The Technological Aspect of Digitalizing Traffic Management in Settlements under Martial Law and During Post-War Reconstruction*

Olena Verenych[1,†], Ihor Vasyliev[1,*,†], Serhii Tymchenko[1,†], Oleksandr Voitenko[1,†] and Andrii Limonov[2,†]

[1] *Kyiv National University of Construction and Architecture, Povitrianych Syl, 31, Kyiv, 03037, Ukraine*
[2] *All-Ukrainian public organization "Guild of Designers in Construction" and All-Ukrainian public organization "Association of Construction Industry Experts"*

Abstract
The article examines the challenges of modernizing transport systems and organizing traffic control in Ukrainian urban areas under martial law and during post-war reconstruction. It identifies the threats and challenges faced by municipal transport networks because of armed aggression and underscores the need to ensure the resilience, safety, and adaptability of urban mobility in accordance with sustainable development principles. The study focuses on the role of the management system of road traffic and traffic flow, particularly its structural components in large cities, as well as the necessity of modernizing enterprises responsible for traffic control as a key element of this system. A conceptual project-management model for modernizing traffic control is proposed, incorporating the principles of sustainability, safety, adaptability, and technological innovation. The article justifies the need to implement advanced information technologies—such as GIS, web cartography, and artificial intelligence—to digitalize road traffic management processes. A technological approach to modernizing the operational workflows of traffic control management enterprises is presented, encompassing the handling of geospatial data related to traffic-control devices, as well as the modeling and analysis of road traffic incidents. Spatial-temporal analysis tools for identifying road traffic incident concentration zones are discussed. The proposed solutions aim to enhance the efficiency of transport system management and strengthen the resilience of urban infrastructure in the face of contemporary threats.

Keywords
Digitalization, road traffic, traffic control, transport system, management, modernization project, spatial data

1. Introduction

Since the large-scale armed aggression against Ukraine began in February 2022, the process of modernizing urban transport systems (TS) was halted. To the unresolved peacetime challenges of municipal TS have now been added the threats and demands of martial law and post-war recovery, which relate to ensuring national defense, strengthening the resilience of urban transport, and developing sustainable urban mobility. This situation has given rise to a diverse set of practical tasks—varying in scope, origin, and location—that municipal TS must address as a matter of urgency. Above all, these tasks concern large cities, which are most vulnerable to military actions and their aftermath.

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[1*] Corresponding author.
[†] These authors contributed equally.
verenhych@ukr.net (O. Verenych); via1968@ukr.net (I. Vasyliev); sergeyt1466@gmail.com (S. Tymchenko); voitenko.os@knuba.edu.ua (O. Voitenko); limonovae13@gmail.com (A. Limonov)
0000-0003-0972-6361 (O. Verenych); 0000-0002-4477-4521 (I. Vasyliev); 0009-00009-3331-318 (S. Tymchenko); 0000-0002-7414-7836 (O. Voitenko); 0009-0006-1402-2659 (A. Limonov)

Amid reduced transport efficiency and service quality, deteriorating environmental conditions and mobility, the transformation of cities into uncomfortable and unsafe living environments, and the ongoing hazards of post-war reconstruction, it is vital for Ukraine's successful and effective socio-economic development—and for enhancing national defense—that municipal TS be modernized in accordance with the principles of sustainable mobility adapted to current threats and challenges. Accordingly, transport solutions must not only be economically efficient, socially inclusive, and environmentally safe but also capable of supporting the country's defense needs against existing and anticipated threats.

Successful modernization of an urban TS is possible only through the planning, design, implementation, and monitoring of specific modernization measures. Crucially, the TS must remain operational throughout this process, that is, continue to carry passengers and freight over designated routes and schedules—which cannot be achieved without effective system control. Naturally, any modernization that entails infrastructure renewal, the introduction of new technologies, or changes in mobility patterns will require coordination between new transport solutions and existing ones. This, in turn, demands a corresponding upgrade of the control system, which must both facilitate the modernization process and ensure the TS's ongoing functionality, seamlessly integrating updated processes into regular operations. Therefore, one of the key directions in urban TS modernization must be the modernization of its control system.

In conditions of martial law and armed conflict, the controllability of an urban TS becomes even more critical, since its complete or partial loss can have catastrophic consequences for the resilience and defense capability of the city, its region, and, in some cases, the entire country.

