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DEVISING A METHOD FOR CATEGORIZING COMBAT WHEELED VEHICLES USING FUZZY CLUSTER ANALYSIS

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The object of this study is combat wheeled vehicles (CWVs). The task addressed is the categorization of CWVs. The devised CWV categorization method is based on the use of the fuzzy c-means (FCM) algorithm, which determines the centers of fuzzy clusters and their corresponding functions and memberships, which can take values in the interval from 0 to 1. Therefore, the degrees of membership of CWV samples to fuzzy clusters have been determined, which together define the fuzzy division of the initial set of CWV samples. The minimum number of samples required to solve the fuzzy clustering problem by determining the values of the objective function and the magnitude of its increment per sample with a sequential increase in the number of samples is 55 pieces. It has been confirmed that the maximum number of clusters at level 6 satisfies the needs of categorization and does not require their increase due to the presence of individual CWV samples with large degrees of membership in 2-clusters. It has been proven that with a weight parameter value of 1.68, the fuzziness of the membership matrix ensures an average level of membership of samples to 6 clusters at a level of not less than 99 %. The proposed CWV categorization method establishes a correspondence between the technical characteristics of the samples and their functional purpose. This makes it possible to take into account the uncertainties caused by the assignment of samples with intermediate characteristics between groups to one group. The resulting categorization results establish benchmarks to which CWV samples should approach when designing CWV types, which are constructed on the basis of unified units and assemblies. The results of this study could be used to determine CWV samples of the same type under conditions of a significant variety of options for providing units

Keywords: wheeled combat vehicle, fuzzy cluster analysis, combat mass, fuzzy c-means algorithm

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1. Introduction

For the development of military equipment, the correct choice of types of weapons is important, which is carried out on the basis of operational-tactical views on the use of troops [1]. This is especially relevant at critical stages of development as a result of technical progress of all means of armed struggle and new forms of warfare [2, 3]. The variety of combat missions performed using combat wheeled vehicles (CWVs) determines the diversity of combat properties that cannot be implemented in a single model, and therefore there is a need to design several types of CWVs [4].

It is clear that, other things being equal, a specialized CWV can more successfully perform specific tasks than a universal CWV [5]. However, successful warfare involves the mass use of CWV models and, as a result, serial production of CWV models adopted for service with the release of the necessary spare parts for them [6, 7].

In order to achieve a high degree of coordination of the characteristics of the existing range of CWV samples with their combat purpose, it is necessary to generalize CWV samples by functional purpose [8]. Categorization makes it possible to implement a formalized, orderly generalization of information [9]. Owing to a thorough categorization, a certain level of development of CWV samples is achieved, their structure is established in a certain general set, etc. [10]. This makes it possible to clearly define the place of CWV samples in the general weapons system.

Conventional categorization involves analyzing CWVs by structural features (number of driving/steering axles, type and location of the engine, type of body, cabin, main transmission, etc.). However, such classification makes it impossible to establish a connection between the technical parameters of CWVs and their functional purpose, which prompts the development of more appropriate methods for categorizing CWVs.

In modern military research [11, 12], the classification of CWVs by the combat mass of the model is widely used. However, in many cases, the use of categorization by such a numerical characteristic of the model is unsuccessful since it requires generalization of characteristics using additional transformations [13].

Therefore, an urgent scientific task is to conduct scientific research on the organization of the CWV model using cluster analysis methods. This will ensure the division of CWV models into groups with maximum similarity within and significant differences between groups. In practical terms, this will simplify the manufacture of CWVs in service, their repair, restoration, and training of personnel.

2. Literature review and problem statement

In order to devise a CWV categorization method, it is first necessary to determine the technical characteristics by which they can be linked into groups. The next step is to choose the type of CWV classification method that could make it possible to establish a correspondence between the technical characteristics of CWV samples and their functional purpose.

The results of studies on the evolutionary development of CWVs from the first to the fourth generation are reported in [14, 15]. In particular, in [14] it is shown that global trends in the development of CWVs provided for the implementation of lethal flexible modular structures with turret systems. New CWV designs are characterized by high reliability and increased survivability under conditions of threats in various theaters of operations, but the disadvantage is limited mobility and increased mass of CWVs. A possible option for eliminating this drawback was the study by regression and variance analyses of two configurations (evolutionary and revolutionary CWV designs) in terms of mass and volume. It is noted that the revolutionary design configuration is better than the evolutionary one since it has a lower combat mass (about 41 tons). However, in addition to the CWV configuration, other factors that contribute to the reduction of the CWV mass have not been studied. All this gives grounds to argue that it is advisable to conduct a study on the influence of technologies, materials, automated control systems on reducing the mass and improving the quality of CWV structures.

