The Tunnel Type Road Interchange Vulnerability Assessment Model

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Abstract. At present, both in Russia and abroad, a new line of work is developed to comprehensively automate the functions of monitoring and controlling security systems, life support and technological processes of potentially dangerous, unique and technically complex objects (high-risk objects), which can also include car interchanges tunnel type. However, these works are unsystematic and do not fully solve the prevention and liquidation issues of emergency situations at the above-mentioned facilities. Moreover, in case of incorrect design of the above-mentioned systems, they can contribute to the deaths of people on the site and beyond. This is confirmed by the accidents’ statistics at these facilities including the road junctions of the tunnel type. The accidents causes’ analysis at high-risk facilities showed that they are largely stipulated by the incorrect definition of vulnerability (threats) assessment for the designed facilities and the facilities under construction. Thus, the model development for assessing the vulnerability of tunnel-type road junctions is an urgent task. To achieve this goal, the main causes of emergencies at tunnel type road junctions are considered and based on them, using a system analysis method and experimental theory, a three-dimensional model that allows, with the expert assessments, to determine the susceptibility of tunnels to various threats types, is developed and tested.

1. Introduction

Unfortunately, at the road junctions of the tunnel type a large number of emergencies occur with loss of life and significant material damage. The analysis of their occurrence causes indicates that not all emergency risks at these facilities were taken into account [1, 2]. In part, this was due to the fact that there are currently no scientifically-based and easy-to-use algorithms for determining the threat degree to the tunnel type road junctions [3]. The aim of the work is the urgent task of model creation for assessing the vulnerability of tunnel-type road junctions.

Scientifically based approaches to creating risk assessment models for the high-risk facilities, which include tunnel type road junctions, have started being developed relatively recently [4, 5].

In the field of methods development for creating the risk assessment models of high-risk objects, a number of studies were carried out in the past. The following names should be noted: V.V. Batyrev, A.A. Volkov, O.S. Volkov, A.P. Popov, N.G. Topolsky, J. Bodie, C.M. Pietersen, W. Zinka, K.
Wawryn, A. Wolski, M. Morris, V.C. Marshall, G.A. Clay, B.J.M. Alle, N.A. Roberts, B.J. Paaske, L. Nesheim, O. Thomassen, L. Tronstad and other Russian and foreign scientists. However, despite the large number of domestic and foreign studies in this field, many issues, related to this study, remain unreached [6, 7, 8]. The analysis of the previously performed work showed the need to improve the methods for assessing the risks at high-risk facilities [9, 10, 11].

2. Methods

EMERCOM of Russia in conjunction with NRU MGSU developed an original technology for creating the automated interconnected systems for monitoring and control of technological processes, safety and life support at high-risk facilities [12, 13, 14]. This technology is based on the structured monitoring and control systems for engineering systems of buildings and structures (hereinafter referred to as CSES). The developed technology allows to prevent or significantly reduce the emergencies’ consequences of various nature, such as fires, explosions, high levels of chemically hazardous substances emergency; increased levels of radiation or bio-hazardous substances, sudden collapse of the object’s supporting structures, etc.

The proposed system in comparison with foreign and domestic counterparts has the following advantages:

- the operation of all technological systems, safety and life support systems in the event of a threat or an emergency occurrence is carried out according to the algorithms predetermined by the relevant organizations and the facility operation service, which allow preventing an accident or minimizing its human and material losses;
- forecasting and prevention of emergency situations is carried out by the means of automated control over the processes’ parameters ensuring the facilities’ functioning and determining the deviations of their current values off the normative ones;
- the possibility of the information automated complex processing on the state of technological systems, life support systems, safety and engineering structures of objects and automatic transmission of the necessary information about their condition and emergency parameters in the form of an established formalized message to the object’s duty service and a unified duty dispatch city service (UDDS) is provided. This information is archived in a database and can be used for analysis by the specialists on duty;
- it is possible to automatically or forcefully launch a system to alert the public about an emergency and the necessary evacuation actions and to automatically or forcefully alert the specialists who are responsible for the safety at high-risk facilities;
- the possibility of remote control from a specialized control center for the life support systems and safety at high-risk facilities in case of emergencies is provided.

