**Aray S. Abedzhanova**[1], **Saken K. Oralbek**[2] DOI: 10.35595/2414-9179-2025-3-31-325-333

# EVALUATION OF TRAFFIC CONGESTION PATTERNS ON THE URBAN STREET NETWORK OF UST-KAMENOGORSK THROUGH THE APPLICATION OF GEOGRAPHIC INFORMATION SYSTEMS


## ABSTRACT

The article examines the assessment of traffic congestion within the street and road network of the city using geoinformation technologies. Traffic flow intensity is one of the key characteristics of road traffic, determining the occurrence of congestion both on major arterial streets and across urban districts as a whole. The collection and calculation of indicators that provide insight into the spatial differentiation of vehicle flow intensity and the distances between vehicles represent a labor-intensive stage in the study of fundamental traffic parameters. The most widespread method for collecting and monitoring traffic data is through stationary data acquisition. However, it should be noted that this approach is time-consuming. Given the rapid development of transport infrastructure, the speed at which stationary observations are conducted does not allow for timely updates on changes in street network congestion levels, and consequently, limits the ability to assess the real-time state of traffic flows. As an alternative to traditional data collection methods, modern sources of geospatial data can be utilized. Services originally designed for real-time traffic monitoring and route optimization can also serve as valuable data sources for traffic congestion assessment models and for studying vehicle emission levels. This study proposes a simulation-based model for evaluating congestion within the urban street network, which enables either the rapid elimination of congestion or its prevention, taking into account the distance between vehicles. The proposed methodology has been tested at the district level and on the primary arterial roads of the city of Ust-Kamenogorsk.


**KEYWORDS:** GIS, traffic parameters, transportation, traffic flow forecasting

## INTRODUCTION

With the increase in socio-economic indicators, population growth, and expanding public needs, motorization is becoming an increasingly serious issue in the cities of Kazakhstan. The improvement of citizens' well-being indirectly contributes to the renewal of the vehicle fleet and the growth in the number of private vehicles. In Ust-Kamenogorsk, as in other major cities across the country, the increasing number of automobiles intensifies both the volume and the share of vehicular contribution to environmental pollution.

It is worth noting that in recent years, the number of vehicles in Ust-Kamenogorsk has increased significantly — by 18 %, according to the Administrative Police Department of the East Kazakhstan Region. According to the report "Number of Vehicles in the East Kazakhstan Region as of 01.01.2025"[3], there were over 110 000 vehicles in 2022, approximately 130 000 in 2023, and


[1] NJSC "D. Serikbayev East Kazakhstan technical university", International school of engineering, 19, D. Serikbayeva str., Ust-Kamenogorsk, 070004, The Republic of Kazakhstan,
*e-mail:* **ms.abedzhanova@mail.ru**

[2] NJSC "D. Serikbayev East Kazakhstan technical university", International school of engineering, 19, D. Serikbayeva str., Ust-Kamenogorsk, 070004, The Republic of Kazakhstan,
*e-mail:* **sakenoralbek@mail.ru**


[3] Bureau of National Statistics. Web resource: https://stat.gov.kz/ (accessed 21.04.2025)

more than 150 000 in 2024. Urban development policy has also contributed to the growth of motorization — large-scale construction in major cities, often implemented without sufficient consideration for necessary social, commercial, and other infrastructure, further encourages people to acquire personal vehicles. In the city of Ust-Kamenogorsk, East Kazakhstan Region, Republic of Kazakhstan, the population increase amounted to approximately 11 %, according to the Bureau of National Statistics under the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan.

As a result of the above-mentioned circumstances, new residential neighborhoods with their own infrastructure have emerged. The majority of the urban development is concentrated on the left bank of the city, particularly in the district near the Silk Fabric Plant. With the increase in construction projects and the expansion of residential districts in Ust-Kamenogorsk, the load on the city's transportation arteries logically grows.

To resolve congestion issues, it is necessary to carry out localized urban surveying, taking into account changes in building density and the transport planning structure. In the context of rapid transport infrastructure development and the growing number of vehicles, the collection and calculation of traffic characteristics — which provide insight into the spatial differentiation of traffic flow — represent a highly labor-intensive stage of research.