This is the approach presented in [15], in which, in addition to mass, the influence of power, power-to-mass ratio, average speed of movement of CWVs, and their general configuration on the quality of CWV design was studied. It is noted that early CWV designs achieved improved firepower and mobility due to technological improvement of subsystems. In the fourth-generation CWVs, the design improvement provided for compact integration of power units, turrets, and crew compartments. However, issues related to the decrease in the CWV's ability to survive under intense combat conditions despite the overall increase in their combat effectiveness remained unresolved. A solution option is to study the degree of improvement in design quality by replacing steel elements with composite ones, introducing active protection systems, reducing weight, expanding combat capability (electronics, communication systems), using unmanned turrets and hybrid drives. In general, the diversity of existing CWV models [14, 15] contradicts modern integrated principles of development of weapons and military equipment, as it does not ensure the uniformity of CWV models in terms of mobility and protection. This also negatively affects the combat capabilities of units, the interaction of forces and means in battle, marching capabilities, and personnel training. All this gives grounds to argue that in order to reduce diversity and increase the level of unification of CWVs, it is advisable to design a rational range of CWV models. It should be systematized and unified according to functional and structural features and values of CWV parameters, which will ensure the prospective need for CWV models with a given technical level.

A partial solution to the specified scientific problem is reported in [1]. A conceptual approach to the design of the latest CWVs is proposed, based on the asymmetric principle of their development. In order to reduce the diversity and increase the level of CWV unification, it is proposed to design a rational range of CWV samples. It should be systematized and unified according to functional and structural features and values of CWV parameters, which will ensure the prospective need for CWV samples with the necessary technical level. The conducted justification of the type of CWV samples involves determining the tasks of CWVs, the list of weapons and special equipment provided for installation on the CWV chassis. Subsequently, the prospective need for CWV samples is determined, the selection of parameters for building a CWV standard size series is selected, and a rational CWV standard size series is built.

All this gives grounds to assert that the initial data for the implementation of the first three stages are the tasks of the ground forces, according to which the place and role of CWVs in them are determined. At these stages, the operational-tactical concept of the CWV model is determined – a system of views on the combat use of the model, which characterizes its purpose, the tasks assigned to the CWV model, and the conditions for their implementation. At the fourth stage, the main parameters for building the CWV type are selected, which determine their design and combat capability. The authors of work [16] listed the parameters obtained through mathematical modeling, on which the level of CWV unification depends. The modeling results, confirmed by experimental data, have gained wide application, providing new opportunities both for building a rational standard-size series of CWVs and in solving strategic tasks of reducing losses among personnel. But the study has limited application. The reason is the unresolved issues related to the definition of the technical characteristics of CWVs, which take into account the payload on the CWV axles, combat mass, wheel formula, engine power, armor. Each of these technical characteristics of the CWV samples, necessary for their combination into groups with similar functional purpose, was studied in [17–21].

In paper [17], as a factor in increasing the level of unification of CWV, dynamic armor was studied – an effective system of protection against high-explosive anti-tank mines and missile threats. Various methods of improving the protective functions of dynamic armor, necessary for increasing the survivability of CWVs in futuristic multi-spectral combat scenarios, were presented. However, issues related to the study of personnel safety factors remained unresolved. A solution to these issues is reported in study [18]. However, in addition to personnel safety factors and dynamic armor, the influence of other factors on increasing the level of unification of CWV was not investigated, which limits the scope of application of the results.

In turn, in [19], the research is focused on the study of the payload as one of the technical characteristics of CWV. It is shown that the payload most fully characterizes the chassis' adaptability to the placement of weapons and special equipment on it, determining the dimensions, mass, and dimensions of the main components and assemblies of the CWV, which ensure the strength of the structure.

In work [20], the results of the study of the combat mass of CWV are reported. It is shown that the combat mass of the CWV (the maximum permissible mass of the CWV sample) is another important factor in increasing the level of unification of the CWV since it remains unchanged throughout the entire period of operation of the standard size series. It is analytically and experimentally confirmed that such characteristics of the combat mass as the location of the center of gravity, moments of inertia, and total mass have a significant impact on the stability of the CWV and its deployment.

