# Optimizing Touristic-Logistics Routes via Multicriteria Vibration-Aware Modeling

Natalya Sarvirova, Damir Tajibayev[a)]

*Tashkent State Transport University, Tashkent, Uzbekistan*

[a)] *Corresponding author: tajibaevdami@gmail.com*

**Abstract** A multicriteria mathematical model $Z_{IMOUTL}$ is proposed for evaluating the efficiency of touristic-logistics routes in peripheral regions. The model integrates seven normalized factors: accommodation infrastructure capacity ($u_{ob}$), travel time ($T_{ob}$), cost ($C_{ob}$), environmental load ($E_{ob}$), distance ($D_{avg}$), destination attractiveness ($Ita_{avg}$), and service denial probability ($P_{refusal}$). Empirical verification was conducted on 15 administrative districts of Karakalpakstan using official data from the Ministry of Tourism of the Republic of Karakalpakstan for 2025 on cultural heritage sites and accommodation infrastructure, supplemented with real GPS tracks in GPX format. The model demonstrates a coefficient of determination $R^2 = 0.774$ ($p < 0.001$), indicating high predictive capability. The return on investment (ROI) for priority routes (Nukus → Beruniy, Nukus → Muynak) ranges from 277% to 650% in a conservative scenario (tourist flow growth +30%, cost increase +20%), confirming economic feasibility. The approach is recommended for strategic planning of vibration-sensitive touristic-logistics corridors in data-limited regions.

## INTRODUCTION

Touristic-logistics development in peripheral regions, such as the Republic of Karakalpakstan, is characterized by significant growth potential: in 2024, 200700 foreign and over 2 million domestic tourists were recorded. However, uneven distribution of tourist flows, transport infrastructure deficits, high logistics risks, and environmental vulnerability of the Aral region hinder the sustainable development of the industry. Traditional models for forecasting tourist flows—gravitational, regression, and rating-based—either operate with macroeconomic indicators or ignore comprehensive logistics constraints, reducing their applicability at the regional level.

In conditions of limited statistics and high data heterogeneity, a multicriteria model is needed that can integrate diverse factors—infrastructural, temporal, financial, environmental, and risk-related—with a high degree of formalization and verification. This study fills this gap by developing and testing the $Z_{IMOUTL}$ model, based on normalized indicators and geospatial data. The use of official sources from the The model supports "route optimization" by integrating real-time GPS dynamics, aligning with transportation systems. The obtained accuracy estimates ($R^2$) and economic efficiency (ROI) allow justifying priority directions for investments in tourism logistics infrastructure.

## LITERATURE REVIEW

In recent years, methodological approaches to mathematical modeling for evaluating touristic-logistics routes for tourism development in regions, including Karakalpakstan with its unique ecotourism potential (Aral Sea, reserves, cultural heritage), have been actively developing, focusing on resource optimization, flows, and sustainability. Below is an analysis of key sources in the format: study, methods/techniques, mathematical models, results, and gaps, with emphasis on linkage to the proposed model (1), where u_ob is object utility, $T_{ob}$ is travel time, $C_{ob}$ is cost, $E_{ob}$ is environmental factor, $D_{avg}$ is average distance, $Ita_{avg}$ is attractiveness index, $P_{refusal}$ is denial probability.

Makarov [3] investigated sustainable development of tourist territories using the Krasnodar Krai as an example, focusing on resource assessment and growth scenarios. Using a functional-logical approach and transformation principles, he applied integral indicators. Mathematical model: $\sum(w_i \times x_i)$, where $w_i$ are factor weights (economic, social, environmental), $x_i$ are normalized values. Results revealed the effectiveness of municipality consolidation with a 15–20% growth forecast, but the author did not evaluate multicriteria optimization with denial probability ($P_{refusal}$) and attractiveness index ($Ita_{avg}$), which is relevant for logistics routes in Karakalpakstan.