The most commonly used method for obtaining traffic data — specifically vehicle flow intensity and traffic density in the city — remains stationary data collection. However, this method is quite time-consuming. The use of data from Geographic Information Systems (GIS), by contrast, allows for more rapid acquisition of information on the traffic load of street network segments [*Alkaissi*, 2024].

In the modern context of rapidly developing urban transport infrastructure and a growing number of vehicles, the use of geoinformation technologies becomes a key tool for effective analysis and management of traffic flows. Geographic Information Systems (GIS) not only accelerate the collection and processing of spatial data but also enable comprehensive analysis of the road network, identification of bottlenecks, and forecasting of congestion development. By integrating data from various sources (GPS, satellite imagery, mobile applications), GIS provide a high level of detail and data relevance, significantly enhancing the capacity for informed decision-making in transport planning [*Sahitya*, *Prasad*, 2024; *Zhang*, *Song*, 2024].

## RESEARCH MATERIALS AND METHODS

To study traffic congestion in the urban street and road network, two main methods are commonly employed. The first is a traditional method based on direct field measurements and manual data collection of traffic intensity, though it is highly labor-intensive and difficult to reproduce consistently. However, this method has several limitations, primarily related to its high labor intensity and the complexity of reproducing observation results with consistency.

The second method enables the estimation of road section traffic intensity without field surveys. It relies on available data about the load on the street-road network by processing and comparing information from various sources. Simulated traffic intensity values can be compared with actual measurements to verify the model. Linear regression models were applied to forecast traffic conditions over time, based on historical data sets.

In recent years, the application of Geographic Information Systems for modeling, evaluating, and optimizing urban transport networks has been widely discussed in the scientific literature. For instance, the development of intelligent transport networks, comprehensive methodologies for assessing urban transport structures, and strategies for analyzing spatial big data within GIS are highlighted in the works of Pomortseva et al. [2024], Sahitya & Prasad [2024], and Zhang & Song [2024], respectively.

In the modern context, increasing attention is being paid to the application of artificial intelligence for intelligent transportation system management. Contemporary traffic flow management systems represent integrated solutions that combine technical, organizational, and software-based measures. In this regard, Geographic Information Systems (GIS) make it possible to collect and process core data on road traffic, contributing to congestion mitigation [*Lahlouh* et al., 2024]. GIS can integrate data from multiple sources — Global Positioning System (GPS) trackers, surveillance cameras, mobile applications such as Yandex.Traffic[1], and satellite imagery — into a unified system, enabling comprehensive analysis of traffic load [*Abedzhanova* et al., 2023].

Thus, the use of GIS in traffic flow estimation and analysis is the most efficient approach, improving the quality, speed, and accuracy of research, while also ensuring comprehensive congestion management in a dynamically changing urban environment.

Furthermore, as noted above, following the application of GIS technologies, it becomes necessary to redistribute traffic flows to alleviate congestion. For this purpose, origin-destination (OD) matrices are used to represent the movement of vehicles between city districts. Each matrix cell corresponds to a specific pair of origin and destination zones and indicates the estimated number of trips between them. In this study, the city was divided into five main zones, and the OD matrix was constructed based on traffic intensity data from Yandex.Maps and direct field observations. This matrix helped to identify uneven traffic distribution and served as a basis for analyzing possible traffic flow redistribution.

As an illustrative example, the intersection of Satpayev Avenue – Esenberlin Avenue – Zhibek Zholy Street – Bazovaya Street is considered, as it is the most congested area in the city of Ust-Kamenogorsk (Fig. 1). Satpayev Avenue is the busiest arterial road, connecting the right bank of the city with the left bank, where the only crossing is the bridge over the Irtysh River.


*Fig. 1. Street Network Map of Ust-Kamenogorsk (Study Area)*

[1] Yandex.Traffic. Web resource: https://yandex.kz/maps/ru (accessed 21.04.2025). Table 1 presents the protocol for calculating the traffic flow intensity at the intersection of Satpayev ave. – Esenberlin ave. – Zhibek Zholy str. – Bazovaya str. in Ust-Kamenogorsk, using the Yandex. Traffic application, as previously mentioned

