Holistic Approach to the Transport Safety Assessment: A Case of Multimodal Transport Ecosystem

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Abstract. This paper explores methodologies, criteria, and frameworks utilized in safety evaluation within multimodal transportations. However, existing approaches to safety assessment have drawbacks when applied to complex systems, such as multimodal transportation. This includes issues, such as achieving local optimum, managing safety without direct infrastructure ownership, and unifying safety estimates across multiple modes of transport. The safety of these systems relies on both objective conditions and subjective factors aimed at preserving integrity and functionality. Therefore, there's a need for modeling safety assessments specifically tailored to multimodal freight transportation. This research utilizes mathematical modeling methods to develop an approach for assessing safety, addressing shortcomings of previous studies. The proposed method was applied to an existing multimodal transportation system, demonstrating its potential in evaluating safety levels and optimizing transportation routes.

Keywords: Transport Safety · Multimodal Transportation · Risk · Reliability · Holistic Mathematical Model

1 Introduction

The concept of "transport safety of multimodal transportation" comprises various aspects of safety, i.e. aviation safety, road safety, rail safety, sea safety and pipeline safety.

An analysis of transportation safety assessment approaches reveals two main perspectives: evaluating safety positively, focusing on reliability and sustainability [1–3], and assessing safety negatively, considering concepts of vulnerability, risk, danger, or threat [4–8]. While risk theory predominates modern safety assessments, some methods incorporate the human factor concept, requiring informal approaches due to complexity [9]. An analysis of scientific papers reveals several issues in this area: local modeling challenge (safety assessments are often specific to individual infrastructure objects or modes of transport, making comparisons difficult due to differing characteristic); one-sided safety assessment (most methods focus solely on assessing the safety of a transport hub or evaluating the probability of emergencies on transportation routes); safety

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management complexity (many methods are only suitable for transport companies that directly control transport infrastructure).

This paper aims to investigate methodological aspects of emergency risk assessment in multimodal transportation and provide a mechanism for selecting the optimal multimodal route during its design stage. It contributes to the literature by offering a new holistic mathematical model for assessing transport safety in multimodal transportation scenarios.

2 Method

The proposed method for transport safety assessment in case of multimodal transportation consists of two stages: evaluation of transport hub safety and assessment of critical failures on transportation routes.

The initial step involves estimating the reliability of transport hubs along a multimodal route. Security system in transport hubs can be considered as a non-redundant recoverable system. The stationary indicators can be expressed in terms of the average time between failures (T), the average recovery time of system elements (T_r), the readiness coefficient (K_r), the system failure rate (λ_s) and the recovery rate (μ_s) [10]:

$$T = \frac{1}{\lambda_s} = \frac{1}{\sum_{i=1}^{n} \lambda_i}; T_r = \frac{1}{\lambda_s} \cdot \sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}; K_r = \frac{T}{T + T_r} = \frac{1}{1 + \sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}} \tag{1}$$

$$K_r(t) = \frac{\mu_s}{\lambda_s + \mu_s} + \frac{\lambda_s}{\lambda_s + \mu_s} exp(-(\lambda_s + \mu_s) \cdot t) \tag{2}$$

The readiness coefficient (K_r) and the readiness function ($K_r(t)$) therefore can be considered as certain assessments of transport safety.

Following the evaluation of transport hub reliability, the next step in the proposed methodology involves conducting a risk assessment for critical failures on transportation routes. The calculation of apriori probabilities of emergency situations (ES) based on the ratio of the number of vehicles caught in an emergency (N_a) to the total number of vehicles passing through a route (N_l) is a straightforward approach to estimate the probability of an emergency occurring on a specific route.

$$P_j^s = \frac{\sum_l N_a}{\sum_l N_l}; \delta^2 = \frac{\left(P_j^s - P_j^e\right)^2}{2}; P_j = \frac{P_j^s + 4P_j^m + P_j^e}{\delta} \tag{3}$$

where P_j is the weighted average probability of occurrence of events j; P_j^s – apriori statistical probability of events j occurrence; P_j^m – the most probable value of events j; P_j^e – apriori (expert) value of the probability of events j occurrence; δ – dispersion coefficient.

Calculating the intensity of critical failures (i) for a specific time period (T) using statistics for each section of the route (l) involves assessing the rate at which critical failures occur within that time frame:

$$\gamma_{ij} = \frac{\sum_l N_i}{T \cdot \sum_l N_l} \tag{4}$$

The probability of failure (P_{ij}) and probability of critical failures (R_{ij}) can be expressed in the following way:

$$P_{ij} = 1 - exp\left(-\gamma_{ij} \cdot T\right); R_{ij} = \sum P_{ij} \cdot P_j \tag{5}$$

The formalized methodological approach requires the following adjustments: when comparing the readiness coefficients of various transport hubs, it's necessary to take into account different volume of their operations; the minimization of critical failures risk causes the need to mirror the safety indicator in order to operate the developed model for general optimization – minimization; enhanced transport safety assessments require methodological expansion through the inclusion of additional criteria, i.e. transportation time and transportation costs.

