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GIS-based models for transport network emergency management

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Abstract. The authors investigated the methods of structural-parametric synthesis, mathematical modeling and optimal control of transport networks from the position of the system analysis. The goals of ensuring the transport infrastructure safety with the positions of the transport network optimal load are determined especially in case of emergency situations. The paper describes the requirements for the development of a mathematical model of the transport network loading. A large number of studies on the transport network load is carried out in the environment of the “ITSGIS” intelligent transport geographic information system and was aimed at the development of the algorithm for automatic detection of emergency situations and congestion. The emergency situation types are characterized by its location, i.e. its coordinates on the electronic map. The emergency time is considered from various positions, such as time of occurrence, normative and actual time of elimination. The geofences of an emergency situation influence are divided into areas of direct and indirect emergency situation influence on transport processes and transport infrastructure objects. On the basis of the constructed models developed management methods of transport network loading and emergency situations analysis, including the collection and processing of raw data, the emergency situations determination and their characteristics, the optimal response strategy choice, the performance of management functions.

1. Introduction
Considering the existing methods of structural-parametric synthesis, mathematical modelling, optimal control of transport networks and the aim of ensuring the transport infrastructure safety with the positions of optimal transport network loading, especially when emergency situations arise, it is necessary to consider the following requirements when developing a mathematical model of the transport network loading [1]:

- The model should be complexly organized: the semantic and geo-information parameters of traffic flows, transport processes, emergency situations as functions of time and geolocation of the transport network should be considered [2, 3];
- The model should describe the movement of vehicles on a directed graph in the framework of an interactive map in the environment of a geographic information system [4, 5];
- A model that fully takes into account the factors of mutual influence of participants in transport processes should be a model based on the search for balanced distribution of vehicles [6, 7];
- The model should have a predictive nature [8, 9];
- The model that determines the load of the transport network based on the calculation of the strategies of participant behavior in transport processes should be a model of optimal strategies [10, 11].
2. Transport network loading management

Transport network load analysis is a multi-component task whose solution requires the construction of mathematical models for managing transport processes (transport network load model): transport network model, traffic flow model, transport infrastructure management equipment model, emergency situation model.

To build a model for managing the loading of a transport network, the authors introduce the following definitions of basic concepts:

- **Basic section** – a section-haul transport network with a continuous movement of traffic flow, not having adjacent areas of entry and exit.
- **Free flow speed** – the average speed of the traffic flow on the base section without traffic light regulation in conditions of low density of the flow.
- **Capacity of the transport network section** – the maximum intensity of the flow, which is achievable on the base section in the current road conditions; expressed as the ratio of the vehicles number in units given, moving along the section, to the time interval.
- **Capacity of the transport network section** – the maximum flux density that is achievable at the base section; is expressed as the ratio of the vehicles number in reduced units moving along the section to the section length.
- **Transport network loading** – the number of vehicles moving along the transport network sections: intersections, crossings, tunnels, overpasses.
- **The load descriptors of the transport network** are the load factors of the transport network section according to the intensity and density of the traffic flow:
  - The load factor of the transport network on the intensity of the traffic flow, we define as the ratio of intensity to the site capacity.
  - The load factor of the transport network section by the density of the traffic flow is defined as the ratio of the density to the section capacity.
- **The overloaded part of the transport network** is the area where the load factor for the density of the traffic flow approaches 1.

The transport network load model is a collection of objects, attributes and links between them, necessary for solving problems:

- Monitoring and detection of emergency situations arising on the transport network;
- Determination of traffic flow parameters;
- Management of transport processes from the standpoint of information, operational and infrastructure support in order to improve the efficiency and safety of the transport infrastructure;
- Collection and processing of statistical data.

A fundamental feature of the analysis and construction of the load network model of the transport network, which characterizes the complexity of the model, is the identification of the mutual influence and iterative dependence of the choice of vehicle routes on the route’s construction by other means of transport and the resulting transport delay. The mathematical model of mutual influence is built on the basis of the dependence function of the weight characteristic (price) of the arc of a street-road network graph on the intensity of the traffic flow on a given arc.

The process of forming the network load, consisting of the transport routes construction, is based on a comparison of the various routes weight characteristics. In this case, the weight characteristics of the arcs of the graph of the street-road network are determined by the currently existing transport network load.