*Table 1. Protocol for Recording Vehicle Traffic Intensity at the Intersection of Satpayev ave., Esenberlin ave., Zhibek Zholy str., and Bazovaya str.*

| No. | Direction | Number of vehicles | | | | Equivalent Intensity, veh/h |
|---|---|---|---|---|---|---|
| | | Passenger Cars | Trucks | Buses | Road Trains | |
| Satpayev ave., from bridge | Left | 301 | 14 | 2 | 1 | 337 |
| | Straight | 720 | 10 | 18 | 2 | 791 |
| | Right | 430 | 21 | 3 | 3 | 489 |
| Satpayev ave., from SFF | Left | 344 | – | – | – | 344 |
| | Straight | 989 | 16 | 20 | – | 1 071 |
| | Right | 17 | 5 | – | – | 27 |
| Esenberlin ave. | Left | – | – | – | – | – |
| | Straight | 206 | 5 | – | – | 216 |
| | Right | 7 | – | – | – | 7 |
| Zhibek Zholy str. | Left | 480 | 20 | 3 | 1 | 531 |
| | Straight | 179 | 6 | – | 1 | 194 |
| | Right | 40 | – | – | – | 40 |
| Bazovaya str. | Left | – | – | – | – | – |
| | Straight | 103 | 9 | – | – | 121 |
| | Right | 217 | 4 | 2 | – | 230 |

Experimental data indicate that in the city of Ust-Kamenogorsk, traffic congestion in the pre-bridge areas near the Irtysh River represents one of the most critical transportation issues.

The main causes of congestion in the pre-bridge area over the Irtysh River include:

- High traffic flow intensity originating from the Silk Fabric Factory (SFF) residential district during morning hours and from the right-bank part of the city, particularly at the intersection of N. Slavskoho Street – Pobedy Avenue – Kazakhstan Street – Permitina Street, leading to a significant overload of the Irtysh Bridge and the adjoining road network.
- Limited bridge capacity — the existing roadway includes four lanes in each direction, which is insufficient for current and projected traffic volumes. One of the main reasons for congestion is the fact that the bridge over the Irtysh River serves as the only major transportation artery connecting two large urban districts.
- Underdeveloped road interchanges at the bridge approaches, resulting in vehicle accumulation and the formation of traffic queues. In particular, the complex intersection configuration at N. Slavskoho Street – Pobedy Avenue – Kazakhstan Street – Permitina Street, where a roundabout is implemented, contributes to reduced traffic speed and an increased number of road traffic accidents.

The number of vehicles continues to grow rapidly, and this factor must be taken into account. The redistribution of traffic flows should be considered as a comprehensive and strategic process, regardless of the size of the urban area. Rationality and efficiency are the two primary objectives that must be achieved through traffic flow redistribution.

## RESEARCH RESULTS AND DISCUSSION

For forecasting and the subsequent redistribution of traffic flows in the city of Ust-Kamenogorsk, it is essential to identify the correlation between traffic intensity, queue length, and vehicle speed at the "bottleneck" locations within the city and certain locations outside the city, from which traffic flows either enter the urban area or are directed to other city districts.

Therefore, based on preliminary experimental studies of traffic characteristics, the intersection of Satpayev Avenue – Esenberlin Avenue – Zhibek Zholy Street – Bazovaya Street was selected as a representative and informative location within the city.

The assessment of sample homogeneity was conducted using mean values, such as hourly traffic intensity during peak periods and queue lengths on different days. To evaluate the homogeneity of means for independent normally distributed variables with equal but unknown variances, the Abbe criterion can be used, the statistic of which is defined by the following ratio (1) [*Abedzhanova* et al., 2010]:

$$q = \frac{1}{2}\left( \sum_{i=1}^{n-1} \left(x_{i+1} - x_i\right)^2 / \sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2 \right) \quad (1).$$

The null hypothesis $H_0$ is tested: $m^*_1(x) = m^*_2(x) = m^*_3(x) = m^*_4(x)$,
against the alternative $H_1$: $|m^*_{i+1}(x) - m^*_i(x)| > 0$.

If the calculated value of the q-statistic exceeds the critical value corresponding to the significance level $\alpha = 0.05$, the hypothesis of equality of the mean values is rejected.

However, since the Abbe q-statistic does not utilize all available information about the observed objects, the Student's t-test is used for pairwise comparison of means, and its statistic can be estimated using the following expression (2):

$$t = \frac{\bar{x} - \bar{y}}{\sqrt{(m-1)D_x + (n-1)D_y}} \sqrt{\frac{mn(m+n-2)}{m+n}} \quad (2),$$

where $\bar{x}$ and $\bar{y}$ — the sample means under investigation,
$D_x$, $D_y$ — the estimates of the variances of the random variables,
$n$, $m$ — the sample sizes,
$(n - 1)$, $(m - 1)$ — the degrees of freedom associated with the variance estimates.