In study [21], the axle load was examined, which, in turn, determines the number of CWV axles (with a known combat weight), as well as the CWV cross-country ability on dirt roads and off-road. A comparison of semi-active and passive types of suspensions in terms of ride comfort, power consumption, and performance when driving on roads of different classes was presented. However, the issues related to the justification of the optimal axle load from the point of view of a given level of cross-country ability and the justification of the wheel formula remained unresolved, which is difficult to implement due to the high cost of the necessary experimental studies. In addition, the work does not contain experimental studies on the operation of all-wheel drive CWVs on roads with improved surface.

The influence of the wheel formula on the CWV cross-country ability was investigated in [22]. It was established that the wheel formula affects the coupling mass coefficient – the ratio of the coupling mass to the combat mass. In the study, the coupling mass is considered to be the part of the CWV mass that creates a load on the drive wheels and is one of the important indicators that determines the level of cross-country ability. Study [22] complements paper [21] but does not take into account the engine power as one of the basic characteristics of CWV samples that determines their functional purpose. In turn, such a study is reported in [23]. It is shown that the engine power determines the traction and dynamic characteristics of CWVs, their cross-country ability, and transmission parameters. Also, the engine power and its type determine the fuel-economic characteristics of CWVs, CWV reliability, ability to operate on different types of fuel, metal consumption of the transmission and CWV as a whole [23]. Studies [22, 23] complement papers [17–20] by establishing the correspondence between the technical characteristics of CWV samples and their functional purpose.

The review of the literature [13–23] allowed us to select the characteristics by which CWV could be assigned to groups where CWV samples with similar functional purpose are combined. These include combat mass, wheel formula, load capacity, engine power, overall dimensions (length, width, height), chassis clearance. It was confirmed that the categorization of CWV samples by combat mass or individual indicators would not lead to the identification of clusters suitable for perception. Therefore, the classification of CWVs according to the above parameters will make it possible to ensure the homogeneity of CWV samples in groups similar in functional purpose. In practice, this will improve the combat capabilities of units, simplify the operation and repair of CWV samples.

CWV categorization methods that make it possible to establish a correspondence between the technical characteristics of CWV samples and their functional purpose are described in studies [24–27].

A new method for vehicle categorization is proposed in [24]. It is shown that the method makes it possible to consider CWV samples both at the stage of determining CWV classes and during CWV classification and assessment of its correctness, demonstrating scalability, as it is capable of covering thousands of classes. An additional advantage of the proposed method is the possibility of automated determination of CWV classes, which significantly reduces the impact of human error and eliminates subjectivity. The effectiveness of the method is confirmed by experimental data. However, the dependence of the method exclusively on a single source of information (magnetic signature) limits its application in certain contexts, and the need for user-specified parameters leads to variability depending on the user's experience. Also, the lack of comparative analysis with existing methods and the potential for an excessive number of classes (subclasses) for designing CWV types highlight areas for further research and improvement.

The authors of study [25] propose the use of automated data analysis methods – clustering or categorization – to establish previously undiscovered relationships between data elements. To classify CWV according to any of its technical characteristics, CWV should be divided into classes. It is noted that the complexity of CWV classification relates to the correct choice of the appropriate analysis method – clustering using k-means or categorization using a neural network (AI). It is shown that the complexity of using automated data analysis methods is the need for significant data sets of parameters to be analyzed.

A simple and accessible method for categorization is reported in [26]. Although the work studies unmanned aerial vehicles, the categorization methodology, hardware, and software development problems with various capabilities in civil and military applications can be adapted to CWVs.

In [27], the average values of specific indicators were determined when dividing CWV into six groups. According to this distribution, carried out by cluster analysis methods, the presence of a clear structure in the data sample of 25 CWV samples was established. However, two CWV samples from the sample when classified by different methods belonged to different groups, which led to a shift in the cluster centers and a change in the order of association with a smaller number of clusters. This drawback indicates the blurring of real clusters in the sense of the gradual transition of samples when changing characteristics from belonging to non-belonging to these clusters, compared to the jumpiness and requires further research.

Based on the above, it follows that the CWV categorization methods given in [24–27] could only partially ensure the homogeneity of CWV samples in groups similar in functional purpose. Therefore, the scientific task is to devise a CWV classification method that will establish a correspondence between the technical characteristics of the samples and their functional purpose and will also make it possible to take into account the uncertainties caused by the assignment of samples with intermediate characteristics between the groups to one group. This will make it possible to set benchmarks to which CWV samples should approach when designing CWV types that will be constructed on the basis of unified units and assemblies.

3. The aim and objectives of the study

The purpose of our study is to devise a method for categorizing wheeled combat vehicles using fuzzy cluster analysis. This will make it possible to ensure the homogeneity of CWV samples in groups similar in functional purpose, improve the combat capabilities of units and personnel training, and simplify the operation and repair of CWV samples.

