UDC 355.41:623.438:519.852

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IMPROVED METHOD FOR TIMELY EVACUATION OF DAMAGED ARMORED VEHICLE SAMPLES UNDER COMBAT CONDITIONS

An improved method for the timely evacuation of damaged armored vehicle samples under combat conditions is considered. The proposed method makes it possible to determine optimal routes for moving damaged vehicles from combat engagement areas to maintenance and repair points, taking into account time constraints, accessibility, and the throughput capacity of repair units. The necessity of formalizing the evacuation process based on mathematical programming is substantiated in order to ensure operational efficiency, safety, and effectiveness of vehicle recovery on the battlefield.

The scientific novelty of the study is identified as the introduction of a mathematical model for constructing evacuation routes based on a coverage function that accounts for accessibility coefficients, damage criticality, and the uniqueness and cost of the equipment. The practical significance of applying the developed method within the decision support system of the technical service of the National Guard of Ukraine is confirmed, as it enhances the effectiveness of organizing evacuation operations under combat conditions.

Keywords: *evacuation, damaged armored vehicles, transportation problem, mathematical programming, coverage function, combat potential, technical support.*

Statement of the problem. Under modern combat conditions, a significant share of losses of armored vehicles (AVs) is attributable not only to irreversible destruction but also to damage that is subject to recovery. The effectiveness of vehicle recovery directly depends on the timeliness of evacuation from combat engagement areas; however, in practice this process is complicated by a number of factors, including the high dynamics of combat operations, complex natural and climatic conditions, limited resources of evacuation units, and insufficient automation of control processes.

The evacuation planning methods currently in use generally do not account for the spatiotemporal variability of battlefield conditions, the level of combat potential of damaged samples, or the risks associated with evacuation routes. This leads to inefficient use of evacuation assets, increased vehicle downtime, and potential losses of personnel.

Therefore, a scientific and practical task arises to develop a method for the timely evacuation of damaged armored vehicles that ensures an optimal allocation of evacuation resources, the determination of rational movement routes, and the prioritization of vehicle recovery while taking into account the dynamic combat environment, natural factors, and the technical condition of the samples.

Analysis of recent research and publications. Issues related to the evacuation and recovery of damaged military equipment have been addressed in a number of studies that form the methodological basis for the development of modern approaches to technical support of troops. In particular, study [1] focuses on field repairs and the operational recoverability of vehicles, which is of interest to the author of this article from the perspective of assessing the real capabilities of repair units. However, [1] does not present a mathematical decision-making model for equipment evacuation and does not define the prioritization of its movement from the combat area.

Publication [2] analyzes the structure of transportation costs in military logistics with regard to environmental conditions and the operational state of equipment. This study is significant from the standpoint of assessing energy and transportation expenditures; however, the authors of [2] do not consider evacuation as a separate object of optimization and, in particular, do not account for the specifics of damaged equipment.

An algorithmic model for route selection in military transportation under complex conditions, which can be adapted to the evacuation task, is proposed in [3]. Nevertheless, the model does not take into account individual equipment parameters, such as the degree of damage or combat potential.

Logistical evacuation processes in the context of transportation support, which are important for structuring material flows, are examined in [4]. However, this study does not cover the specifics of evacuating damaged armored vehicles under combat conditions and does not consider the dynamic nature of the situation.

The authors of [5] analyze fleet management in humanitarian logistics, emphasizing route optimization under uncertainty. These approaches are relevant to military logistics; however, the researchers do not consider equipment as a combat object that requires assessment of combat capability and importance.

Publication [6] addresses the optimization of logistics processes in the Armed Forces of Ukraine and proposes measures to improve the efficiency of troop support. Despite its high practical significance, this work does not detail the process of equipment evacuation and does not provide a mathematical model for the allocation of evacuation resources.

Study [7] analyzes the functioning of military logistics under crisis conditions, emphasizing the need for adaptability and operational control. However, the presented model does not cover the specifics of evacuating damaged vehicles and does not take into account risk indicators, accessibility, or combat potential.

Research [8] is one of the fundamental works for studying the transportation problem in a military context, particularly with respect to multimodal transportation. Nevertheless, it is not adapted to the task of evacuating damaged equipment and does not consider combat threat factors.

A comprehensive analysis of evacuation means and their effectiveness, which is important for critically assessing the technical capabilities of units, is conducted in [9]. However, this study does not contain a formalized model for optimizing evacuation routes.

The authors in [10] examine the impact of transportation infrastructure on the effectiveness of military logistics, which can be partially applied to evacuation analysis. However, they do not take into account combat conditions, equipment damage, or variable route accessibility.