The null hypothesis $H_0$: $\bar{x} = \bar{y}$ is tested against the alternative $H_1$: $\bar{x} \neq \bar{y}$ under the assumption of homogeneity of variance estimates and normal distribution of $X$ and $Y$. The null hypothesis is rejected if $|t\_obs| > t\_crit(\alpha/2;\, k)$, where $\alpha$ is the significance level, and $k$ is the number of degrees of freedom, $k = n + m - 2$.

To assess the homogeneity of traffic flows at the intersection of Satpayev Avenue – Esenberlin Avenue – Zhibek Zholy Street – Bazovaya Street, both the Abbe and Student's t-tests were applied (Table 2).

*Table 2. Results of Abbe's q-statistic and Student's t-statistic Calculations*

| No. | Parameter | Value |
|---|---|---|
| 1 | Abbe's q-statistic | 1.72 |
| 2 | Student's t-statistic | 1.83 |
| 3 | Critical value of Abbe's q-statistic | 1.45 |
| 4 | Critical value of Student's t-statistic | 2.06 |

Comparison of the obtained values with the critical values at the significance level $\alpha = 0.05$ showed that Abbe's q-statistic (1.72) exceeds the critical value (1.45), while Student's t-statistic (1.83) is lower than the critical value (2.06). Based on this, it can be concluded that the traffic flows at this intersection are heterogeneous. In this context, non-homogeneous traffic flows refer to differing traffic intensities, vehicle types, and movement patterns depending on the time of day and direction of flow. This may be due to various factors, such as different traffic intensities at different times of the day, varying composition of traffic flow, the influence of traffic light control, and the presence of pedestrian crossings. To identify the relationship between intensity, queue length, and speed at the intersection of Satpayev Ave. – Esenberlin Ave. – Zhibek Zholy St. – Bazovaya St., a correlation analysis was conducted (Table 3).

*Table 3. Correlation coefficients between traffic intensity, queue length, and speed*

| No. | Parameter | Intensity | Queue Length | Speed |
|---|---|---|---|---|
| 1 | Intensity | 1 | A.AA | B.BB |
| 2 | Queue Length | A.AA | 1 | C.CC |
| 3 | Speed | B.BB | C.CC | 1 |

Based on the general patterns of traffic flow, the following results can be expected:

- Intensity and queue length: positive correlation (A.AA). The higher the traffic intensity, the longer the queue at the intersection. The values will likely be positive and moderately strong (e. g., 0.6–0.8);
- Intensity and speed: negative correlation (B.BB). The higher the traffic intensity, the lower the speed. The values will be negative (e. g., from 0.5 to −0.7);
- Queue length and speed: negative correlation (C.CC). The longer the queue, the lower the speed. The value will be negative (e. g., from −0.4 to −0.6).

The results of the correlation analysis revealed a direct relationship between traffic intensity and queue length (A.AA = 0.7), as well as an inverse relationship between intensity and speed (B.BB = −0.6), and queue length and speed (C.CC = −0.5). These results confirm the impact of traffic intensity on the occurrence of congestion situations.

Based on data on the movement of vehicles between different districts of the city, correspondence matrices were constructed.

The analysis of these matrices allowed identifying the most congested routes and directions of traffic (Fig. 2). The traffic flow intensity data were collected using the Yandex.Maps traffic service.

The graph will visually represent the most congested routes and traffic directions in the city, which will aid in making decisions to optimize the transportation system. The analysis of the correspondence matrix showed that the highest traffic intensity is observed on the SFF-Menovnoe route, which is where shopping centers, government institutions, educational institutions, etc. are located. To reduce congestion in the most problematic sections of the road network, it is recommended to implement intelligent transportation systems, change the operating mode of traffic lights, and build new roads and interchanges.

In addition, it is advisable to conduct a detailed simulation of traffic scenarios based on current data to assess the potential impact of the proposed measures. By modeling various traffic management strategies — such as dynamic signal control, alternate routing, and congestion pricing — the city administration can forecast outcomes and select the most effective solutions. These models will also help evaluate how infrastructure investments (like new interchanges) may redistribute traffic flows and reduce load on critical corridors such as the SFF-Menovnoe axis.