The principal operational process within an urban TS is road traffic—defined as the regulated movement of vehicles along the urban street and road network (USRN), in accordance with established rules under specific road conditions. The TS's controllability is ensured by the Management system of road conditions and traffic flow in the settlement (hereinafter, Management System or MS).

In large cities, the MS comprises the local executive authority—typically a specialized municipal department—and the communal enterprises (or institutions) responsible for maintaining the USRN and traffic control (TC).

Road traffic operates through the "Road Conditions–Traffic Flows" system (hereinafter, "RC–TF System"), in which each traffic flow consists of elementary subsystems of "vehicle–driver–road." In these subsystems, the driver functions as the control element, operating the vehicle in response to prevailing road conditions. When an elementary "vehicle–driver–road" subsystem joins a traffic flow, the driver's ability to control the vehicle becomes significantly constrained—control is exercised only within the dynamics and patterns of the flow. Those flow dynamics, in turn, emerge from the interaction of numerous internal and external factors, such as road state and parameters, meteorological conditions, technical characteristics and number of vehicles, driver condition, information support, traffic regulations, and TC measures.

The increasing complexity and volume of traffic flows—as well as their merging or crossing—make the RC–TF System more intricate, less controllable, and less stable. Road conditions and traffic flows cannot realign themselves without external intervention. There is a clear need for a MS that, within its temporal and spatial management framework, can exert executive influence on the RC–TF System by making decisions, implementing them, monitoring their execution and outcomes, and, when necessary, adjusting those decisions.

An analysis of annual average road utilization, vehicle numbers, and air-quality data [1, 2, 3, 4, 5] shows that, despite certain operational strengths, the organizational structure and composition of the MS in Kyiv, Kharkiv, Odesa, and Dnipro had notable shortcomings [6] even before the war. This underscored the need for its modernization and supported the transition toward intensive development of urban TC based on sustainable mobility principles.

Under martial law and during post-war reconstruction, modernizing municipal MS becomes even more critical, as it raises transport resilience to a level that enables authorities to make timely, well-informed decisions regarding the TS's operation and to address practical challenges of both civilian and military nature.

In general, the tasks associated with the routine carriage of passengers and freight are continuous in nature, exhibiting certain spatial–temporal dynamics of traffic flows. However, at critical moments—extraordinary or shock situations—civilian or military–related tasks arise that demand rapid intervention and swift decisions by the MS: redeployment of security forces and emergency services; movement of specialized vehicles; clearance of road traffic incidents (RTI), industrial incidents, or disasters; transport of troops, military equipment, and weapons; evacuation of civilians and material assets. In some cases, the sequence of events can be anticipated, and pre-defined solutions are developed—for example, an evacuation plan in the event of an industrial accident or a temporary alternative-route scheme if a bridge is destroyed.

Most of these tasks can only be accomplished through more flexible and cost-effective soft measures of traffic control. This requirement must be considered when modernizing the MS, so that the TS unit responsible for traffic organization assumes a leading role in MS. Currently, in major cities, this function of MS is represented by the specialized department of the local executive authority together with the municipal enterprise/institution (hereinafter, "the Enterprise"). The Enterprise's activities are focused on implementing the traffic-control decisions issued by the specialized department to which it reports.

For the MS to make rapid, high-quality decisions—especially under martial law and during post-war reconstruction—it must process large volumes of reliable, up-to-date information on traffic flows and road conditions. This is only possible through the application of advanced information technologies (GIS, web cartography, artificial intelligence) enabling continuous data collection, processing, storage, analysis, and visualization during traffic modeling and forecasting, traffic-control design, maintenance and monitoring of traffic-control devices, and real-time traffic management using Intelligent Transportation Systems (ITS) and Automated Traffic Control Systems (ATCS), as well as accident analysis and the provision of services to stakeholders.

Having analyzed the following (i) The challenges of developing municipal transport systems in peacetime; (ii) The threats and demands posed by martial law and post-war reconstruction; (iii) Persistent external threats; (iv) The imperative to modernize both urban transport systems and the MS—especially in large cities, regional centers, industrial hubs, and cities with populations over 50,000, considering the Trans-European Transport Network; (v) The increasing complexity of tasks and the heightened requirements for speed, flexibility, and quality in decision-making; (vi) The growing informational burden and the current state of information-technology development; (vii) The distribution of functions among the MS's structural elements, and the leading role of the Enterprise in providing data for traffic-management and organization—it is deemed most appropriate, within the framework of modernizing the Control System, to focus first on upgrading the Enterprise.