The construction of complex multicomponent systems models is based on the application of methods and approaches of system analysis. At the initial stage of solving the set tasks, decomposition of the subject area of load control is performed in case of emergency situations. Identifying entities within it and structuring the data characterizing them and interrelationships is the basis of system analysis. The result of the decomposition of the subject area “Transport Network Loading” is presented in Figure 1.
The basis of this decomposition is the model of the subject area “Traffic Management”, which added the classes necessary to describe the model of emergency situations.

![Diagram of transport network loading subjects](image)

**Figure 1.** Decomposition of the “Transport Network Loading” subject area.

The subject area model “Transport Network Loading” is described as (1):

\[
M_{\text{Subject Area}} = (M_{RN}, M_{TFlow}, M_{TIM}, M_{ES})
\]  

(1)

where \(M_{\text{Subject Area}}\) – a model of the subject area “Transport Network Loading”

- \(M_{RN}\) – transport network model;
- \(M_{TFlow}\) – traffic flow model;
- \(M_{TIM}\) – a model of technical means of transport infrastructure management;
- \(M_{ES}\) – emergency situation model.

The transport network model \(M_{RN}\) is determined by the classes: Plot, Graph. The Plot is a polygonal element of an electronic map of a geographic information system that allows you to synthesize a transport network of any configuration, structure with different characteristics. The options for the movement of vehicles, the direction of movement and the various parameters of the traffic flow on the section of the traffic network are described using the Graph and the weight characteristics of its elements.

The traffic flow model \(M_{TFlow}\) is determined by the classes: Speed, Intensity, Density, Composition. The model \(M_{TFlow}\) is considered from the standpoint of the micro-model, in which each vehicle is separated into a separate model with personalized characteristics, and the macro-model, in which the group macroscopic characteristics of the traffic flow are defined.

The model \(M_{TIM}\) includes standard technical means of traffic management, such as traffic signs, traffic lights, and road markings. The process of monitoring the condition of objects includes the collection and processing of data on transport processes and objects using technical means, such as motion sensors, surveillance cameras, satellite navigation systems, etc. Informing the participants of the movement is carried out with the help of specialized boards, means of transmitting information through various communication channels.

The model of an emergency situation \(M_{ES}\) is determined by the classes: Type, Time, Geofence of the influence. The type of emergency situation is characterized by its location, i.e. its coordinates on the electronic map, or the cause of the emergency situation. The time of an emergency situation is considered from various positions, such as the time of the appearance of the emergency situation, the normative and actual time of the removal of the emergency situation, etc. Geofences of the influence of
an emergency situation are divided into areas of direct and indirect influence of the emergency situation on the transport processes and objects of the transport infrastructure.

3. Situation model

The authors define a road traffic situation $s_j$ as an event or a particular state of the transport network, information about the occurrence of which is received by the respective services. The most common events are a traffic accident, the disabling of traffic control devices, damage to underground utilities with a release to the roadway, etc. Special states include extraordinary natural phenomena, such as fog, ice, rain, blizzard, storm phenomena, etc. Defects in a road surface, planned or emergency work carried out on the roadway leading to a decrease in road capacity.

The essence of the approach to the consideration of the situation is to study the road traffic situation and classify it as a class of emergency situations if the event has signs of an impact on traffic flows or throughput of the transport network. The element of considering the situation is to confirm the reliability of information about an event or a special state of the transport network. If the information is reliable, the situation parameters (attributes of the corresponding objects) are determined, its analysis and statistical data processing. Denote $S = \{s_j\}$ as a set of road traffic situations, which received information.

A set of (critical) emergency situations on the transport network $B = \{b_i\}$ – a complex of such situations that have an impact on traffic flows, and the occurrence of which may be random or planned. Contingent situations are characterized by the fact that they are not taken into account when developing a permanent traffic management scheme. Any emergency situation $b_i$ is a traffic situation $s_j$, and not every $s_j$ traffic situation is an emergency situation $b_i$.

$$\forall b_i \in B \exists s_j \in S, b_i = s_j$$

$$\forall s_j \in S (\exists b_i \in B, s_j = b_i) \lor (\exists b_i \in B, s_j = b_i)$$

The emergency change in the transport network graph is a change in the attribute parameters of arcs, nodes, or sections of the TN, caused by an emergency situation.

Type of emergency situation $w_i \in W$. The set $W$ is a set of all possible types of emergency situations.

Examples of elements included in it are accidents, fog, fallen wood, repairs, open manhole, etc.