Analysis of international experience shows that the application of GIS for spatial analysis of accident-prone areas and the development of intelligent transport systems enhances the safety and efficiency of urban transportation infrastructure. For instance, Abdelali et al. demonstrated the effectiveness of GIS in identifying hazardous segments of the road network in Constantine, Algeria, thus improving accident analysis accuracy in rapidly growing traffic environments [*Abdelali* et al., 2024]. Sheng emphasized the role of ITS in the transport planning for small and medium-sized cities, highlighting its relevance to urban scales comparable to Ust-Kamenogorsk [*Sheng*, 2024]. Pomortseva et al. substantiated the use of GIS as a core tool in developing intelligent urban transport networks, contributing to sustainable traffic management and improving road infrastructure capacity [*Pomortseva* et al., 2024]. Furthermore, Zagorodniy et al. explored prospective directions for deploying information transport systems, underlining the necessity to align urban transport policy with modern digital solutions [*Zagorodniy* et al., 2024].

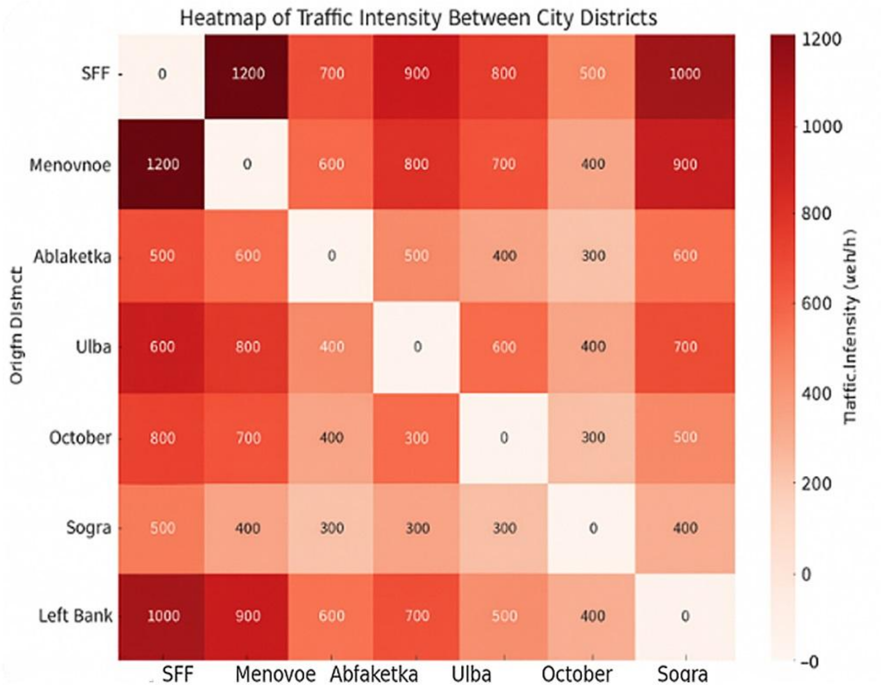


*Fig. 2. Heat map of traffic flows*

**CONCLUSIONS**

In this article, a GIS-based analysis of traffic congestion on the urban road network was conducted. The research results identified the approaches to the Irtysh Bridge as the area with the greatest traffic load, connecting the left and right parts of the city.

This conclusion is supported by the correlation analysis (Table 3), which showed a strong link between traffic intensity, queue length, and reduced speed at bottleneck locations. Additionally, the highest equivalent traffic flow intensity was recorded on Satpayev Avenue near the Irtysh Bridge (see Table 1), confirming that this segment experiences the heaviest congestion among all analyzed intersections.

To improve the transportation situation in Ust-Kamenogorsk, it is recommended to implement the following measures:

- construction and organization of multi-level intersections on the approaches to the bridge (Satpayev Ave., Kazakhstan St.) to increase the capacity of the road network;
- implementation of smart traffic lights that switch traffic light signals based on the number of vehicles in each direction. The smart traffic light receives information about the traffic

flow from video cameras, processes it, and, according to a pre-set algorithm, decides in which direction and for how long to open the traffic;
- redistribution of traffic flows based on correspondence matrices.