For the purpose of legal and technical regulation of measures for the organization of integrated safety and emergency prevention at high-risk facilities, based on the above-described technology, the following standards have been developed:

- national standard GOST R 22.1.12-2005 “Safety in emergencies. Structured monitoring and control system for engineering systems of buildings and structures. General requirements”;
- methodology for safety and life support systems’ evaluation at potentially hazardous facilities, buildings and structures, certified by the Government Commission for the Prevention and Response of Emergencies and Ensuring Fire Safety, protocol of December 19, 2003. No. 1;
- methodology for monitoring the buildings, structures and load-bearing structures’ state. General provisions and requirements, certified by the Government Commission for the prevention and elimination of emergency situations and ensuring fire safety, protocol dated 18.03. 2009, No. 3.

It is also noted that the need to monitor the state of the foundation, building structures and engineering support systems during the construction and (or) operation of a building or structure was reflected in the Federal Law of December 30, 2009. No. 384-FL Technical Regulation “On the Safety of Buildings and Structures”.
For the CSES to work correctly when designing it at a specific facility, threats of a natural, man-made, criminal and terrorist nature must first be identified with an estimate of their occurrence probability and possible damage [15, 16]. Secondary effects from the potential threats should also be considered. Conducting a comprehensive, science-based assessment of threats and measures to counter them is a rather complex and time-consuming task [17, 18]. Therefore, the development of threat assessment algorithms for the tunnel-type road junctions is an urgent task [19].

In order to simplify the preparation of the evidence-based initial data for the CSES creation at high-risk facilities, the authors developed a three-dimensional model for assessing the vulnerability of tunnel type road junctions; the model allows using the expert assessments to determine the susceptibility of tunnels to various types of threats (Figure 1).

The following designations are introduced to this model:

- $A_1...A_n$ - is a list of threats to the tunnel protection elements (fires, explosions, accidents with the release of emergency and chemically hazardous substances, etc.).
- $B_1...B_k$ – define the measures aimed at countering threats to tunnel protection elements (fire extinguishing systems, access control and management systems, video surveillance, warning system, etc.).
- $C_1...C_i$ – are the elements of the transport interchange object protection of the tunnel type (road users, tunnel maintenance personnel, vehicles, tunnel engineering structures, etc.).
- $D_1...D_m$ – denote the damage that may be caused to the protection elements of the facility as a result of an emergency (death or injury to people, damage to vehicles, damage to tunnel structures and equipment, destruction of the road surface, etc.).

As a result of the emergencies at the facility, if the measures taken are insufficient, the threat, acting on the protection element, causes material, physical and moral (to a road user) damage.

To assess the risk, it is necessary to enter the relative amount of damage, taking as 100% the total damage that the protection element may suffer (for example, death in a tunnel or complete collapse of the tunnel). We take such damage equal to 1. In the event when the protection element received minor damage (for example, people in the tunnel received minor damage (bruises, slight malaise, small cuts, etc.), then the damage in relative units can be, for example, from 0.1 to 0.3.

Figure 1. Three-dimensional security model of tunnel type road junction
The threat risk affecting a specific element of protection, the ability to take adequate measures of protection against this threat, as well as the magnitude of the possible damage are probabilistic. The most effective way to evaluate such events is expert-statistical method of analysis. If the expert has the statistics on incidents and accidents at a particular facility, then he is very likely to identify the main causes of emergencies and propose the measures to eliminate them or reduce the severity of the emergencies’ consequences [20, 21, 22]. But, as a rule, such data are not available, and the experts have to evaluate all possible types of threats for all available security elements [23, 24]. In this case, it is necessary to take into account the threat probability and the magnitude of the possible damage from it [25].

The risk value for the j-th element of the object - Rj protection is defined as the total value of the probabilities’ multiplication for the security threat impact on each protection element and the possible damage for each protection element:

\[
R_j = \sum_{n=1}^{N} P_{anj} \cdot P_{dnj}, \tag{1}
\]

where:
\[P_{anj}\] – is the probability of the n-th threat affecting the j-th element of the object’s protection.
\[P_{dnj}\] – is the probable value (in relative units) of damage to the j-th element of the object’s protection when exposed to the n-th threat.
\[N\] – is the number of possible security threats to the object’s security features.