Thus, the analysis conducted by the author of the article indicates that the reviewed studies address individual aspects of military logistics, transportation support, and equipment recovery, but do not propose a comprehensive mathematical method for determining optimal evacuation routes for damaged armored vehicle samples while accounting for risks, accessibility, energy expenditures, the degree of damage, and the combat potential of the equipment. This substantiates the need to develop an improved method for timely evacuation that will enhance the effectiveness of technical support of troops under combat conditions.

The purpose of the article is to develop and scientifically substantiate an improved method for the timely evacuation of damaged armored vehicle samples under combat conditions, which ensures the optimal allocation of evacuation resources and the determination of rational routes for vehicle movement.

Summary of the main material. The proposed method for the timely evacuation of damaged armored vehicle (AV) samples under combat conditions is intended for the prompt recovery on the battlefield or evacuation of damaged armored vehicles in modern combat environments. It is advisable to apply this method:

– at the stage of planning technical support measures (in particular, measures for organizing the recovery of armored vehicles directly during combat engagement) under modern combat conditions;

– in the process of developing regulatory (guiding) documents on technical support (substantiation of regulatory data for organizing technical reconnaissance, evacuation, and repair of damaged armored vehicle samples during combat engagement);

– during organizational measures related to the reform of technical support units and military formations, in order to substantiate the organizational and staffing structure of repair and recovery bodies.

The procedure for determining and constructing evacuation routes for damaged armored vehicles is carried out based on the principles of mathematical programming, which makes it possible to formalize the decision-making process under multifactor constraints and a dynamic combat environment. The essence of the method lies in finding such a variant of allocation of evacuation assets and movement directions that ensures an optimal balance between safety, speed, and energy efficiency of moving equipment from the combat engagement area to designated repair and recovery points.

The basis of the method is the classical linear transportation problem, adapted to modern requirements for organizing the process of evacuating damaged equipment under combat conditions (Figure 1).

Location of damaged armored vehicles	Maintenance and repair point					Available damaged armored vehicles
	B_1	…	B_j	…	B_n	
A_1	X_{11} C_{11}	…	X_{1j} C_{1j}	…	X_{1n} C_{1m}	a_1
…	…	…	…	…	…	…
A_i	X_{i1} C_{21}	…	X_{ij} C_{ij}	…	X_{in} C_{im}	a_i
…	…	…	…	…	…	…
A_m	X_{m1} C_{m1}	…	X_{mj} C_{mj}	…	X_{mn} C_{mm}	a_m
	b_1	…	b_j	…	b_n	
	Capacity of maintenance and repair points					

Figure 1 – Graphical representation of the linear transportation problem

For the given case, each damaged armored vehicle sample identified at the stage of technical reconnaissance is considered as a source, while each collection or repair point (maintenance and repair point, MRP) is treated as a consumer of evacuation resources. The available damaged armored vehicles at specified coordinates and the technical capacities of the MRPs are denoted by a_m and b_n respectively. The valu C_{ij} determines the equivalent evacuation cost, which is calculated using an integral coverage function while taking into account complicating factors, and X_{ij} represents the volumes of transportation of damaged equipment from a specific evacuation location to a specific MRP, ensuring an optimal balance between safety, speed, and energy efficiency.

When solving this problem, the following conditions must be satisfied:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} = X_{ij}C_{ij} \to \min; \qquad (1)$$

$$\sum_{i=1}^{m} X_{ij} = a_i \ (i = \overline{1,m}),$$

$$\sum_{j=1}^{n} X_{ij} = b_i \ (i = \overline{1,n}), \qquad X_{ij} \geq 0; \qquad (2)$$

$$a_1 = a_i = a_m. \qquad (3)$$

The organization of evacuation of damaged armored vehicle samples based on the developed mathematical framework is carried out according to a clearly defined sequence of stages, which ensures a rational allocation of evacuation resources and minimizes the time required to return equipment to a combat-ready state.

At the first stage, input data are collected, including the results of technical reconnaissance, data from unmanned surveillance systems, information on the number and types of damaged samples, their technical condition, as well as the spatial coordinates *(x, y)* of each sample. In parallel, a matrix of the capabilities of maintenance and repair points (MRPs) is formed, taking into account their throughput capacity, distance, and availability of repair facilities.

At the second stage, the equivalent evacuation cost is calculated for each damaged equipment sample, taking into account:

– the accessibility indicator $A(x, y, t)$, which describes natural and weather conditions;

– the importance coefficient of the armored vehicle sample K_m^B (combat readiness index, uniqueness and cost, combat potential);

– the risk assessment $R(x, y)$ and the movement complexity $S^r(x, y)$ for each route.