The justification for the proposed measures stems from the results of the correlation analysis, which revealed a strong link between traffic congestion and factors such as queue length, vehicle intensity, and delays at major intersections. The high values of traffic flow intensity and low vehicle speeds observed at bottleneck locations, especially on the approaches to the Irtysh Bridge, indicate that the current infrastructure is unable to efficiently handle the existing traffic load.

The introduction of multi-level intersections would reduce the number of conflict points and streamline vehicle movement by separating traffic flows across different levels. In parallel, the implementation of smart traffic lights — capable of adjusting signal phases in real time based on traffic conditions — would optimize throughput at intersections, minimize idle times, and help maintain uniform vehicle speeds. These measures are supported by findings from similar studies in other urban areas [*Lahlouh* et al., 2024], where adaptive traffic control systems led to a measurable reduction in congestion and travel time.

The prospects for the development of transport infrastructure are directly linked to the implementation of Geographic Information Systems and intelligent systems, as confirmed by modern research. The role of spatial data and GIS in informed decision-making for transport system development is emphasized by Zhang and Song [2024], while the strategic directions for the advancement of information-based transport systems are outlined by Zagorodniy et al. [2024].

Further research may be directed towards developing more accurate algorithms and methods for traffic management to eliminate traffic congestion.

## REFERENCES

*Abdelali B., Moufida B., Oualid M., Redjal O.* Analysis of Traffic Accidents Using Geographic Information Systems (GIS): A Case Study of the City of Constantine, Algeria. International Journal of Innovative Technologies in Social Science, 2024. V. 3. No. 43. DOI: 10.31435/rsglobal_ijitss/30092024/8233.

*Abedzhanova A. S., Dzhaxylykov A. F., Rasskazov P. A., Apshikur B., Islyam G.* Automated System for Optimizing the Movement of Urban Passenger Transport Using GIS. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences — ISPRS Archives, 2023. V. XLVIII-5/W2-2023. P. 1–8. DOI: 10.5194/isprs-archives-XLVIII-5-W2-2023-1-2023.

*Abedzhanova A. S., Kornev V. A., Makenov A. A.* Justification of the Installation Location of Transport Detectors in Local Traffic Management. News of the Scientific and Technical Society “Kahak”, 2010. No. 3. P. 55–58 (in Russian).

*Alkaissi Z.* Traffic Congestion Evaluation of Urban Streets Based on Fuzzy Inference System and GIS Application. Ain Shams Engineering Journal, 2024. V. 15. No. 6. Art. 102725. DOI: 10.1016/j.asej.2024.102725.

*Lahlouh A., Ben D. N., Cheikh S.* Analyzing Traffic Congestion Patterns in M’diq: A GIS Study, 2024. P. 137–186. DOI: 10.4018/979-8-3693-6452-9.ch005.

*Pomortseva O., Kobzan S., Panteleeva N.* Application of Geoinformation Systems in the Development of the City’s Intelligent Transport Network. IOP Conference Series: Earth and Environmental Science, 2024. V. 1415. No. 1. Art. 012022. DOI: 10.1088/1755-1315/1415/1/012022.

*Sahitya K. S., Prasad C.* A Methodology for a Comprehensive Evaluation of an Urban Transport Network Structure Using Geographical Information Systems (GIS). Slovak Journal of Civil Engineering, 2024. V. 32. No. 2. P. 48–57. DOI: 10.2478/sjce-2024-0013.

*Sheng J.* Research of Transport Planning and Design of Small and Medium-Sized Cities Based on an Intelligent Transport System. World of Transport and Technological Machines, 2024. V. 2. No. 84. P. 58–64. DOI: 10.33979/2073-7432-2024-1-2(84)-58-64.

*Zagorodniy N., Golovkin M., Bondar A.* Research of Promising Directions for the Development of Information Transport Systems. World of Transport and Technological Machines, 2024. V. 1. No. 84. P. 39–47. DOI: 10.33979/2073-7432-2024-1-1(84)-39-47.

*Zhang Z., Song Y.* Spatial Big Data and Analysis Strategies Supporting Geographic Information System for Transportation (GIS-T) in Conceptual Design, Modelling, and Decision-making: A Review. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2024. V. X-4-2024. P. 461–468. DOI: 10.5194/isprs-annals-X-4-2024-461-2024.