Given the complexity and critical importance of modernizing the Enterprise, the central role of information in this process, and the risks and challenges of martial law and post-war recovery, the Enterprise's modernization at every stage should proceed via a comprehensive, systematic application of project-management methodologies. To this end, we propose to implement the Enterprise's modernization by digitalizing its operational processes for TC and organization as part of the broader urban traffic-control modernization project.

2. Conceptual model for managing an urban traffic management modernization project

The conceptual model for managing an urban traffic-control modernization project (hereinafter, "the conceptual model") is a generalized, logical, and structured representation of the project's core management elements, the interrelationships among them, and the sequence of actions required for the effective implementation of changes in traffic control. This model provides an overarching view of the project-management process and enables the identification of key objectives, resources, stakeholders, implementation methods, and expected outcomes.

The purpose of the conceptual model is to ensure effective management of projects aimed at improving traffic control, enhancing road-traffic safety and the efficiency of passenger and freight transport, and promoting broader adoption of advanced information technologies in the context of implementing sustainable urban mobility.

Developing the conceptual model facilitates a systematic approach to introducing innovations in traffic control, thereby improving the quality of traffic control in the municipality, enhancing mobility, reducing transport's negative environmental impact, and increasing the resilience of the municipal transport system to adverse influences.

The conceptual model serves as an essential strategic-management tool for traffic-control modernization projects. It ensures alignment of all participants' actions, efficient use of resources, and achievement of the established goals in municipal transport policy.

To support continued sustainable development of municipalities under martial law and during post-war reconstruction—given the unresolved transport challenges of peacetime and their exacerbation due to the effects of armed aggression—the conceptual model is proposed to incorporate the following **principles**:

- **Sustainability**. Any traffic-management solution within the municipality's TS in the frame of TC must be economically efficient (achieved by optimizing traffic flows and reducing travel time), environmentally friendly (aimed at lowering CO_2 emissions, noise pollution, and energy consumption), and socially inclusive (prioritizing the most vulnerable populations).
- **Safety**. TC measures should focus on reducing road-traffic accidents, preventing the formation of high-accident zones, and improving conditions for pedestrians, persons with reduced mobility, micromobility users, and cyclists.
- **Adaptability**. TC interventions must enable the transport system to flexibly respond to changes in traffic patterns within the urban street and road network caused by evolving road and external conditions—such as motorization trends, demographic shifts, land-use planning, legislative updates, technological advances—as well as the risks and challenges posed by martial law and post-war reconstruction.
- **Technological capability**. TC measures should leverage modern technologies (AI, IoT, GIS, web cartography) to analyze real-time traffic data and support timely, well-founded traffic-management decisions.

The proposed conceptual model is characterized by the following **main structural elements (components):**

- **Stakeholders**: government and local authorities, patrol police, carriers, contracting organizations, the community, and road users.
- **Resources: financial (budget), material**: equipment, human (staff, specialists, managers, project team), information (current and archival spatial, attribute, and metadata on traffic flows, traffic-control devices, and urban street and road network).
- **Implementation Phases** (carried out through the following processes): Analysis of the current state (traffic data, accident statistics, environmental conditions), Planning (defining objectives and modernization priorities, identifying problems, drafting plans and schedules), Design (developing traffic-management modernization solutions), Implementation (deploying the modernization measures), Monitoring (evaluating effectiveness via KPIs (e.g., accident rates, network load, time lost in congestion)), Adjustment (refining, modifying, and adapting tasks and schedules based on feedback and updated data).
- **Technologies and tools for implementation**: project-management methodologies (PMBOK, PRINCE2, etc.), Gantt charts for scheduling, SWOT analysis for identifying project

strengths and weaknesses, key performance indicators (KPIs), and execution-tracking software (e.g., MS Project)

- **External factors influencing model implementation**: weather conditions, the state of the urban street and road network and vehicles, spatial land-use organization, legal and regulatory framework, seasonal/weekly/daily traffic fluctuations, etc.
- **Traffic-control infrastructure**: road signs, traffic lights, road markings, surveillance cameras, Intelligent Transportation Systems (ITS), and Automated Traffic Control Systems (ATCS).

All elements of the conceptual model are interconnected. For example, resources are used to achieve objectives through the implementation of specific solutions, and management tools enable tracking the effectiveness of each phase and making timely adjustments.