The equivalent evacuation cost C_{ij} is determined using the proposed integral coverage function J_{ij}^{cf} taking into account the importance coefficient K_m^{im} and is expressed as follows:

$$C_{ij} = \frac{J_{ij}^{cf}}{K_i^{im}} \,. \quad (4)$$

The integral coverage function will take the following form

$$J_{ij}^{cf} = \frac{1}{L} \int_{L_{ij}} \left(\frac{1}{A(x,y,t)} + \eta \cdot S^r(x,y) + +\delta \cdot R(x,y) \right) dl, \quad (5)$$

which characterizes the coverage of the evacuation action area while simultaneously minimizing the risk function $R(x,y)$, the movement complexity $S^r(x,y)$ and the accessibility indicator $A(x,y,t)$ along the evacuation route L_{ij}, s well as accounting for the corresponding weighting coefficients η and δ.

Accessibility indicator

$$A(x,y,t) \in [0;1], \quad (6)$$

determines the degree of feasibility of conducting evacuation from the area (x, y) at time t and accounts for natural factors, including meteorological conditions, illumination, and season. For example, at night under adverse weather conditions, when rainfall has degraded unpaved roads, the accessibility significantly decreases, whereas during daylight hours and in the absence of precipitation it remains high. The values of the main indicators of the accessibility function are presented in Table 1.

Table 1 – Values of the main indicators of the accessibility function

No.	Meteorological conditions	Illumination	Season	Accessibility function
1	Clear	Daytime	Summer	0.950
2	Cloudy	Daytime	Winter	0.722
3	Clear	Twilight	Winter	0.646
4	Cloudy	Twilight	Winter	0.578
5	Clear	Twilight	Autumn	0.532
6	Fog	Daytime	Summer	0.500
7	Snow	Daytime	Autumn	0.455
8	Cloudy	Nighttime	Summer	0.425
9	Blizzard / Snowstorm	Daytime	Summer	0.400
10	Light rain / Drizzle	Nighttime	Summer	0.375
11	Thunderstorm	Twilight	Summer	0.360
12	Thunderstorm	Daytime	Spring	0.338
13	Cloudy	Nighttime	Spring	0.319
14	Fog	Twilight	Spring	0.300
15	Fog	Twilight	Autumn	0.280
16	Light rain / Drizzle	Nighttime	Autumn	0.262
17	Heavy rain	Nighttime	Winter	0.234
18	Heavy rain	Nighttime	Spring	0.206
19	Fog	Nighttime	Autumn	0.175
20	Blizzard / Snowstorm	Nighttime	Autumn	0.140

The importance coefficient of a specific damaged equipment sample K_m^{im} is defined as the product of the combat readiness index, the uniqueness and cost coefficient K_i^{cc}, and the combat potential K_i^{cp} of the given equipment sample, which is expressed as a percentage:

$$K_i^{im} = K_i^{ir} \cdot K_i^{cc} \cdot K_i^{cp} \cdot 100 \,. \quad (7)$$

In the proposed method for calculating the combat readiness index (K^{ir}) of an armored vehicle sample, such characteristics as the importance and criticality of line-replaceable units (LRUs) are used. The set of LRUs constitutes the armored vehicle sample by means of a digital twin.

The importance of an LRU is a statistical characteristic determined by the design. LRU importance is described by the importance coefficient (W), the value of which ranges from 0 to 1.

This is a constant that depends on the type of equipment and the role of the LRU in the functioning of the entire armored vehicle sample. For example, the engine has very high importance (W = 0.18), while the track has high importance (W = 0.12), but lower than that of the engine. The sum of the importance coefficients of all LRUs of an armored vehicle sample must be equal to 1 (or 100%):

$$\sum_{i=1}^{M} W_i = 1, \quad (8)$$

where W_i is the importance coefficient of the i-th line-replaceable unit (LRU);

M is the total number of LRUs that constitute the armored vehicle sample.

The criticality of an LRU is a dynamic characteristic determined by the type and degree of damage to the LRU. As an indicator, the criticality coefficient (C) is selected, which also takes values from 0 to 1. This is a variable value that depends on the consequences of LRU damage and characterizes how dangerous such damage is for the armored vehicle sample as a whole.

The value of the criticality coefficient is determined on the basis of statistical data on repairs of various LRUs and an analysis of the consequences of damage to the considered element with respect to ensuring the survivability of the entire vehicle, in combination with the expert assessment method.

