits beyond those of stricter regulation. Since the parameters are not audited, these are policy directions, not validated investment recommendations.

It is also clarified by the results what harmonization of ADR, RID, and IMDG means for a transit country. For Azerbaijan, the Baku International Sea Trade Port at Alat is the point where all three regimes meet: cargo arriving by ferry under the IMDG Code is transferred to rail under RID or to road under ADR within the same terminal. It follows from the model that the costs of this interface - transfer charges, dwell time, and transfer risk - are incurred on every route, so improvements at the port benefit all configurations at once. Practical measures include mutual recognition of dangerous-goods documentation across modes, a single electronic consignment record that accompanies the cargo from Khorgos to the European Union (EU) border, joint inspections at the port and at land border crossings, common training and certification of dangerous-goods safety advisers, and coordinated emergency-response plans among port, rail, and road authorities. This direction is supported by evidence that electronic transit systems such as the New Computerised Transit System (NCTS) improve the traceability of consignments and reduce transit time and border delays [13]. In model terms, such measures lower the transfer parameters cc, ct, and cr and the border-waiting times τ, and, where they extend vessel or terminal certification, turn arcs with $\delta = 0$ into admissible ones.

The main limitations are the illustrative parameters, deterministic demand and network conditions, and the absence of the real-time operational adjustment. Future work should calibrate the model with verified tariffs, customs times, ferry schedules, capacities, and accident statistics obtained from corridor operators and national authorities; adopt stochastic or robust formulations that account for demand and disruption uncertainty; and refine the maritime segment to capture port handling risk, mode-dependent ferry waiting times and measured (rather than assumed) distributions of weather-related closures on the Caspian Sea, IMDG segregation requirements on the confined vehicle decks of Ro-Ro vessels, and the limited emergency-response capacity available during a crossing. Carbon emissions, resilience indicators, and larger multi-corridor instances solved with NSGA-II or similar metaheuristics are further extensions.

6 Conclusion

In this conceptual, simulation-based study, a MOMILP framework was developed for configuring the rail-truck-ferry networks for HazMat transportation along the Middle Corridor, jointly minimizing cost, risk, and transit time under capacity, transfer, border, and ADR/RID/IMDG admissibility constraints. Under illustrative parameters, rail-oriented configurations substantially reduce risk with only moderate increases in delivery time, the Tbilisi-Kars rail link limits corridor throughput until the Caspian ferry availability falls below about 83%, and the all-rail solution is stable across risk weights unless cost is disregarded and safety receives a weight below about 0.36.

In this study, the HazMat network design is extended to a multi-jurisdictional corridor with a maritime segment, and a transparent tool for exploring efficiency-safety trade-offs is offered to stakeholders. For transit countries such as Azerbaijan, the results indicate that harmonizing ADR, RID, and IMDG procedures at modal interfaces - above all at the Baku ferry terminal - can reduce transfer time and risk on every route, while extending ferry certification may enlarge the range of hazard classes the corridor can carry at all. Specific routing or capacity-expansion decisions should nevertheless be re-evaluated with verified operator, tariff, and accident data, and future research should incorporate uncertainty and real-time information systems.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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