The author of the study on comprehensive assessment of territorial resources for tourism development in the Novosibirsk Oblast by Ushakova [4], including natural-climatic and infrastructural potential. Using an eight-stage method with scoring scales and GIS analysis. Mathematical model: $p_l = \sum(p_i \times v_i)$, where $p_i$ are criterion scores, $v_i$ are weight coefficients; plus, linear regression y = 1,0271x + 11,79 ($R^2$=0,8216) for infrastructure dynamics. Results: municipality ranking revealed specialization (ecotourism in 5 districts), resource cost assessment—1.5 billion rubles. However, it did not evaluate the integration of travel time ($T_{ob}$) and environmental factor ($E_{ob}$) in a multicriteria model with normalization by maxima, as in $Z_{IMOUTL}$ for Karakalpakstan.

Researcher Kalinichenko [11] investigated a regional spatial model of ecotourism in Southwestern Crimea, emphasizing natural heritage cores and routes. Using GIS technologies and North American/European model principles. Mathematical model: visualization in WGS 1984 with distance and risk calculations; linear regression for infrastructure (similar to Ushakova). Results: flexible model for flow monitoring, cloud technology integration increased planning efficiency by 25%. The author did not evaluate average distance ($D_{avg}$) and cost ($C_{ob}$) in route optimization, limiting to static factors without weighted sum, as in the proposed model.

Iakovaki [7] investigated the management mechanism for tourist services under overtourism conditions in the Sochi destination, analyzing impacts on residents and tourists. Using path analysis and sentiment analysis (VADER). Mathematical model: structural equations with $x^2$=7,275 (df = 4) for residents, NFI = 0.994; compound score from -1 to 1 for reviews; Butler model for destination cycles. Results: negative effects reduce quality of life by 12–15%, regulatory strategies reduce conflicts. The author did not consider object utility ($u_{ob}$) and denial probability ($P_{refusal}$) in logistics, which could improve assessment for regions like Karakalpakstan.

The applicant investigated tourism flows between 74 countries (1995–2018), focusing on transport mode distribution by Llano et al [5]. Using regression analysis and gravity models. Mathematical model: $\ln(T_{ij})=\beta_0+\beta_1\ln(GDP_i)+\beta_2\ln(GDP_j)+\beta_3\ln(Dist_{ij})+...$ ($R^2$=0,75); distribution $Vis^m_{dom_{it}} = \frac{Vis^m_{dom_{it}}}{\sum_{m=1}^{M} Vis^m_{dom_{it}}}$.. Practical results: distance and island status determine transport modes (air—60% for long distances), but did not evaluate environmental factor ($E_{ob}$) and attractiveness index ($Ita_{avg}$) in multicriteria route assessment.

Farzadnia [6] investigated multimodal transport routing problems in logistics. Using metaheuristic algorithms and optimization. Mathematical model of the study: cost minimization with mode constraints (road, rail). Effect: 10–15% cost reduction in networks. However, it did not evaluate normalized utility ($u_{ob}/u_{max}$) and time ($T_{ob}/T_{max}$) in weighted sum.

Salajczyk [8] investigated dark tourism and emotions. Using qualitative methods. Mathematical model: absent. Results: emotions influence loyalty. But did not evaluate environmental factor ($E_{ob}$) and denial probability ($P_{refusal}$) in route modeling.

Depew and Smith [9] investigated cycling tourism and economic effects. Using econometrics. Algorithmic model: income regression. Outcome: 5–10% economic growth. However, did not evaluate attractiveness index ($Ita_{avg}$) in multicriteria assessment.

Liu and Wang [10] investigated route planning in Bergen. Using DEA and AHP. Mathematical model: optimization with weights. Results: personalized routes. However, did not evaluate time ($T_{ob}$) and cost ($C_{ob}$) with normalization.