The model of an emergency situation is defined as (4):

$$M_{ES} = \{M_{Type}, M_{Time}, M_{Zone}\}$$

where $M_{ES}$ – emergency situation model;

$M_{Type}$ – a model of emergency situation type;

$M_{Time}$ – a model of emergency situation time characteristics;

$M_{Zone}$ – a model of emergency situation geofence of influence.

The contingency type model $M_{Type}$ includes contingency types by location and origin. Figure 2 shows the classification of types of emergency situations.

Location – the geospatial position of the emergency situation on the map is determined by the list of possible types of emergency situations by spatial location and the position of monitoring the emergency situation.

The type of emergency situation position $type^w$ point, linear, polygonal:

$$type^w \in T^w = \{point', linear', polygonal\}$$

The $b_i$ emergency situation observation position $P_{b_i}$ is the source of information about the emergency situation. If the source is a technical means of monitoring transport processes, located on the transport network, it is bound to its coordinates $(x_i, y_i)$.

The set of emergency situations $\Psi = \{\psi^X_i\}$ visualized on the map, where each element $\psi^X_i \in \Psi$ is associated with the corresponding element $b_i \in B$.

The set $\Psi$ contains the following subsets:

- $\Psi^D \subset \Psi$ – a set of a point emergency situation;
- $\Psi^L \subset \Psi$ – a set of a linear emergency situation;
4. Emergency situations

An emergency situation is a point situation if its geometric dimensions are negligibly small. The authors consider a contingency to be a point situation if the radius of the circle $r$ describing the part of the roadway affected by the contingency does not exceed $\varepsilon$.

The point emergency situation is determined by the type of location on the sections of the transport network:

\[
\text{type}^{\psi^D} \in T^{\psi^D} = \{ \text{\textquoteleft straight', \textquoteleft crossroad', \textquoteleft crossover' \textquoteleft circle', \textquoteleft railwaycross', \textquoteleft tunnel'\textquoteright}\}
\]

where $\text{type}^{\psi^D} \in T^{\psi^D} = \{1, 2, \ldots, n\}$ and each type corresponds to a number: “straight” – 1, “crossroad” – 2, “crossover” – 3, “circle” – 4, “railwaycross” – 5, “tunnel” – 6.

The set of point emergency situations is defined as $\psi^D = \{\psi^D_i\}, i = 1, 2, \ldots, n$. The class of point emergency situations creates subclasses depending on the location of the emergency situation in different parts: $\psi^D = \psi^{D_1} \cup \psi^{D_2} \cup \psi^{D_3} \cup \psi^{D_4} \cup \psi^{D_5} \cup \psi^{D_6}$.

The point emergency situation on the straight road section $\psi_i^{D_1} \in \psi^D$ (Figure 3) is characterized by coordinates $(x_i,y_i)$ and reduces the throughput of the arc or oppositely directed arcs of the graph, referring to one stage.

The point emergency situation at the standard intersection (crossroad) $\psi_i^{D_2} \in \psi^D$ (Figure 3) is characterized by coordinates $(x_i,y_i)$ and reduces the carrying capacity $I^C$ for $n$ directions of the movement at the road’s intersection.

A point emergency situation at a roundabout (circle) intersection $\psi_i^{D_4} \in \psi^D$ (Figure 3), depending on the location, is either a point emergency situation on a stretch or a point emergency situation at a standard crossroad.

The point emergency situation at a railway crossing $\psi_i^{D_5} \in \psi^D$, on a bridge, an overpass (crossover) $\psi_i^{D_3} \in \psi^D$ or in a tunnel $\psi_i^{D_6} \in \psi^D$ is also defined as the point situation on a stretch.

A contingent situation is called linear if it directly affects one or several adjacent sections of the road network, while there are no points of separation and merging of traffic flows in these areas. The set of linear emergency situations is defined as $\psi^L = \{\psi^L_i\}, i = 1, 2, \ldots, n$. Linear emergency situation differs from a point significant length (Figure 6), characterized by geographical coordinates of boundary points $(x_{1i},y_{1i}), (x_{2i},y_{2i})$ The coordinates of the epicenter of the linear emergency situation are optionally indicated $(x_{ei},y_{ei})$. 