Implementing projects according to this model makes it possible to achieve the following expected outcomes (i) reduced accident rates on the urban street and road network (RTI); (ii) shorter travel times; (iii) improved environmental conditions in the municipality, especially on RTI sections with the highest traffic intensity; (iv) increased public satisfaction with the services provided by the transport system; (v) more informed decision-making regarding the development and planning of the municipal transport system and land-use planning; (vi) enhanced controllability and resilience of the transport system, including against the risks and challenges of martial law and post-war reconstruction.

To provide a clearer understanding of the conceptual model's structure, we present it as a block diagram (graphical structural model) that illustrates the dynamic project-management process, the model's main components, and their interrelationships (Figure 1).

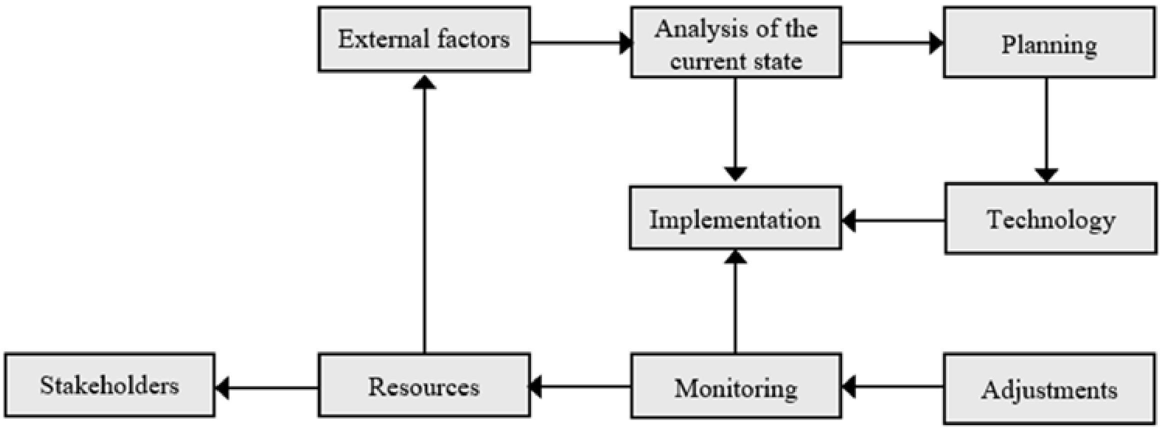

Figure 1: Block diagram of the conceptual model for managing urban traffic-control modernization projects.

3. Requirements for TC modernization under martial law and post-war reconstruction conditions

Experience from individual territorial communities and findings from research indicate that under conditions of armed aggression, modernizing traffic-control measures to address martial law and post-war reconstruction is critically important for enhancing transport resilience.

Modernization of traffic-control measures should proceed in several stages and include: (i) threat analysis; (ii) risk assessment; (iii) updating multi-level strategies and plans to current conditions, including cross-border coordination with neighboring countries.

Concurrently, the regulatory and methodological framework for traffic-control design must be adapted alongside traffic-flow modeling and forecasting.

The modernized traffic-control measures are proposed to be divided into three groups (i) **Short-term measures** (temporary or critical restorative actions) to ensure evacuation, movement of emergency services, and remediation of local damages; (ii) **Medium-term measures** to maintain and restore critical infrastructure and address the aftermath of local damage over an intermediate period; (iii) **Long-term measures** to reestablish sustainable mobility and adapt or transform mobility conditions under martial law and during post-war community reconstruction in line with sustainability principles.

Short-term measures (temporary or critical restorative actions) are necessary to ensure the uninterrupted operation of main roads, highways, artificial structures, and the overall RTI before, during, and immediately after the onset of armed aggression or the threat or occurrence of emergencies.

During this period, urgent and uncoordinated evacuation of part of the population by private vehicles begins. Long queues form at fuel stations and for essential goods. As a result of these events, the number of RTI. Drivers, without waiting for the appropriate services, abandon their vehicles and evacuate via alternative routes. All these events and their consequences create significant traffic delays, leading to substantial material losses, human costs, and time expenditure.

To prevent such outcomes in the future, it is necessary to develop measures to (i) rapid segregation of traffic flows; (ii) ensuring unhindered movement of emergency services; (iii) organized evacuation by private vehicles; (iv) containment of excessive traffic volumes; (v) implementation of filtering measures; (vi) remediation of localized damage to road-transport infrastructure.

The implementation of the measures listed above requires the development of TC schemes or plans featuring the placement of TCD. According to [7], a TC scheme is a drawing that uses conventional symbols to show the placement of traffic-control devices on a road (street) segment or at locations of road-service facilities.