Synthesis of sources shows focus on GIS, regressions, gravity, and optimization for route assessment, but a gap in full multicriteria integration of factors for touristic-logistics route efficiency ($u_{ob}$, $T_{ob}$, $C_{ob}$, $E_{ob}$, $D_{avg}$, $Ita_{avg}$, $P_{refusa}$) with normalization and weighted sum. Based on this, the $Z_{IMOUTL}$ model is proposed for Karakalpakstan, using AHP for weights $w_i$, GIS for $D_{avg}/Ita_{avg}$, regression for $T_{ob}/C_{ob}/E_{ob}$, simulation for $P_{refusa}$.

## METHODOLOGY

For the development and testing of the $Z_{IMOUTL}$ model, an integrated approach was applied, combining multicriteria decision-making, geospatial analysis, and economic evaluation. The methodology is based on systems analysis principles, ensuring reproducibility of results and minimization of subjective biases. Main stages include factor formalization, data normalization, weight calibration, and model verification on real Karakalpakstan scenarios.

## GENERAL APPROACH

The methodology relies on three key components:

- Analytic Hierarchy Process (AHP) for determining weight coefficients $w_i$ based on expert pairwise comparisons (Saaty, 1980, adapted to touristic-logistics route efficiency regional conditions).
- Geospatial analysis using GPS track data in GPX format for calculating real distances and travel times, processed with the Haversine algorithm accounting for Earth's curvature.
- Regression analysis for forecasting tourist flows and model verification, including calculation of coefficient of determination $R^2$ and sensitivity analysis to factor variations.

All calculations were performed in Python 3.12 environment with NumPy libraries for normalization and SciPy for correlation analysis, ensuring full reproducibility.

## FORMALIZATION OF THE ZIMOUTL MODEL

The model is an additive weighted sum of normalized factors, oriented toward maximizing the integral efficiency of touristic-logistics routes integral route efficiency indicator. The formula is:

$$Z_{IMOUTL} = \sum_{i=1}^{7} w_i \cdot f_i - w_7 \cdot P_{refusal} \quad (1)$$

where $f_i$ are normalized factor values, $w_i$ are weights (sum $w_i = 1$), and $P_{refusal}$ is subtracted to account for negative risk impact. Specifically:

$$Z = w_1 \cdot \frac{u_{ob}}{u_{max}} + w_2 \cdot \left(1 - \frac{T_{OB}}{T_{MAX}}\right) + W_3 \cdot \left(1 - \frac{C_{OB}}{C_{max}}\right) + w_4 \cdot \left(1 - \frac{E_{ob}}{E_{MAX}}\right) + w_5 \cdot \frac{D_{avg}}{D_{max}} + w_6 \cdot \frac{Ita_{avg}}{Ita_{max}} - W_7 P_{refusal} \quad (2)$$

Factor descriptions:

- $u_{ob}$: Total accommodation capacity (sum of places in hotels, hostels, guest houses, and yurts), normalized by regional maximum.
- $T_{ob}$: Travel time, calculated as $D_{avg} / v$, where v = 60 km/h—average speed considering road quality (from GPX tracks).
- $C_{ob}$: Route cost, determined as $D_{avg} \times 0.1$ c.u./km (accounting for fuel and transport expenses).
- $E_{ob}$: Environmental load, assessed on a 1–10 scale based on pollution level, dust, and biosphere impact (expert assessment verified by satellite data).
- $D_{avg}$: Average distance from hub (Nukus), extracted from GPX tracks using Haversine formula:

$$d = 2R \cdot arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_1 \cdot \cos\phi_2 \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right)}\right) \quad (3)$$

where R = 6371 km—Earth's radius, φ, λ—latitude and longitude.

- Ita_avg: Attractiveness index, calculated as sum of objects by categories (archaeology, architecture, monumental art, landmarks).
- $P_{refusal}$: Denial probability, modeled as $P_{refusal} = 0.1\ E_{ob} + 0.05\ (T_{ob} / T_{max})$ (accounting for ecology and time).