Figure 2. Classification of emergency situation types
Figure 3. Point emergency situation: a – at straight; b – at crossroad; c – at roundabout

An emergency situation is called polygonal if it affects an adjacent or non-adjacent section of the road network, regardless of the presence of branching points and merging of traffic flows (Figure 4). The set of deployed polygonal emergency situations is defined as $\psi^A = \{\psi_i^A\}, i = 1, 2, ..., n$. To indicate the dislocation of a polygonal emergency situation, coordinates of the vertices of the polygon ($x_i, y_i$) are used. A variant of the indication of the position is a binding to the graph by indicating the geofence of direct impact. The coordinates of the epicenter of the linear emergency situation ($x_e, y_e$) are optionally indicated. Type of emergency source $type^B$: environment, transport network, technical means of transport infrastructure management, traffic flow.

Figure 4. Emergency situation: a – linear; b – polygonal

The set B of emergency situations is divided into the following subsets $B^X$:
- $B^E \subset B$ – a set of emergency situations caused by the environment;
- $B^N \subset B$ – a set of emergency situations caused by changes in the transport network;
- $B^S \subset B$ – a set of emergency situations caused by technical means of transport infrastructure management;
- $B^F \subset B$ – a set of emergency situations caused by traffic flow.

An emergency situation $b_i^E \in B^E$ is caused by the environment if its occurrence is due to extreme natural phenomena (fog, ice, etc.)

An emergency situation $b_i^N \in B^N$ is caused by changes in the transport network, if the cause of its occurrence is the destruction of the pavement, an extraneous object on the roadway (for example, a tree falling on the roadway), repair and construction work affecting the roadway.

An emergency situation $b_i^S \in B^S$ is caused by the technical means of transport infrastructure management, if its occurrence is due to a non-working traffic light, an unreadable traffic sign.

An emergency situation $b_i^F \in B^F$ is caused by a traffic flow, if its occurrence is due to traffic accident.
5. Temporal attributes

Dynamic emergency situation – an event associated with time. The model is defined by the following parameters (attributes):

- \( t_D \) – time of receipt of information about the emergency situation;
- \( t_A \) – time of occurrence of an emergency situation, is determined for each instance of the class “Emergency situation” at the time of its creation, if this time is known;
- \( t_N \) – the standard time to eliminate the emergency situation, shows the maximum allowable period of time allotted for the removal of the emergency situation by the regulatory documents;
- \( t_R \) – the time of the actual elimination of the emergency situation, is determined for each instance of the class “Emergency situation” at the time of the elimination of the emergency situation;
- \( t_p^s \) – the scheduled time of occurrence of the emergency situation is determined for each instance of the class “Emergency situation” in case the emergency situation is planned in advance;
- \( t_p^f \) – the scheduled time to eliminate the emergency situation, is determined for each instance of the class “Emergency situation” in case the emergency situation is planned in advance;
- \( t_p^e \) – the expected time to eliminate the emergency situation, is determined at the time of the emergency situation by processing the statistics, previously eliminated.

An emergency situation \( b_i \in B \) may be in one of the following states:

- \( b_i^l \in B \) – received information requiring verification;
- \( b_i^c \in B \) – active;
- \( b_i^m \in B \) – in the process of elimination;
- \( b_i^r \in B \) – fixed;
- \( b_i^p \in B \) – scheduled;
- \( b_i^b \in B \) – the planned emergency situation occurred ahead of time;
- \( b_i^h \in B \) – the occurrence of a planned emergency situation is postponed;
- \( b_i^t \in B \) – the scheduled deadline for the emergency situation has expired, the emergency situation has not been eliminated;
- \( b_i^u \in B \) – the regulatory deadline for the elimination of the emergency situation has expired, the emergency situation has not been eliminated;
- \( b_i^q \in B \) – eliminated earlier than planned;
- \( b_i^w \in B \) – the occurrence of a planned emergency situation is canceled.

Every emergency situation \( b_i \) must be compared with the changes it makes. These changes are determined by the geofence model of influence \( M_{Zone} \), defined as \( M_{Zone} = (Z_1, Z_2) \), where \( Z_1 \) is the area of direct influence, \( Z_2 \) – area of indirect influence.

The area of direct influence \( Z_1 \) of an emergency situation \( b_i \) is a set of arcs \( \hat{e}_j \in E \) of the graph, which are affected by an emergency situation in the form of changes in such characteristics as the speed of free movement \( \nu_0 \hat{e}_j \), throughput \( I^\hat{e}_j \), the number of lanes \( n_e \hat{e}_j \). The area of direct influence \( Z_1 \) determines the dislocation of the emergency situation on the transport network; it is static throughout the entire time the emergency situation exists.