TC schemes do not define road geometry, travel routes, checkpoints, or similar elements.

The development of TC schemes must be carried out in accordance with officially developed and approved population-evacuation plans, as well as the designated locations of filtering points, checkpoints, emergency-services routes, and so on.

Medium-Term Measures. Restoring road-transport infrastructure in frontline territories and areas liberated after temporary occupation requires both emergency actions and medium-term interventions.

Measures to ensure the operation and restoration of critical infrastructure should be categorized by scope and scale, based on the experience of repairing and rebuilding major cities that were partially occupied or on the front line—such as Mykolaiv, Chernihiv, Kharkiv, and Sumy. In these cities, since the onset of armed aggression, bridges and other artificial structures, roads, rail tracks, and overhead lines for electrified public transport were destroyed and partially rebuilt.

To reconstruct major structural elements, it is necessary to develop design and cost-estimate documentation, obtain the required approvals, undergo expert review, and secure final authorization. Depending on the level of destruction, the design phase can take from two months to two years. Construction timelines, contingent on funding and security conditions, can also extend to several years. To maintain critical infrastructure during the design and construction period, rapid temporary solutions are needed. Such solutions may include modular or custom-designed temporary structures. These approaches were employed after the bridges over the Irpin River on the Novo-Irpin highway were blown up on 25 February 2022 during the defense of Kyiv [8].

Long-Term Measures. In the context of current challenges related to the destruction and reconstruction of communities, this process should be seen as a unique opportunity not only to build new infrastructure but also to foster progressive territorial development. In particular, restoring areas affected by military aggression requires not only technical and engineering solutions but also alignment with modern trends in land-use planning and sustainable development [9].

During community reconstruction, it is essential to uphold the principles of sustainable development, which aim to meet the needs of the present without compromising the ability of future generations to meet their own. Efforts must focus on reducing emissions and improving energy efficiency in accordance with the 17 Sustainable Development Goals that Ukraine has committed to achieve by 2030. Community territories can be divided into three zones: urban centers, their peripheries, and the inter-settlement areas. Most challenges arise within the urban centers—where population, industrial facilities, transport infrastructure, and social services are concentrated—leading to network overload, congestion, and related issues. A three-tiered management approach—addressing traffic flows, mobility, and spatial planning—is intended to resolve these problems by optimizing intersections and expanding transport networks [9].

Based on an analysis of contemporary street-and-road design trends in Ukrainian municipalities and global best practices, the following principles for reallocating street-road space have been formulated (i) Equitable Access: ensuring that public spaces are accessible to people of all social groups, ages, and abilities; (ii) Safety: providing citizens with the confidence to feel secure on their city's streets; (iii) Diversity of Activities: offering all social groups a variety of accessible recreational and social opportunities in public spaces; (iv) Comfortable Microclimate: ensuring that street environments are pleasant and comfortable for residents; (v) Aesthetics: creating visually attractive urban spaces [10].

4. Technological aspect of modernizing traffic control operational processes

The technological aspect of modernizing the Enterprise involves integrating advanced information technologies into its operational processes, which encompass several technological workflows, including: (i) Geospatial data processing; (ii) Use of base mapping; (iii) Maintenance of a TCD location database; (iv) Collection of source data on TCD placement, composition, and condition; (v) Creation and use of a unified electronic TC scheme; (vi) Handling of geospatial TC data in a networked environment; (vii) Management of paper-based documentation; (viii) Design, modeling, and analysis of TC schemes; (ix) Urban street and road network analysis.

Geospatial data processing. These workflows involve the collection, validation, entry, storage, analysis, and visualization of geospatial data on base objects, traffic-control devices, and other municipal infrastructure. They rely on modern GIS technologies.

Use of base mapping. Utilizing vector data and raster images from a 1:2,000-scale topographic plan, cartographic materials of other scales, and open web-mapping resources (e.g., Google Maps, Google Earth, OpenStreetMap) is performed using QGIS and the PostgreSQL DBMS. This setup allows for: (i) Building a database of base geospatial infrastructure objects; (ii) Entering and editing coordinate, attribute, and metadata; (iii) Creating and composing cartographic outputs at various scales, content levels, and generalization; (iv) Printing maps and generating raster outputs; (v) Storing data in multiple geospatial vector and raster formats (Shapefile, GeoJSON, KML/KMZ, GML, DXF, GeoTIFF) [11].