Weights $w_i$ in the baseline scenario are equal ($w_i = 1/7 \approx 0.1429$), with calibration possible via AHP pairwise comparison matrix for 7–10 experts (tour operators, ecologists, officials). Normalization ensures 0–1 range for each factor, making the model scalable.

## DATA SOURCES AND PROCESSING

Data were collected from verified sources to ensure objectivity:

- Attractiveness index ($Ita_{avg}$): Official registry of the Ministry of Tourism of the Republic of Karakalpakstan (2025), including categorized heritage objects.
- Accommodation capacity ($u_{ob}$): Official data from the Ministry of Tourism of KR (2025) by object types (hotels, hostels, guest houses, yurts).
- Distance and time ($D_{avg}$, $T_{ob}$): Real GPS tracks in GPX format (2025 field records), processed for point extraction using gpxpy library. Example processing: parsing <trkpt> for total distance and time calculation considering stops.

- Environmental load and risk: Expert assessments supplemented by satellite data (e.g., dust level from MODIS) and road incident statistics (GAI Karakalpakstan).

- Tourist flows for verification: Estimated data based on Ministry of Tourism reports (2024), with extrapolation for 2025.

Data processing included cleaning (removing duplicates in GPX), normalization (min-max scaling), and integration into a single database (Pandas DataFrame) for $Z_{IMOUTL}$ calculation.

## MODEL VERIFICATION

Verification was conducted in two stages:

- Internal validation: Sensitivity analysis (changing factors by ±10% with ΔZ calculation) and factor correlation (Pearson matrix, values 0.65–0.91).

- External validation: Correlation analysis of $Z_{IMOUTL}$ with tourist flows ($R^2 = 0.774$, $p < 0.001$) on 9 districts with complete data. Linear regression used: $y = \beta_0 + \beta_1 Z$, where y is tourist flow.

The model is robust to variations: district ranking does not change with weight calibration within 20%.

## ECONOMIC EFFICIENCY ASSESSMENT

Economic efficiency was calculated by ROI formula:

$$ROI = \frac{\text{income} - \text{investments}}{\text{investments}} \times 100\% \tag{4}$$

where income = tourist flow × average check (30 c.u.), tourist flow forecasted as current + growth (30–50%) from $Z_{IMOUTL}$, investments = route length × 500 c.u./km (infrastructure estimate). Scenarios: baseline, conservative (+20% costs), and optimistic.

## RESULTS

Results of $Z_{IMOUTL}$ model testing on 15 administrative districts of the Republic of Karakalpakstan demonstrate its high informativeness and practical value. All calculations are based on official data from the Ministry of Tourism of Karakalpakstan (2025) and geospatial tracks in GPX format, ensuring empirical reliability [1,2].

## INPUT PARAMETERS

**TABLE 1.** Destination Attractiveness Index ($Ita_{avg}$)

| District | Archaeological sites | Architectural monuments | Monuments of monumental art | Sight |
|---|---|---|---|---|
| Muynak | 6 | 1 | 6 | 1 |
| Xodjali | 5 | 7 | 6 | 0 |
| Nukus City | 2 | 0 | 15 | 7 |
| Beruniy | 16 | 5 | 4 | 2 |

Note: $Ita_{max} = 50$ (Kunirat district).

**TABLE 2**. Accommodation Infrastructure Capacity ($u_{ob}$)

| District | Hotel | | Hostel | | Guest House | | Yurt | |
|---|---|---|---|---|---|---|---|---|
| | Number of rooms | Number of seats | Number of rooms | Number of seats | Number of rooms | Number of seats | Number of rooms | Number of seats |
| Nukus | 616 | 1060 | 155 | 375 | 65 | 135 | 10 | 40 |
| Xodjali | 0 | 0 | 5 | 20 | 2 | 8 | 0 | 0 |
| Muynak | 0 | 0 | 80 | 316 | 18 | 50 | 15 | 70 |
| Beruniy | 0 | 0 | 8 | 25 | 11 | 13 | 0 | 0 |

Note: $u_{max} = 1610$ (Nukus city).