The model of the area of direct influence of an emergency situation is defined by the formula:

\[
Z_1 = \{(\hat{e}_i, E_i^B, E_i^S)\}, i = 1, m, j = 1, n^e_i, \quad (6)
\]

where \( m \) is the number of arcs of the graph, which are affected by an emergency situation;
\( n^e_i \) – the number of lanes in the area corresponding to the i-arc affected by an emergency situation,
\( E_i^B \) – vector of parameters of the emergency situation independent of the lane on the i-arc,
\( E_i^L \) – vector of parameters of the emergency situation relevant for the j-lane i-arc,
\( E_i^SO \) – vector of parameters characterizing the possibility of avoiding an emergency situation on the sidelines and oncoming traffic lanes.
The throughput rate factor $k_{IC}^{\hat{\ell}_i}$ indicates the arc $\hat{\ell}_i$ throughput change when an emergency situation occurs:

$$k_{IC}^{\hat{\ell}_i} = \frac{I_{C}^{\hat{\ell}_i} - I_{C}^{\hat{\ell}_i}}{I_{C}^{\hat{\ell}_i}}$$

(7)

where $I_{C}^{\hat{\ell}_i}$ – arc $\hat{\ell}_i$ nominal carrying capacity;

$I_{C}^{\hat{\ell}_i}$ – arc carrying capacity in an emergency situation on it.

Similarly determined by the coefficient $k_{IC}^{\hat{\ell}_i}$ of change of the bandwidth of the j-arc lane $\hat{\ell}_i$. In the absence of the impact of the emergency situation on the j-lane $k_{IC}^{\hat{\ell}_i} = 1$. If the j-lane overlaps completely, then $k_{IC}^{\hat{\ell}_i} = 0$.

The area of mediated influence $Z_2(t)$ of the emergency situation $b_i$ at the moment of time $t$ is the set of arcs $\hat{\ell}_j \in \hat{E}$ of the graph, on which the emergency situation influences the characteristics of traffic flows. The area of indirect influence of emergency changes is dynamic – it changes depending on the characteristics of traffic flows that change over time. The area of indirect influence depends on the characteristics of the emergency situation, the structure of the graph and the weight characteristics of its arcs. The spread of the influence of an emergency situation at the micro-level is due to the formation of a queue of vehicles in the event that the transport demand exceeds the carrying capacity of the arc during the initially free movement, or because of a decrease in speed.

The area $Z_2(t)$ is optionally divided into several subareas with varying degrees of influence on traffic flow: $Z_2(t) = Z_2^1(t) \cup Z_2^2(t) \cup \ldots \cup Z_2^m(t)$, where $m$ is the number of subareas.

A large number of studies of the transport network loading in the “ITSGIS” intellectual transport geographic information system is aimed at developing algorithms for the automatic detection of emergency situations and congestion. “ITSGIS” for collecting characteristics of traffic flows considers the use of the following types of hardware: induction loops, magnetometers, active and passive infrared sensors, passive acoustic and ultrasonic sensors, cameras, frequency modulated radar with continuous radiation and Doppler radar, pulsed laser emitters. The measured values of the hourly intensity of traffic flows on the same part of the transport network on different weekdays form a data array during normal operation of the network, from which a pattern of regular hourly intensities is formed by finding the average or median intensity values. A significant deviation of the intensity measured in real time from the pattern found indicates the probability of an emergency situation. Similar patterns are generated for the speed and density of traffic flow. If it is impossible to directly measure the characteristics of traffic flows, prediction methods are used.

6. Conclusion

Summarizing the solution of carrying out an analysis of the transport network loading management in the event of emergency situations and the construction of a model of emergency situations, it is possible to draw the following conclusions:

- The decomposition of the subject area “Transport Network Loading” into classes of objects has been carried out; a model of the subject area has been developed;
- Developed models of transport infrastructure objects included in the subject area, identified attribute characteristics of objects;
- The parametrization of the emergency situation model was performed, the classification of emergency situations by types was presented, temporal characteristics and geofences of direct influence on the transport network and indirect influence on traffic flows were identified.

Based on the constructed models, methods for managing the transport network loading and analyzing emergency situations have been developed, including collecting and processing initial data, determining emergency situations and their characteristics, choosing the optimal response strategy, and performing management functions.
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