To achieve the goal, the following tasks were set:

– to determine the belonging of CWV characteristics to the corresponding clusters;

– to determine the distribution of CWV samples in the case of six clusters.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is CWV samples.

The hypothesis of the study assumes that by using fuzzy cluster analysis, it is possible to propose a method for categorizing CWVs, which would make it possible to link their technical characteristics to groups with similar functional purpose.

When using fuzzy cluster analysis, the assumption was adopted that there are groups of samples in the CWV set that are linked by the same functional purpose.

The simplification was that the technical characteristics of CWVs for processing were selected from open sources without taking into account the latest modifications, the characteristics of which are not published.

4. 2. Methodology for conducting CWV categorization using fuzzy cluster analysis

The requirement of uniqueness of clustering of CWV samples is a rather rough and strict requirement. Fuzzy clustering methods weaken this requirement. The weakening is carried out by introducing fuzzy clusters and their corresponding membership functions, which can take values in the interval from 0 to 1. Thus, in general, the task of fuzzy clustering is to find the degrees of membership of CWV samples to fuzzy clusters, which together determine the fuzzy division of the initial set of CWV samples. In this case, the condition must be met, which is due to the need to overlap the fuzzy distribution of the clear set of elements A:

$$\sum_{k=1}^{c}\mu_{Ak}\left(a_i\right)=1,\ \ \forall a_i\in A, \tag{1}$$

where c is the number of fuzzy clusters A_k; $\mu_{Ak}(a_i)\in[0,1]$ is the value of the clustering object a_i belonging to the fuzzy cluster A_k; i is the number of clustering objects.

The centers $\vartheta_k=\left(\vartheta_1^k,\vartheta_2^k,\ldots,\vartheta_q^k\right)$ of fuzzy clusters A_k are determined for each fuzzy cluster for each categorization feature and expression:

$$\vartheta_j^k=\left(\sum_{i=1}^{n}\left(\mu_{Ak}\left(a_i\right)\right)^m x_j^i\right)\left(\sum_{i=1}^{n}\left(\mu_{Ak}\left(a_i\right)\right)^m\right)^{-1}, \tag{2}$$

where $m\in(1,\infty)$ is a weight parameter that determines the fuzziness, blurriness of elements in clusters; x_j^i is the value of the j-th feature of the i-th clustering object; $j=\overline{1,q}$; q is the number of categorization features.

The fuzzy clustering problem can be stated as follows: for a given set of elements A, the number of fuzzy clusters c and the parameter m, it is necessary to determine the values of the membership functions of CWV samples to fuzzy clusters A_k, at which the minimum of the objective function is achieved:

$$f\left(A_k,\vartheta_j^k\right)=\sum_{i=1}^{n}\sum_{k=1}^{c}\left(\mu_{Ak}\left(a_i\right)\right)^m\sum_{j=1}^{q}\left(x_j^i-\vartheta_j^k\right)^2, \tag{3}$$

and the restrictions (1) are satisfied, as well as:

$$\sum_{i=1}^{n}\mu_{Ak}\left(a_i\right)\succ 0,\ \ \forall k\in\left\{2,\ldots,c\right\}, \tag{4}$$

$$\sum_{i=1}^{n}\mu_{Ak}\left(a_i\right)\prec n,\ \ \forall k\in\left\{2,\ldots,c\right\}. \tag{5}$$

Condition (4) excludes the appearance of empty fuzzy clusters in the desired fuzzy clustering, and condition (5) – the membership of all elements in one cluster.

In this case, the minimization of the objective function (3) minimizes the deviation of all clustering objects from the centers of fuzzy clusters in proportion to the values of the membership functions of these objects to the corresponding fuzzy clusters.

The advantage of stating the fuzzy clustering problem in this form is the interpretation of both the desired fuzzy clusters, which are determined by the membership functions, and their typical representatives or centers, which are also determined as a result of solving the problem.