The final step involves analysis of the constructed assessment table under conditions of uncertainty with the help of the following decision-making criteria [11]:

- Laplace criterion:

$$\overline{F} = F\left(\overline{X}, Y\right) = min_{1 \le i \le m}\left(\frac{1}{n}\right)\sum_{j=1}^{n} a_{ij} \tag{7}$$

Wald's criterion:

$$\overline{F} = F\left(\overline{X}, Y\right) = min_{1 \le i \le m} max_{1 \le j \le n} a_{ij} \tag{8}$$

Hurwitz criterion. "Optimism coefficient" a is within $0 \le \alpha \le 1$:

$$\overline{F} = F\left(\overline{X}, Y\right) = min_{1 \le i \le m}\left[\alpha min_{1 \le j \le n} a_{ij} + (1 - \alpha) max_{1 \le j \le n} a_{ij}\right] \tag{9}$$

Savage's criterion:

$$\overline{F} = F\left(\overline{X}, Y\right) = max_{1 \le i \le m} min_{1 \le j \le n}\left(a_{ij} - min_{1 \le i \le m} a_j\right) \tag{10}$$

The multimodal route, which appears most often, during using these criteria can be considered as the optimal one. By combining these two assessments, the method provides a holistic view on the transport safety in a multimodal transportation ecosystem.

3 Findings

This section presents results of transport safety assessment in case of multimodal transport ecosystem using the proposed algorithm. Three multimodal cargo transportation routes were considered to test the algorithm:

Multimodal route №1 (MR1): seaport of Houston (US HOU) → Marseille-Fos Port (FR FOS) → Marseille Provence Airport (MRS) → Rzeszów Airport (RZE) → warehouse (WH).
Multimodal route №2 (MR2): seaport of Houston (US HOU) → Port of Genoa (IT GOA) → Milan Malpensa Airport (MXP) → Rzeszów Airport (RZE) → warehouse (WH);
Multimodal route №3 (MR3): seaport of Houston (US NYC) → seaport of Piraeus (GRPIR) → Eleftherios Venizelos airport (ATH) → Rzeszów Airport (RZE) → warehouse (WH).

The transport hub's reliability assessment is based on the processing of statistical information on safety system failures of the correspondent hubs [12–17].

Table 1. Data on safety system failures by transportation hubs [12–17]

Transport hub	Operating incidents	Acts of unlawful interference	Other
US HOU	94	14	0
MRS	49	19	5
FP FOS	110	21	0
IT GOA	127	23	3
RZE	34	10	0
MXP	25	19	1
BTS	120	8	5
GR PIR	93	7	0
ATH	45	6	2

The evaluation process adopted a time unit of one day. The purposed method was tested on Rzeszów Airport (RZE). System failure rate (λ_s), mean time between failures, average recovery time and readiness coefficient equal (Table 1):

$$\lambda_s = 0.0186 + 0.0038 = 0.0225 \tag{11}$$

$$T = \frac{1}{\lambda_s} = 44.64 \approx 45(days);\ T_r = 12.167 \approx (12\,days);\ K_r = 0.7858 \tag{12}$$

The transition time of RZE is 75 days. The reliability of other transport hubs on the routes is calculated in the same way with the help of MatLab software.

The risk assessment is thereafter performed on the selected multimodal routes, using the statistical data on the number of vehicles involved in an accident on the routes [18, 19].

The probability of risk of an accident in sea transportation USHOU - FPFOS is calculated by the types of failures:

$$\gamma_{dmg} = \frac{N_{dmg}}{T_i \cdot S_T} = \frac{11234}{12745 \cdot 7} = 0.1259 \tag{13}$$

The probability of vehicle damage (P_{dmg}) in case of emergency and risk of its damage during transportation (R_{dmg}) are determined in the following way:

$$P_{dmg} = 1 - exp\left(-\gamma_{dmg} \cdot T_i\right) = 0.623; R_{dmg} = R_{exp} \cdot P_{dmg} = 0.00192 \quad (14)$$

Risk of vehicle destruction during transportation was calculated similarly. The risk of a transport accident along the USHOU - FPFOS route is determined by summing the values of critical failures in emergency situations:

$$R_1 = R_{dmg} + R_{dst} = 0.0011 \quad (15)$$

The next step is selection of the optimal route, based on various criteria. A weighting factor is implemented based on the turnover share of each point within the transport hub system. The comparative non-safety values for transport hubs are determined by subtracting the product of the hub's readiness coefficient and its weighting factor from one. Similarly, the comparative non-safety value of a multimodal route is derived as the average of these values across its transport hubs. The absolute values should be transformed into the relative ones (Table 2).

Table 2. Relative values of factors of multimodal routes assessment

Route	Time	Costs	Risk	Non-safety on TH
MR1	0.8953	1	0.8863	0.9944
MR2	0.9321	0.9500	0.8855	0.9931
MR3	1	0.9768	1	1

The following step is to analyze the formed table using the criteria of decision-making in conditions of uncertainty (Table 3).

Table 3. Results of the analysis by the criteria of decision-making in uncertainty

Criterion	MR1	MR2	MR3
Laplace's	1.2587	1.2536	1.3256
Savage's	0	0	0
Hurwitz's	−0.3204	−0.3219	−0.3837
Wald's	1	0.9931	1

According to the results of calculations, the multimodal route №1 is the optimal route from the point of view of transport safety: seaport of Houston (US HOU) → Marseille-Fos Port (FR FOS) → Marseille Provence Airport (MRS) → Rzeszów Airport (RZE) → warehouse (WH).

4 Conclusions

Globalization of the economy and evolution of modern supply chains lead to the development of different multimodal transportation routes. Regrettably, the matter of safety assessment for multimodal transportation has not been extensively explored.

The paper proposes a new holistic approach to safety assessment for multimodal transportation, addressing existing shortcomings in methodologies. This approach enables the evaluation of both transport hub safety and critical failures on transportation routes. By using this method, alternative multimodal transportation routes can be assessed based on selected criteria, allowing for improvements in transport safety during route design. This approach facilitates the identification of potential weaknesses and the development of strategies to mitigate risks, enhancing overall safety in multimodal transportation operations.

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