The combat readiness index (K^{bz}) of an armored vehicle sample is calculated according to the following expression

$$K^{bz} = 1 - \sum_{i=1}^{N} \left(\frac{K_i^{sp}}{K^{spD}} \cdot W_i \cdot r_i \right), \quad (9)$$

where N is the number of damaged LRUs after combat actions;

$\frac{K_i^{sp}}{K^{spD}}$ is the normalized coefficient of the degree of damage of an LRU relative to the damage level D with K^{spD} = 4 (0 – 0; 1 – 0.25; 2 – 0.5; 3 – 0.75; 4 – 1.0);

r_i is the criticality indicator of the i-th LRU.

The uniqueness and cost coefficient of an equipment sample K_i^{im} is expressed through the relative value significance of the damaged sample within the set of available types of weapons and military equipment. Its value reflects how valuable a particular sample is compared to other units subject to evacuation or repair.

The assessment is carried out on the basis of the market (or book) value of the sample using linear scaling:

$$K_i^{cc} = \frac{C_i - C_{\min}}{C_{\max} - C_{\min}}, \quad (10)$$

where C_i is the market or replacement value of the i-th damaged equipment sample;

$C_{\min}$ is the minimum value among the considered samples;

$C_{\max}$ is the maximum value within the sample.

The combat potential is considered as the ratio of the actual combat capabilities to the reference ones:

$$K_i^{cp} = \frac{Q_i}{Q_{\max}}, \quad (11)$$

where Q_i is the total volume of functional capabilities of a specific equipment sample (firepower, mobility, protection, information capability, etc.);

$Q_{\max}$ is the maximum value among samples of this class.

If Q_i is decomposed into components, the following expression is obtained

$$Q_i = \alpha_1 M_i + \alpha_2 Z_i + \alpha_3 V_i + \alpha_4 I_i, \quad (12)$$

where M_i is the mobility (speed, cross-country ability, cruising range);

Z_i is the level of protection;

V_i is the firepower (effectiveness of target engagement per unit time);

I_i is the denotes information and communication capabilities (surveillance, communication, and guidance systems);

α_k is the weighting coefficients determined depending on the type of equipment (for example, for armored personnel carriers or infantry fighting vehicles, α_2 and α_3, prevail, while for command vehicles α_4 is dominant).

At the third stage, the transportation problem is solved.

The solution of the transportation problem within the proposed method is carried out by searching for an optimal plan for distributing evacuation flows between sources (areas where damaged equipment is located) and consumers (maintenance and repair points, MRPs) under conditions of limited resources and a variable combat environment. In this context, the transportation problem is interpreted as a model for the optimal use of available evacuation assets with minimal expenditures of time, energy, and risk.

For each possible pair "damaged equipment detection point – repair point", a cost matrix C_{ij}, is formed, whose elements describe the equivalent evacuation cost of a unit of equipment from the i-th area to the j-th MRP. This cost incorporates the risk function $R(x,y)$, the accessibility function $A(x,y,t)$, the movement complexity $S^r(x,y)$, and the importance coefficient of the equipment sample K_i^{im}. Using this matrix, the objective function is determined, which minimizes the total system cost subject to constraints on the amount of damaged equipment a_i at each location and the capacity of the MRPs b_i (2):

$$Z = \sum_{i=1}^{m}\sum_{j=1}^{n} X_{ij}C_{ij}, \quad (13)$$

$$Z^* = \min\{Z\}. \quad (14)$$

The solution of the problem (finding Z^*) is performed according to the classical linear programming scheme adapted to real-time conditions. At the first step, an initial feasible evacuation plan is determined using the northwest corner method or the least-cost method. Subsequently, an iterative improvement of the plan is carried out using the potentials method, which makes it possible to find the optimal distribution of flows X_{ij}^*, at which the objective function Z reaches its minimum.

In the event of dynamic changes in the situation, for example, when route passability or the accessibility function $A(x,y,t)$ changes, the problem is solved in a quasi-real-time mode using an iterative recalculation mechanism. In this case, the system automatically updates the cost matrix C_{ij} and adjusts the evacuation plan based on current data.

The resulting optimal plan determines the sequence and directions of movement of damaged equipment samples, ensuring a balance between operational efficiency, safety, and effective use of evacuation assets. Thus, the transportation model serves as the mathematical core of the decision support system for commanders of repair and evacuation units, providing well-grounded planning of actions under complex combat environment conditions.