When calculating the risk magnitude, it is also necessary to take into account the protection element’s significance. The greatest importance is the life and health of people. The second most important element is the throughput of the tunnel, as the movement of vehicles ensures the city life.

In the proposed model, if we reveal the connections not only along the surface edges, it is possible to see that all the components in the model influence each other (Fig. 2, 3).

**Figure 2.** A fragment of a three-dimensional model that allows analyzing the mutual influence of threats, security measures, security elements, and damage

After analyzing Figure 3, it is possible to see that:
\[A\] – when the threat is applied to the tunnel protection elements, the damage caused by them occurs;
$B$ – the existing security measures to some extent counteract threats and reduce damage from emergencies;  
$C$ – the protection elements may suffer as a result of emergency if there are no security measures;  
$D$ – the amount of damage to the protected element against emergencies depends on the importance degree of the protection element, the probability and number of the security threats that can affect it and the security measures that defend this protection element.

Security measures are determined by the significance coefficient (rating) for each $i$-th event:  
$K_1$ is determined by the number of threats to which this measure opposes;  
$K_2$ depends on what damage the preventive measure prevents. The more damage is prevented, the higher is the measure rating that counteracts this threat.  
$K_3$ is determined by the protection elements’ number.

![Diagram](image)

**Figure 3.** Fragment of a three-dimensional model for the tunnel road junctions’ protection, laid out on a plane

Taking into consideration the importance, that this security measure protects, we get:

$$K_{3_i}^{'} = K_{3_i} \cdot K_{impt}$$  

(2)

where:  
$K_{impt}$ (from 0 to 1) – is the security element importance coefficient.  
$K_{3_i}$ - depends on the damage, which eliminates the security measure for all the protected elements.  
The protective measure rating is also affected by the stage at which a security threat is addressed.
The highest rating of the protective measure is achieved when the threat has not been realized (warned).

We denote the increasing coefficient of such measure as \( K_{\text{warn}} \).

In case of emergencies, it is necessary to take measures to reduce the emergencies’ consequences severity. The measure that reduces the emergency consequences severity has an increasing coefficient - \( K_{\text{decl}} \).

To restore the facility after emergency, the appropriate measures should be taken. The faster the damage caused to an object is eliminated, the greater is the coefficient of this measure increase \( K_{\text{lcon}} \).

If the threat counteraction measure is valid at all 3 stages (warning, liquidation, operability restoration), then the coefficients are summed up:

\[
K_{\text{rad}} = K_{\text{warn}} + K_{\text{decl}} + K_{\text{lcon}}
\]  

(3)

The highest rating will have the security measure \( i \), which includes all the increasing factors:

\[
Q_i = K_{1i} + K_{2j} + K_{3k} + K_{4l} + K_{\text{lcon}_i}
\]  

(4)

Thus, it is possible to determine the vulnerability coefficient of the tunnel type traffic interchange as \( K_{\text{val}} \):

\[
K_{\text{val}} = \sum_{j=1}^{J} \frac{R_j}{N \times L \times Q_{nj} \alpha_{nij}}
\]  

(5)

where:

\( R_j \) – is the risk value for the \( j \)-th element of the object’s protection (formula 1);

\( J \) – defines the total number of security features;

\( Q_{nj} \) – is the effectiveness of the \( i \)-th security measure for the \( j \)-th security object’s element with the \( n \)-th threat;

\( \alpha_{nij} \) - is the influence degree coefficient of the \( i \)-th security measure for the \( j \)-th security object’s element with the \( n \)-th threat;

\( N \) – is the total number of possible threats;

\( I \) – is the total number of security measures (events) to protect the facility.