Maintenance of the TCD location database. The TCD Location Database (hereinafter, "the DB") is a hardware–software system for collecting, storing, processing, and providing thematic information on the presence, composition, technical characteristics, and other details of TCDs and other infrastructure elements within the municipality's street-road network. The DB is maintained using the PostgreSQL DBMS and PostGIS extension, which support storage, indexing, and querying of geospatial data. Data on TCDs and other infrastructure elements are entered into the DB based on inspection results, condition monitoring of TCDs, installation, repair, and maintenance work of TCDs; design documentation for construction, repair, and reconstruction of RTI segments; TC design projects; and requirements or directives from the patrol police. Before entry, all information is verified for completeness, data-format consistency, currency, internal integrity, and non-contradiction with existing geospatial records in the DB.

For collecting source data on the location, composition, and condition of TCDs during RTI of the settlement, condition monitoring, and maintenance work, it is recommended to use field-data-collection applications (collectors) such as Mapit GIS on mobile devices. These tools allow users to capture the TCD's geolocation, enter attribute data, and perform photo and video recording with subsequent automatic recognition of TCDs [11].

Creation and use of a unified electronic TC scheme. A unified electronic TC scheme for the municipality is the consolidated current and archival electronic cartographic representation of TCDs and other infrastructure elements across the entire urban area, displayed on a single base map using standardized cartographic symbols. This scheme is produced using QGIS and PostgreSQL.

The unified TC scheme is essentially the cartographic visualization of the Database on the base map, augmented with TCDs and other thematic infrastructure objects in the accepted symbol set.

Within QGIS, custom forms allow users to: (i) Enter coordinate, attribute, and metadata for objects; (ii) Create and compose map outputs at various scales, contents, and levels of generalization; (iii) Print maps and generate raster exports; (iv) Store data in multiple geospatial vector and raster formats (e.g., Shapefile, GeoJSON, KML/KMZ, GML, DXF, GeoTIFF). By recording each TCD's status (planned, active, removed) in the database, it is possible to generate maps that reflect devices according to their status. Leveraging QGIS's database-query capabilities, users can produce thematic map layers showing query results on the unified TC scheme. Approved TC diagrams (in raster form) can also be overlaid on the scheme, georeferenced to the established coordinate system.

Handling TC geospatial data online. Utilizing QGIS, PostgreSQL, PostGIS, spatial-data web servers (MapServer, GeoServer, QGIS Server), JavaScript mapping libraries (OpenLayers, Leaflet), field-data apps (Mapit GIS), and artificial-intelligence tools provides extensive capabilities for managing geospatial data both within the Enterprise's intranet and on the Internet. This applies to office-based tasks as well as field operations for TCD inspection, monitoring, installation, repair, and maintenance; TC design; and processing of governmental directives and patrol-police requirements (Figure 2).

The proposed mechanism enables publishing and searching geospatial data on the Internet using standard protocols (WMS, WMTS, WFS, WCS, CSW). This allows data access not only through QGIS but also via a dedicated web portal and chatbot, both of which can run on desktops and mobile devices.

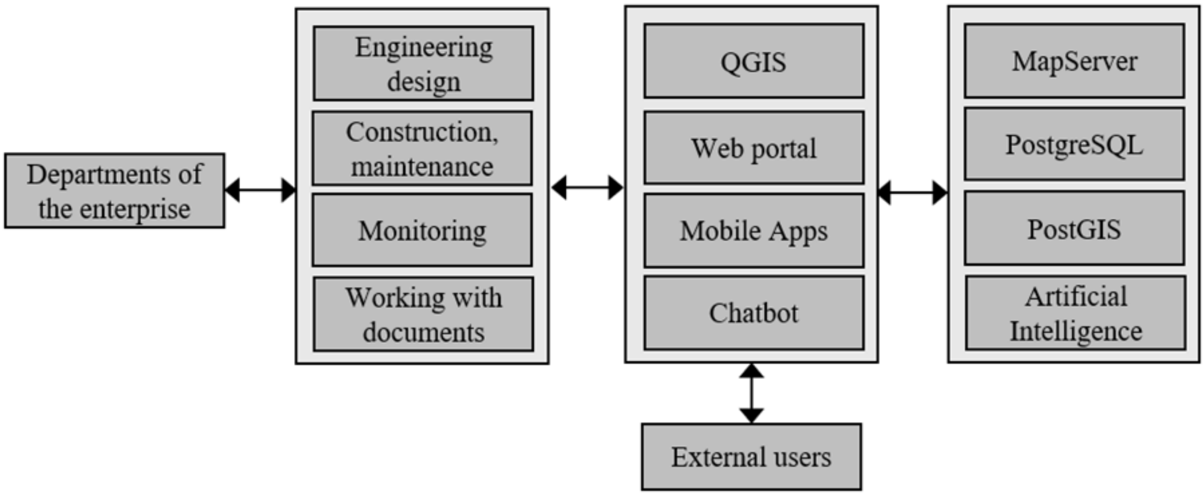

Figure 2: Unified workflow for handling TC geospatial data online.