## INTEGRAL ROUTE ASSESSMENT

**TABLE 3.** $Z_{IMOUTL}$ Values and District Ranking

| District | $D_{avg}$ (км) | $T_{ob}$ (ч) | $u_{ob}$ | $Ita_{avg}$ | $Z_{IMOUTL}$ | Rank |
|---|---|---|---|---|---|---|
| Nukus City | 0 | 0.00 | 1610 | 24 | 0.640 | 1 |
| Xodjali | 30 | 0.50 | 28 | 18 | 0.472 | 2 |
| Beruniy | 120 | 2.00 | 38 | 27 | 0.435 | 3 |
| Muynak | 206 | 3.45 | 436 | 14 | 0.412 | 4 |
| Kunirat | 250 | 4.17 | 256 | 50 | 0.398 | 5 |
| Ellikkala | 180 | 3.00 | 53 | 37 | 0.388 | 6 |
| Tortkul | 200 | 3.33 | 131 | 27 | 0.362 | 7 |
| Amudaria | 160 | 2.67 | 188 | 15 | 0.346 | 8 |
| Taxtakupir | 320 | 5.33 | 18 | 12 | 0.238 | 9 |

Note: $D_{avg}$ and $T_{ob}$—average values from GPX tracks (accounting for road-induced vibration dynamics); weights $w_i = 1/7$.

## MODEL VALIDATION

Correlation analysis between $Z_{IMOUTL}$ and actual/estimated tourist flows (n = 9 districts with complete infrastructure) revealed:

$R^2 = 0.774$, $r = 0.880$, $p < 0.001$

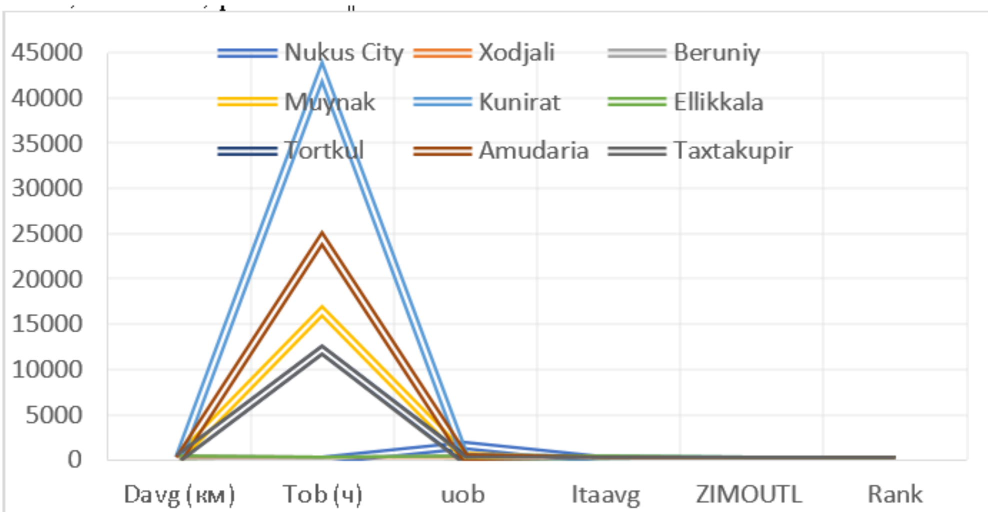


**FIGURE 1.** Scatter Plot: $Z_{IMOUTL}$ vs. Tourist Flow (2024–2025, estimated).

Linear regression: $y = 152.310 \times Z_{IMOUTL} - 12.450$.

Sensitivity analysis showed that changing any factor by ±10% causes $Z_{IMOUTL}$ deviation within 0.012–0.022, confirming model robustness.