The result of solving the fuzzy clustering problem is the membership matrix:

$$M=\begin{pmatrix}\mu_{A_1}\left(a_1\right) & \mu_{A_1}\left(a_2\right) & \mu_{A_1}\left(a_n\right)\\ \mu_{A_2}\left(a_1\right) & \mu_{A_2}\left(a_2\right) & \mu_{A_2}\left(a_n\right)\\ \ldots & \ldots & \ldots\\ \mu_{Ac}\left(a_1\right) & \mu_{Ac}\left(a_2\right) & \mu_{Ac}\left(a_n\right)\end{pmatrix}, \tag{6}$$

and the coordinate matrix of cluster centers:

$$N=\begin{pmatrix}\vartheta_1^1 & \vartheta_2^1 & \ldots & \vartheta_q^1\\ \vartheta_1^2 & \vartheta_2^2 & \ldots & \vartheta_q^2\\ \vartheta_1^c & \vartheta_2^c & \ldots & \vartheta_q^c\end{pmatrix}. \tag{7}$$

Since the objective function (3) is not convex, and constraints (1), (4), (5) together form a non-convex set of admissible alternatives, in the general case the fuzzy clustering problem belongs to multi-extreme nonlinear programming problems.

To find the matrix M that minimizes the criterion $f\left(A_k, \vartheta_j^k\right)$, the fuzzy c-means algorithm (FCM) is used, which is based on the Lagrange multiplier method [28]. It makes it possible to find a local optimum, so different results can be obtained for different runs. In the first step of the calculations, the membership matrix is generated randomly. Then, an iterative process of calculating the cluster centers and recalculating the elements of the membership matrix is carried out:

$$\mu_{\tilde{A}k}\left(a_i\right)=\left(\sum_{l=1}^{c}\left(\frac{\left[\sum_{j=1}^{q}\left(\left(x_j^i-\vartheta_j^k\right)^2\right)\right]^{\frac{1}{2}}}{\left[\sum_{j=1}^{q}\left(\left(x_j^i-\vartheta_j^l\right)^2\right)\right]^{\frac{1}{2}}}\right)^{\frac{2}{m-1}}\right)^{-1} \text{ at } \sum_{j=1}^{q}\left(x_j^i-\vartheta_j^k\right)^2 \succ 0,$$

$$\mu_{\tilde{A}k}\left(a_i\right)=\begin{cases}1, & l=k,\\ 0, & l\neq k\end{cases} \quad \text{at } \sum_{j=1}^{q}\left(x_j^i-\vartheta_j^k\right)^2=0. \quad (8)$$

For the analysis, the technical characteristics of 25 CWV models [20] were used, which are given in Table 1.

The calculations continue until the change in the matrix M, characterized by the value $||M-M^*||^2$, where M^* is the matrix of the previous iteration, becomes less than the predetermined stopping parameter ε.

5. Results related to devising a method for categorizing wheeled combat vehicles using fuzzy cluster analysis

5. 1. Determining the membership of CWV characteristics to the corresponding clusters

Processing the CWV characteristics listed in Table 1 by the FCM method makes it possible to obtain the membership functions of CWV samples to six clusters (Table 2).

To determine the minimum number of samples required for an adequate solution to the fuzzy clustering problem, the values of the objective function and the magnitude of the objective function increment per sample were determined with a sequential increase in the number of samples. The resulting dependences are shown in Fig. 1.