Primary GIS Tool: QGIS is the main software for geospatial data handling, offering an extensive feature set needed by staff who process source data, build complex database queries, and design intricate cartographic outputs.

Secondary Interface: The web portal provides a robust, yet streamlined, functionality set. Unlike QGIS, it is optimized for routine tasks that do not require QGIS's advanced capabilities (Figure 3).

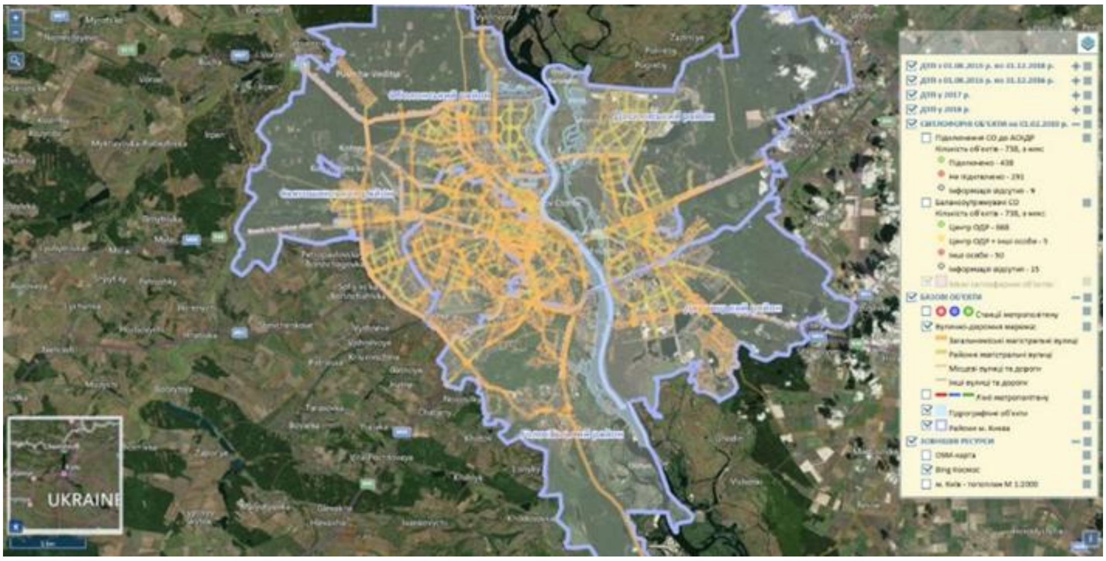

Figure 3: Example of a web portal developed using the OpenLayers JavaScript library.

For example, the web portal is suitable for executing standard database queries, searching for documents, and composing and printing routine documents and map outputs. Using the web portal does not require the advanced software skills needed for QGIS—especially when guided by prepared instructions and recommendations for portal functionality. A significant advantage of the web portal is its accessibility on mobile devices, which is not possible with the full-feature versions of QGIS.

The simplest way to work with geospatial information is via a chatbot installed on a mobile device, which enables completion of basic tasks, such as identifying a traffic sign's reference number from its photo, recording and transmitting TCD data, or obtaining documentary confirmation of the legitimacy of an installed traffic sign on the RTI. When using the chatbot, the user can receive rapid results through artificial-intelligence features—for example, recognizing a traffic sign from a photo and returning its reference number according to the traffic regulations.

Handling Paper Documents. This process involves both archival and current paper records, including design documentation, TC schemes, traffic-signal connection plans, signal timing charts, equipment inventories, technical passports, asset registers, discrepancy reports, work-completion certificates, and directives from the patrol police.

The workflow includes: scanning paper documents; entering document metadata into the database; verifying documents and their metadata; cataloging; viewing; parameterized search (by date, type, purpose, author, status, address); printing; and generating documents based on specific types and database queries.