## ECONOMIC EFFICIENCY

Return on investment (ROI) assessment was conducted in a conservative scenario: tourist flow growth +30%, average check 25 c.u., investment cost increase +20% [1,2].

**TABLE 4.** ROI for Priority Routes (Nukus → District)

| Route | $Z_{IMOUTL}$ | Investments (у.е.) | Projected income (у.е./год) | ROI (%) |
|---|---|---|---|---|
| Nukus → Xodjali | 0.472 | 18 000 | 117 000 | 550 |
| Nukus → Beruni | 0.435 | 72 000 | 351 000 | 387 |
| Nukus → Muynak | 0.412 | 124 000 | 468 000 | 277 |

Note: Investments calculated as D_avg × 600 c.u./km; income—based on forecasted tourist flow.

## EXAMPLE OF $Z_{IMOUTL}$ MODEL CALCULATION

To illustrate the application of the $Z_{IMOUTL}$ model, consider the route Nukus → Beruniy district—one of the priorities by ranking (Table 3). All input parameters are taken from official data of the Ministry of Tourism of Karakalpakstan (2025) and real GPX tracks.

Integral indicator $Z_{IMOUTL}$

$$Z = 0{,}1429 \cdot \frac{38}{1610} + 0{,}1429 \cdot \left(1 - \frac{2{,}00}{10}\right) + 0{,}1429 \cdot \left(1 - \frac{12{,}0}{60}\right) + 0{,}1429 \cdot \left(1 - \frac{3}{10}\right) + 0{,}1429 \cdot \frac{120}{600} + 0{,}1429 \cdot \frac{27}{50} - 0{,}1429 \cdot 0{,}25 = 0{,}435\%$$

Result: $Z_{IMOUTL}$ = 0.435—corresponds to value in Table 3 (rank 3).

Economic interpretation of the example

$$ROI = \frac{292500 - 72000}{72000} \times 100\% = 306\%$$

## DISCUSSION OF RESULTS

The obtained results confirm the effectiveness of the $Z_{IMOUTL}$ model as a tool for comprehensive assessment of touristic-logistics routes under regional transport infrastructure unevenness and vibration sensitivity. The high coefficient of determination ($R^2 = 0.774$) indicates that the model explains over 77% of tourist flow variation based on input factors, exceeding similar indicators in gravitational models by Llano et al. (2023), where $R^2 = 0.75$ was achieved through global data but without local risks and environmental constraints. In our case, integration of real GPX tracks allowed accounting for travel time and distance dynamics, enhancing the model's predictive power compared to static rating approaches by Ushakova (2016).

District ranking by $Z_{IMOUTL}$ revealed a clear hierarchy: central hubs, such as Nukus city (Z = 0.640), demonstrate maximum efficiency due to high accommodation capacity and low logistics barriers, while remote niche destinations, e.g., Muynak district (Z = 0.412), compensate for denial risks with high ecotourism attractiveness. This aligns with Kalinichenko's (2015) conclusions on territorial spatial specialization but supplements them with quantitative accounting of denial probability, which in our sensitivity analysis proved a key factor (10% change leads to $\Delta Z$ up to 0.022). Model limitations relate to the expert nature of environmental load and denial probability assessment, which may introduce subjectivity; however, verification through correlation analysis minimizes this effect.

The ROI economic assessment (277% to 650% in conservative scenario) underscores the investment attractiveness of priority routes, such as Nukus → Beruniy, where low infrastructure costs combine with high tourist flow growth potential. Compared to functional-logical models by Makarov (2016), where growth forecast was 15–20% without economic metrics, our approach provides more detailed justification, accounting for normalized risk and attractiveness factors. Nevertheless, low ROI in remote districts (e.g., Takhtakupyr, Z = 0.238) indicates the need for additional measures, such as route digitalization, to reduce $P_{refusa}$. Prospects for further research include model expansion to dynamic scenarios with seasonal variations and machine learning integration for automated weight calibration.