Table 1

Technical characteristics of CWV samples

CWV model (manufacturer, year of implementation)	Combat mass, kg	Wheel arrange-ment	Load capacity, kg	Motor power, kW	Length, m	Width, m	Height, m	Chassi clearance, m
Akrep (Otokar, 1994)	3.600	4×4	800	100	4.19	1.91	2.56	0.229
Land Rover D130 (Land Rover, 1983)	2.400	4×4	705	91	3.722	1.79	1.96	0.229
Auverland A4 AVL (Panhard, 2008)	5.100	4×4	1.130	112	4.233	1.96	2.03	0.23
Cobra (Otokar, 1997)	6.500	4×4	1.250	142	5.5	2.22	2.1	0.4
Eagle I (MOWAG, 1999)	4.500	4×4	2.200	119	4.9	2.28	1.75	0.4
Eagle IV (MOWAG, 2003)	8.800	4×4	2.100	186	5.4	2.3	2.3	0.4
AGF (Rheinmetall, 2002)	3.300	4×4	1.000	116	4.88	1.82	1.87	0.4
Dingo 2 (Krauss-Maffei Wegmann, 2000)	12.500	4×4	2.600	163	6.1	2.3	2.5	0.48
Cougar (Force Protection, 2002)	17.200	4×4	2.720	246	5.91	2.74	2.64	0.41
Cougar HE (Force Protection, 2002)	23.590	6×6	5.900	246	7.08	2.74	2.64	0.41
LMV (Iveco, 2001)	7.100	4×4	2.900	142	4.8	2.2	2.05	0.473
Tiger (GAZ, 2004)	7.200	4×4	3.100	153	5.7	2.3	2.4	0.4
Stryker (General Dynamics Land Systems, 2002)	17.200	8×8	4.700	261	6.95	2.72	2.64	0.5
M-ATV (Oshkosh Corporation, 2009)	14.700	4×4	1.800	276	6.27	2.49	2.7	0.4
HMMWV M1097A2 (AM General, 1993)	4.672	4×4	1.996	119	4.84	2.18	1.88	0.4
HMMWV M1114 (AM General, 1993)	5.489	4×4	1.043	142	5	2.3	1.9	0.4
HMMWV M1151A1(AM General, 2006)	6.101	4×4	1.370	142	4.9	2.18	1.82	0.43
RG-32M (BAE Land Systems South Africa, 2002)	6.700	4×4	1.600	137	5.05	2.2	2.31	0.41
RG-31 (BAE Land Systems South Africa, 2000)	7.280	4×4	2.000	205	6.4	2.47	2.63	0.4
RG-33L (BAE Land Systems South Africa, 2006)	26.332	6×6	8.762	298	8.5	2.4	2.9	0.36
RG-33(BAE Land Systems South Africa, 2007)	17.252	4×4	3.768	298	6.7	2.4	2.9	0.36
SPV-3 (GAZ, 2008)	12.000	4×4	2.000	246	5.9	2.5	2.6	0.5
AMV (Patria, 2004)	16.000	8×8	8.000	405	7.7	2.8	2.3	0.4
ALSV (Chenowth Racing Products, 1996)	1.600	4×4	640	119	4.1	2.11	2.01	0.4
DPV (Chenowth Racing Products, 1991)	1.600	4×4	681	149	4.09	2.11	2.01	0.4

Table 2

Membership functions of samples to six clusters

Sample	Cluster					
	1	2	3	4	5	6
Akrep	0.03	0.09	0.01	0.01	0.85	0.01
Land Rover D130	0.02	0.06	0.01	0.01	0.88	0.02
Auverland A4 AVL	0.15	0.76	0.02	0.01	0.05	0.01
Cobra	0.04	0.92	0.01	0.00	0.02	0.00
Eagle I	0.06	0.80	0.02	0.01	0.12	0.01
Eagle IV	0.73	0.13	0.08	0.02	0.03	0.00
AGF	0.03	0.11	0.01	0.01	0.83	0.01
Dingo 2	0.10	0.04	0.72	0.12	0.02	0.00
Cougar	0.01	0.01	0.07	0.90	0.00	0.00
Cougar HE	0.04	0.02	0.11	0.82	0.01	0.00
LMV	0.91	0.04	0.03	0.01	0.01	0.00
Tiger	0.10	0.72	0.04	0.02	0.11	0.01
Stryker	0.73	0.08	0.12	0.04	0.02	0.01
M-ATV	0.02	0.01	0.93	0.04	0.00	0.00
HMMWV M1097A2	0.04	0.86	0.01	0.01	0.08	0.00
HMMWV M1114	0.03	0.94	0.01	0.00	0.02	0.00
HMMWV M1151A1	0.80	0.11	0.04	0.02	0.03	0.00
RG-32M	0.09	0.84	0.02	0.01	0.03	0.00
RG-31	0.10	0.32	0.06	0.03	0.47	0.03
RG-33L	0.00	0.00	0.02	0.97	0.00	0.00
RG-33	0.06	0.04	0.46	0.41	0.02	0.01
SPV-3	0.18	0.07	0.66	0.06	0.02	0.01
AMV	0.85	0.08	0.04	0.01	0.02	0.00
ALSV	0.02	0.02	0.01	0.01	0.04	0.90
DPV	0.01	0.01	0.01	0.01	0.02	0.95

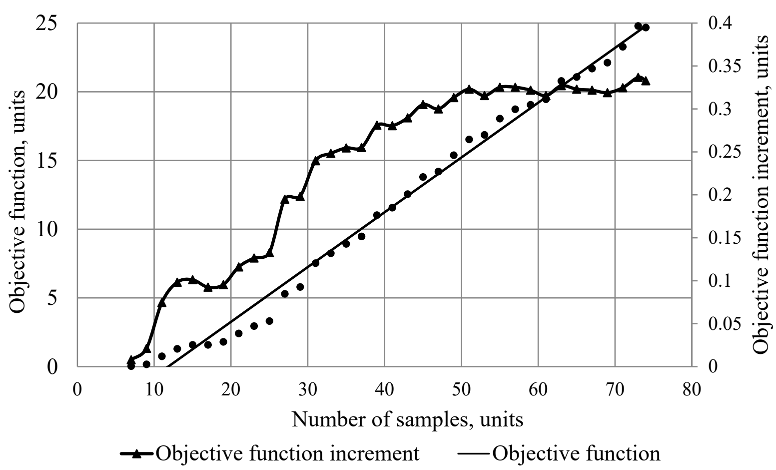

Fig. 1. Dependence of the objective function on the number of samples

Thus, it can be stated that the results of determining the value of the membership matrix for 74 CWV samples to a specific cluster according to (6) showed that using a sample of 55 samples is sufficient to determine the coordinates of the cluster centers and perform categorization in relation to the number of CWV samples.