These operations are performed online via the web portal, which users access with a login and password.

TC Design, Modeling, and Analysis. This process relies on a variety of software tools—both specialized (e.g., PTV Vissim, PTV Visum, AIMSUN, TransModeler, SUMO, Synchro/SimTraffic, LISA+, TORUS Roundabouts, Road Safety Audit, iRAP, HDM-4) and GIS/CAD systems.

The primary task is to provide accurate input data for design, modeling, and analysis, and to import the resulting outputs into the database. However, importing results from external software poses challenges due to the lack of a unified data-exchange format, which can lead to data loss or distortion. Consequently, integrating these results requires using a base GIS (in our case, QGIS), substantial time investment, and highly skilled personnel.

When using the base version of the GIS, its functionality supports only standard spatial-analysis tasks—such as overlay analysis—which, depending on task complexity, may necessitate extending the GIS functionality by programming additional functions or modules, or by employing external software.

Execution of Installation, Repair, and Maintenance Works for TCDs. This process largely takes place directly on the RTI of the municipality. Given the often-adverse working conditions—due to weather, time constraints, and, since the onset of armed aggression, the threat of shelling—it is crucial to be able to prepare accompanying documentation conveniently, quickly, and on the move. For this purpose, a mobile application should be used that allows workers to enter the necessary data on completed tasks, save them to the database (or, if offline, store them locally on the device and later transfer them for database entry), generate the required document, create metadata for the document, and print it.

Accident Data Analysis. The task of road traffic incident analysis involves identifying high-accident locations and concentration zones to design safety-enhancement measures. This task's specificity requires more advanced GIS functionality than is available in base versions of systems like QGIS, necessitating the development of specialized software.

The situation is further complicated by the lack of precisely recorded accident coordinates, making the identification of high-accident sites less accurate, since locations must often be inferred from postal addresses recorded in accident reports.

Accident-location analysis can be performed by calculating Levenshtein distances using the Wagner–Fischer algorithm, implemented in a custom Python 3.7 application with the Psycopg2 library [12]. To identify accident-concentration zones and create thematic maps, QGIS can then be used.

For in-depth analysis of the spatial distribution of accidents, the Kernel Density Estimation method can be used to generate heat maps and identify accident concentration zones (hotspots) [13]. This approach effectively uncovers risk clusters that may go unnoticed with traditional tabular analysis.

Another common tool is cluster analysis, in particular the DBSCAN or K-means methods, which detect groups of incidents with high spatial and temporal density. Applying these techniques enables automatic identification of so-called "black spots"—locations with statistically significant accident recurrence [14].

Temporal-spatial trend analysis offers a more comprehensive approach by accounting for changes in accident metrics over time. GIS platforms allow not only mapping where accidents occur but also when. For example, constructing space-time cubes and detecting spikes in accident rates across different years or seasons helps to track how hotspots evolve over time [15]. Such analysis is especially useful for evaluating the effectiveness of implemented measures—for instance, whether accident rates decreased after installing a traffic signal or whether a new accident cluster emerged following the opening of a shopping center [16, 17]. Ultimately, the city gains a four-dimensional accident model (X, Y, time, intensity), significantly enhancing the quality of decision-making.

5. Conclusions

Based on the research conducted, the following conclusions can be drawn:

- The need to modernize municipal transport systems in Ukraine is driven by both existing peacetime challenges and the new demands of martial law and post-war reconstruction, which require rapid, effective, and resilient traffic-control solutions.
- Ensuring controllability of the transport system is a critical factor for its resilience and functionality, especially in emergencies. A modern control system must be capable of making timely management decisions, implementing them, and adapting to changes.
- The conceptual model for managing the traffic-control modernization project proposed in this work is a systematic strategic-management tool. It enables coordination among all stakeholders, rational resource use, and achievement of sustainable results.
- Modernizing the control system—focused on the development of the specialized municipal enterprise—should proceed through digitalization of operational processes. The key to success is the adoption of advanced information technologies, including GIS, analytical platforms, ITS, and ATCS.

- The digital transformation of traffic-control processes must encompass geospatial data processing, maintenance of the TCD location database, creation of electronic TC schemes, traffic modeling, accident-data analysis, and transparent interaction between authorities and the community.
- The proposed approaches contribute to enhanced road-traffic safety, reduced accident rates, shorter travel times, improved quality of transport services, increased national defense capability, and greater resilience of urban transport systems to external threats.

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Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT to: Grammar and spelling check. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the publication's content.

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