The reciprocal of the vulnerability coefficient is the object’s security coefficient - \( K_{\text{prot}} \):

\[
K_{\text{prot}} = \sum_{j=1}^{J} \frac{\sum_{n=1}^{N} \sum_{i=1}^{I} Q_{nj} \alpha_{nij}}{R_j}
\]  

(6)

Applying more effective (rating) measures to protect the facility, we make it less vulnerable to emergencies and thereby seek to optimize the integrated security system of the tunnel type road junctions. The protective measures that do not have a significant impact on the tunnel type road junctions’ safety level are very costly and should not be used, and it is better to insure the risks against which they should be directed.

3. Results

To determine the tunnel-type road junctions’ integrated safety level, it is necessary to fill in the entire cubic model, not only along the external faces, but also inside. For the convenience of filling out the model, a table was proposed, a fragment of which is presented below.

When filling out the table, the experts can use the available statistics, if it is not available, the experts use their own practical experience and evaluate the event’s probability. To reduce the subjective factor’s influence, it is advisable not to use the group methods of examination, when the
opinion of some experts may affect the opinion of others. When assessing the tunnel-type road junctions’ vulnerability, the competence of experts should be taken into account.

For the examination, it is advisable to involve from 8 to 12 experts. After averaging, their opinions can be tabulated. It is also necessary to enter the data into the cube (three-dimensional model) in the form of “+” or “-”. To simplify this procedure, the authors develop an appropriate program. The three-dimensional model will clearly show in which sections there are unprotected places in the integrated security system of tunnel type road junctions. Processing the results can be carried out using the proposed formula, or using other mathematical devices (for example, game theory or set theory).

Table 1. Fragment of a model for ensuring the tunnel-type road junctions’ integrated safety.

| EXPERT REVIEW |
|----------------|
| N | Protection element | Threat | Probability of threat realization (from 0-1) | Damage | Security measures | Rating of security measures (from 0-1) | Note |
| 1 | Road user | Car accident | 0.2 The death in an accident | 1 | Police call | 0.8 |
| | | | 0.3 Grievous bodily harm | 0.8 | Call an ambulance | 0.9 |
| | | | 0.5 Less severe injuries | 0.6 | Evacuation of injured | 0.9 | the emergency exits |
| | | Stress | 0.3 Evacuation of vehicles | 0.4 |
| 2 | Motor transport | Fire as a result of an accident | 0.8 Total loss of a vehicle | 1 | Fire extinguishing. Police Call, Ambulance | 0.8 |
| | | Major accident | 0.4 Expensive repair | 0.8 Evacuation of injured | 0.9 | the emergency exits |
| | | Minor accident | 0.2 Minor repairs | 0.3 Evacuation of the vehicle | 0.5 | the emergency gates |
| | | Insignificant accident | 0.2 No serious consequence | 0.1 Disposal after fire extinguish | 0.2 |
### 4. Summary

Thus, the developed model for assessing the tunnel-type road junctions’ vulnerability makes it possible to visualize what types of threats can affect various elements of an object’s protection and what security measures counteract these threats. The data obtained will allow carrying out the scientifically-based work on the tunnel type road junctions’ CSES creation and thereby significantly reduce (according to the preliminary expert estimates, by at least 50%) the accidents’ risk at these facilities.

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|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 1 | Road users | 1 | Explosio n and fire in a tunnel (attacks) | 0.3 | The death of road users as a result of the attack | 1 | The use of fire fighting Police call. Ambulance Call |
|   |   |   |   |   |   |   |   |
|   |   |   |   |   |   |   |   |
|   |   |   |   |   |   |   |   |
|   |   |   |   |   |   |   |   |
| 2 | Tunnel supports | 0.8 | Explosio n and fire in the tunnel (terroris t attacks) | 0.6 | Complete destructio n | 1 | Installatio n of temporary supports |
|   |   |   |   |   |   |   |   |
|   |   |   |   |   |   |   |   |
|   |   |   |   |   |   |   |   |

- 0.8 Grievous bodily harm
- 0.8 Evacuatio n of injured
- 0.5 the emerg ency exits

- 0.4 Getting less severe bodily harm
- 0.7 Evacuatio n of vehicles
- 0.8 the emerg ency gates

- 0.2 Injury of light bodily injury
- 0.6 Alert and evacuatio n
- 0.4

- 0.3 Partial failure
- 0.6 Repair of the base of the supports
- 0.6
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