In the improved method for the timely evacuation of damaged armored vehicle samples under combat conditions, the results obtained through the application of a comprehensive method of operational search, identification of armored vehicle damage, and determination of the level of combat readiness are used. The presented improved method makes it possible to take into account all factors and conditions necessary for effective planning and successful execution of combat missions.

The scientific novelty of the proposed improved method, in contrast to currently applied approaches, lies in the fact that the procedure for determining and constructing evacuation routes is carried out through mathematical programming using linear allocation, which incorporates an integral coverage function under the condition of minimizing risks and energy expenditures, as well as multicriteria optimization of the potential of damaged armored vehicles.

Conclusions

The article develops and scientifically substantiates an improved method for the timely evacuation of damaged armored vehicle samples under combat conditions. The method is based on the principles of mathematical programming, which ensure the formalization of the decision-making process when selecting evacuation directions and rationally allocating evacuation resources.

It is shown that adapting the linear transportation problem to combat application conditions makes it possible to determine optimal routes for vehicle movement while taking into account risks, natural factors, the degree of damage, and the combat potential of the samples. The proposed integral coverage function enables a comprehensive assessment of the safety and feasibility of each route, as well as the influence of terrain accessibility, movement complexity, and the probability of adverse events along the route.

It is determined that the use of the combat readiness index, the uniqueness and cost coefficients of equipment, and the combat potential indicator ensures a well-grounded prioritization of evacuation for individual samples when the number of evacuation assets is limited. The implementation of an iterative scheme for solving the transportation problem allows for prompt adjustment of the evacuation plan and its adaptation to changes in the combat environment.

The obtained results indicate that the application of the improved method makes it possible to reduce the time damaged equipment remains in the risk zone, increase the efficiency of the use of evacuation units, and reduce the probability of equipment loss. This confirms the practical significance of the developed method and the expediency of its implementation in the decision support system of the technical service of the National Guard of Ukraine and other military formations performing tasks under intensive combat conditions.

Further scientific research should be directed toward the formation of general purpose requirements and the development of a concept for the employment of combat evacuation and repair equipment.

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The article was submitted to the editorial office 20.11.2025

УДК 355.41:623.438:519.852

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УДОСКОНАЛЕНИЙ МЕТОД СВОЄЧАСНОЇ ЕВАКУАЦІЇ ЗРАЗКІВ ПОШКОДЖЕНОЇ АВТОБРОНЕТАНКОВОЇ ТЕХНІКИ В УМОВАХ ВЕДЕННЯ БОЙОВИХ ДІЙ

Розглянуто вдосконалений метод своєчасної евакуації зразків пошкодженої автобронетанкової техніки в умовах ведення бойових дій, який спрямований на підвищення ефективності технічного забезпечення військових підрозділів і мінімізацію часу повернення техніки до стану боєготовності. Актуальність проблеми зумовлена високими темпами маневрено-вогневих дій, зростанням частки пошкодженої техніки, що підлягає відновленню, а також необхідністю зменшення ризиків для особового складу під час евакуаційних заходів.

Запропонований метод ґрунтується на використанні адаптованої лінійної транспортної задачі, яка дає змогу формалізувати процес розподілу евакуаційних потоків між районами розташування пошкодженої техніки та пунктами технічного обслуговування і ремонту. В основі моделі лежить інтегральна функція покриття, що враховує природно-кліматичні умови, доступність місцевості, ризики, енергетичні витрати, бойовий потенціал та технічний стан кожного зразка техніки. Серед додаткових критеріїв – показник важливості зразка, який містить індекс боєздатності, коефіцієнти унікальності та дорожнечі, а також потенціал відновлення. Це уможливлює визначення пріоритетності евакуації у разі обмежених ресурсів.

Розроблено алгоритм розв'язання транспортної задачі в режимі реального часу із застосуванням методів лінійного програмування та ітераційного перерахунку, що забезпечує динамічну адаптацію плану евакуації до змін бойової обстановки. Отримані результати свідчать, що використання вдосконаленого методу дасть змогу суттєво зменшити час перебування пошкоджених зразків техніки у зоні ризику, підвищити ефективність роботи ремонтно-евакуаційних органів та знизити ймовірність втрати техніки.

Практичне значення розробленого методу полягає у можливості його впровадження в систему підтримки прийняття рішень технічної служби Національної гвардії України, що забезпечить підвищення узгодженості, оперативності й обґрунтованості евакуаційних дій у сучасних бойових умовах.

Ключові слова: *евакуація, пошкоджена автобронетанкова техніка, транспортна задача, математичне програмування, функція покриття, бойовий потенціал, технічне забезпечення.*

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