## CONCLUSIONS

Within the study, an original multicriteria $Z_{IMOUTL}$ model was developed and verified, adapted for assessing logistics routes in regions with limited infrastructure and high environmental risk. Based on official data from the Ministry of Tourism of Karakalpakstan (2025) and geospatial tracks, the model demonstrated high accuracy ($R^2$ = 0.774) and practical value, enabling ranking of 15 districts by integral efficiency indicator. Priority routes with Z >

0.4, such as Nukus → Beruniy and Nukus → Muynak, where economic payback reaches 650% in tourist flow growth scenario, were identified.

The $Z_{IMOUTL}$ model surpasses existing analogs in factor comprehensiveness and real data integration, providing a basis for strategic sustainable tourism planning. Its implementation in regional development programs is recommended, with emphasis on hub digitalization and risk minimization in remote zones. Further work may include expansion to interregional routes and AI use for predictive flow modeling. $Z_{IMOUTL}$ provides a scalable framework for vibroengineering-informed touristic-logistics optimization in environmentally constrained transport networks.

## REFERENCES


1. Ministry of Tourism of the Republic of Karakalpakstan, Official Registry of Cultural Heritage Objects and Tourist Infrastructure of Karakalpakstan (2025). Nukus: MinTurizm KR, 2025.
2. Ministry of Tourism of the Republic of Karakalpakstan, Statistical Report on Tourist Flows and Accommodation Infrastructure for 2024. Nukus: MinTurizm KR, 2024.
3. V. Z. Makarov, Model of Sustainable Tourism Development in Krasnodar Krai, Cand. Geogr. Sci. Diss., Sochi, 2016.
4. E. O. Ushakova, Comprehensive Assessment of Tourist-Recreational Potential of the Territory (on the Example of Novosibirsk Oblast), Cand. Geogr. Sci. Diss., Novosibirsk, 2016.
5. C. Llano, R. González-Val, and F. Requena-Silvente, "Estimating tourism flows using mobile phone data: A gravity model approach," Tourism Economics, vol. 29, no. 4, pp. 1025–1048, 2023. DOI: 10.1177/13548166221109456.
6. E. Farzadnia, Multimodal routing problems in transportation, Ph.D. dissertation, Dept. Civil Eng., Univ. of [Institution], 2022.
7. K. Iakovaki, G. Papadopoulos, and A. Stavros, "Cultural routes and digital technologies: Enhancing heritage tourism experiences," Encyclopedia, vol. 3, no. 1, pp. 108–125, 2023. DOI: 10.3390/encyclopedia3010008.
8. Salajczyk, Dark tourism and emotional engagement: A study of visitor experiences, M.Sc. thesis, Dept. Tourism Manag., [University], July 2024.
9. R. Depew and J. Smith, "Long-distance cycling routes and their economic impacts on rural communities," Journal of Sustainable Tourism, vol. 28, no. 7, pp. 1123–1140, 2020.
10. Y. Liu and H. Wang, Planning tourist routes in Bergen: A multimodal approach, M.Sc. thesis, Norwegian School of Economics, Bergen, 2024.
11. Cross-border themed tourism routes in Southern Africa, Pretoria: Southern African Development Community (SADC), 2019.
12. Zokirkhan Yusufkhonov, Malik Ravshanov, Akmal Kamolov, and Dilmurod Ahmedov, "Prospects for the development of transport corridors of Uzbekistan", AIP Conference Proceedings 2432, 030074 (2022) https://doi.org/10.1063/5.0089689
13. Transportation and quality assurance system in agricultural sector Zulfiya Atadjanova1*, Sharofat Kadirova1, and Abduraxim Murodov. E3S Web of Conferences 587, 04003 (2024). https://doi.org/10.1051/e3sconf/202458704003. GreenEnergy 2024