5. 2. Determining the distribution of CWV samples in the case of six clusters

The determined distribution of CWV samples in the case of six clusters is given in Table 3.

Table 3

CWV distribution in the case of six clusters

Cluster name	Average values in clusters according to the FCM A/B/C* method	Intervals of values in clusters at a membership level of 0.8 A/B/C	Intervals of values in clusters at a membership level of 0.9 A/V/C
Light strike CWVs	0.8	0.8	0.8
	113	100–125	100–125
	115	115	115
Light tactical CWVs	2.2	1.5–2.3	1.5–2.3
	35	33.3–40	33.3–40
	254	193–299	193–299
Medium tactical CWVs	3.6	2.6–4.2	3.3–4.1
	23	18.1–29.2	19.1–27.5
	318	271–357	271–357
Heavy tactical CWVs	4.5	3.5–5.2	3.9–4.9
	23	18.6–28.6	18.6–27.4
	474	425–506	482–496
High mobility MRAP	6.2	5.5–7.1	5.8–7.1
	20	16.7–27.5	18.6–21.8
	392	371–441	371–427
Patrol MRAP	7.6	6.9–9.1	6.9–8.5
	18	14–19.8	14–19.6
	570	508–665	545–602

*Note: * – A is the axle load, t; B is the specific power, kW/t; C is the mass of the sample per cubic meter of volume, kg/m^3.*

However, for practical use, it is advisable to determine the interval values of the cluster centers. For this purpose, it is necessary to take the characteristics of CWV samples, the level of belonging to which to the cluster has a value greater than a certain value. The results for 80 % and 90 % of the membership level are also given in Table 3.

6. Discussion of results based on the categorization of wheeled combat vehicles using fuzzy cluster analysis FCA

The theoretical foundations of the proposed research method are generally outlined in [27]. Unlike the previously proposed method, in this study, due to the use of FCA, it became possible to use any set of initial data to analyze the CWV sample.

The analysis of membership functions (Table 2) reveals that the CWV samples, which according to hierarchical agglomerative and iterative clustering methods were assigned to different clusters (RG-31, RG-33) [27], have high values of membership in different clusters. This indicates their intermediate position in the categorization and the feasibility of using this method. In order to more accurately determine the average values of specific characteristics in clusters, an analysis of the sample including 74 samples was carried out. For this purpose, it is necessary to determine the value of the weight parameter for this type of problem.

To determine the value of the weight parameter, a preliminary calculation and analysis of the membership degree matrix obtained at $m=2$ was carried out. The analysis performed revealed that the average level of membership of samples to 6 clusters is 90.2 % and indicates a significant blurring of the membership matrix. In further calculations, the value of m decreased and when the value of $m=1.68$ was reached, the average level of membership of samples to 6 clusters was 99 % (the calculation results are given in Table 2). The membership of a sample to 6 clusters actually indicates a case when each categorization feature occupies an intermediate position between two cluster centers and these intervals are adjacent and do not overlap.

Experience in solving applied problems of fuzzy clustering shows that the most effective way to obtain adequate results is to repeatedly execute the fuzzy clustering algorithm for different initial fuzzy breakdowns. The results are compared by the values of the objective function of the obtained fuzzy breakdowns in order to make a final decision on the desired fuzzy clustering.

It has been established that after reaching a sample size of 55 CWV samples, the increase in the objective function by one sample with a further increase in the number of samples stabilizes, which indicates the establishment of the minimum sample size.

The results of our study, shown in Fig. 1 and Table 2, allow us to ensure an increase in the accuracy of determining the average values of specific indicators in clusters by fuzzy cluster analysis methods. In this case, uncertainties caused by the assignment of samples with intermediate characteristics to one group are taken into account and the belonging of existing and promising samples to a specific group is established or their intermediate position is determined.

When determining the intervals of characteristics, the exclusion of samples with a lower degree of belonging than the basic one makes it possible to establish ranges of specific indicator values, which is of great importance when forming possible variants of unified CWV families.

The development of the basic CWV sample is carried out taking into account the provision of the required technical level and quality of modifications created on its basis. At the same time, the maximum possible unification of the components of the basic sample and its modifications is ensured. In addition, the possibility of developing modifications is provided by additional attachment, removal, replacement or change in the spatial combination of various components.

The transmission parts and mechanisms of the basic model must provide the necessary strength and reliability. This rule forces the partial use of units, parts, and mechanisms that operate with lower, compared to the maximum permissible loads. The margin of safety in this case is expedient to determine under the condition of ensuring the performance of the basic model of tasks for its intended purpose with the maximum possible level of protection, the need for which was identified as a result of an expert survey.

Within each defined group of homogeneous samples (clusters) there should be no more than one base sample. Given that the basis of the family is a unified driving axle, designed for the same axle load, unification of components between different groups of homogeneous samples is possible in the case of close values of the axle load. An example of such groups in Table 3 can be medium and heavy tactical CWVs.

Modifications are created in accordance with the specific purpose, taking into account the required level of protection and the results of analysis of existing unified families. Experience shows that the degree of unification of CWVs, which are manufactured by well-known world companies, depends on both the required CWV parameters and production and economic factors. Therefore, the results of analysis of existing unified CWV families should be used for an approximate selection of the number of families and determining the possibility of creating modifications within a specific standard size. Among the identified possible options for CWV unification, the rational option will be the one that has the smallest number of unified families and the lowest operating costs.

The proposed CWV categorization method provides the opportunity to design rational protection options and justify specific technical solutions to increase the level of survivability of samples within groups. This became possible through the determination of additional protection mass and engine power, the installation of which will change the functional purpose of the sample. In addition, the need to ensure the required level of protection under conditions of mass restrictions when creating families requires the implementation of measures alternative to homogeneous armor. And the effectiveness of structural measures to ensure protection is determined by the level of ballistic and mine protection of the sample under conditions of restrictions imposed by the categorization.

The proposed CWV classification method, unlike existing ones, makes it possible to establish a correspondence between the technical characteristics of the samples and their functional purpose. It also provides the possibility of developing rational protection options and substantiating specific technical solutions to increase the level of survivability of CWV, which minimizes the costs of ensuring protection.

In order to reduce the diversity and increase the level of unification of promising CWV samples, it is proposed to use the devised categorization method when substantiating the rational range (type) of CWVs at the stage of forming possible unification options.

Thus, when substantiating the CWV type at the stage of forming possible CWV unification options, a CWV categorization method using fuzzy cluster analysis is proposed. The results of our study, given in Table 3, make it possible to take into account the uncertainties caused by the assignment of samples with intermediate characteristics to one group. As well as to establish the belonging of existing and promising CWVs to a specific group or to determine their intermediate position. These results also allow us to determine the ranges of values of specific indicators that characterize the combat properties of CWVs. It becomes possible to determine the boundaries (contours) of unified CWV families by forming groups of homogeneous samples according to the features that characterize the combat properties of CWV samples. It is also possible to determine the values of parameters that are regulated by the type and provide the possibility of constructing machines for various purposes on the chassis of the base sample.

The derived experimental dependences in Fig. 1 and categorization (Table 3) are new in that they were obtained using FCA and were not used in the analyzed literary sources.

The limitations of our studies are related to a specific set of CWVs; the results are limited to the conditions of the experiment.

The disadvantages of the study include the fact that such a categorization feature as the mass of the sample per cubic meter of volume (*C*) is determined by the overall dimensions of the CWV. In this case, the overall dimensions of the CWV sample are represented by a parallelepiped. This approach does not take into account the complex geometry of the CWV, which must be taken into account in further studies. In addition, the classification feature of the load on the axis (*A*) does not take into account the possible difference in the magnitude of the load on different axes of the CWV.

The practical significance of our research results is that they could be used to determine the same type of CWV samples under conditions of a significant variety of options for providing units.

7. Conclusions

1. It has been established that to solve the problem of CWV categorization by the method of fuzzy cluster analysis, it is necessary to use a sample of at least 55 CWV units. At the same time, the fuzziness of the membership matrix ensures the average level of membership of samples to 6 clusters at a weight parameter value of 1.68 at a level of at least 99 %.

2. Our distribution of CWV samples into six clusters is sufficient to meet the needs of categorization and does not require an increase in the number of clusters due to the presence of individual CWV samples with high degrees of membership in 2 different clusters with existing differences in one classification feature.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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