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# Model of the Optimal Maneuver Route

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## Abstract

The chapter deals with the mathematical model for planning the optimal movement route, which has been implemented in the Tactical Decision Support System (TDSS). The model processes and evaluates the data contained in the five raster layers, which are tactically relevant for planning the movement route of troops or autonomous vehicles on the battlefield. The basis for calculating the optimal movement route is a ground surface layer, which is then modified by algorithmic and criterion relationships with the layers of hypsometry, weather attack, and the activities of enemy and friendly units. The result of mathematical model calculations is a time-optimized and safe movement route displayed on the topographic basis. The experiments realized have verified the function of the optimal movement route model when neither the reconnaissance group nor the autonomous vehicle was observed by the enemy. The total time of the UGV with the use of the TDSS to cover the route of maneuver was 67 minutes shorter than the real time of the BRAVO group movement with the use of the TDSS and 105 minutes shorter than the real time of the ALFA group without the use of the TDSS. The comparison of responses to the attack shows that the BRAVO group using the Maneuver Control System (MCS CZ) as part of the TDSS has destroyed the attackers faster by 71 seconds than the ALFA group without the use of the TDSS.

**Keywords:** autonomous vehicle navigation, optimal route of maneuver, off-road capability, passability, terrain analysis

## 1. Introduction

Over the past 10 years, a considerable progress has been observed in the field of autonomous systems in various fields of activity. Currently, autonomous systems are used and will continue to be used in all spatial dimensions, i.e., ground, aerial (space), as well as maritime ones. One of the criteria for the division of autonomous systems is a degree of autonomy. The system (vehicle) can be fully autonomous, when all the functions that the system has to carry out are controlled by a vehicle itself. The semiautonomous system is autonomous only in some of its partial functions, when the complex decision function is edited and controlled by the operator. In the case of ground autonomous systems

(Unmanned Ground System (UGS)), it is necessary to deal with two management processes in terms of their movement. On the one hand, it is a direct movement control in the field where the most important factors are microrelief and various types of obstacles and, on the other hand, the process of planning and creating the optimal movement route itself before completing the task itself.

In the past, the problem of searching for the optimal movement route was already dealt with using both vector and raster graphics. Based on the values of edges or raster cells, the shortest route between two points can be found using the mathematical algorithms described in [1, 2]. Some publications can also be found that describe models for moving different elements through the terrain. Based on passability parameters, they assess the movement possibilities for personnel and wheeled and tracked vehicles. These models can be found in [3–5]. The vector format of geographic data offers another route planning for autonomous vehicles. This format is commonly used by GPS receivers with the use of the road structure and graph theory. The graph of the road structure includes nodes and edges in the form of crossroads and roads. It is called “edge-defined,” which means that the only criteria are the edge value and the movement direction. The shortest path includes the sum of all edge values between the beginning and the end with the smallest value. Outside the network of paths, the vector model navigates directly to the target, without any analysis of the influence of the vegetation and the relief. Another planning strategy of movement for autonomous vehicles can be a “potential field” consisting of a limited space of artificial potential values. Autonomous vehicles operating in the area mentioned move from the position with the highest potential to the position with the lowest potential. However, it is very difficult to use the potential field in real-world situations.

Many articles deal with a series of “tracking strategies,” route planning, and obstacle avoidance in the case of autonomous vehicles. For example, [6] deals with obstacle avoidance in an urbanized environment and the comparison of techniques for the movement planning of autonomous and semiautonomous vehicles. The content of most articles aims at the movement planning strategies. These are characterized by route planning algorithms implemented in the planning process.

The tracking strategies, threat assessment, and route planning as part of the collision avoidance system are described in [7]. The most important part evaluates particular current methods in each collision avoidance strategy according to their advantages and disadvantages. The safety and fast resolution of collision situations is an important precondition for the efficient operation of fully automated vehicles.

The potential of unmanned marine vehicle (UMV) development is analyzed in [8]. One of the goals of the US Navy in the field of UMVs is to improve their autonomous movement planning and integrate the obstacle avoidance process at sea. The purpose of the UMV development mentioned is to prevent anticipated marine accidents and the future use of fully autonomous ships.

The cross-country movement analysis and the terrain passability testing are specified in [9]. Terrain passability is affected by many factors; it represents a key factor in achieving success in military operations. The geographic factors of the area of operations and the technical parameters of the vehicles define the capabilities of military units to move on the battlefield.

The optimal movement route model implemented in the Tactical Decision Support System (TDSS) can be used for planning and creating a movement route. The TDSS has been developed at the University of Defense in Brno, the Czech

Republic, since 2006<sup>1</sup>. The implemented model of the optimal movement route uses a raster digital data model, map algebra algorithms, and associated criterion assessments of the effects of the situation to process the effects of the situation on the battlefield. The model raster has an optional resolution, which means it indicates how large area of a given terrain the cell represents. An important feature of each raster cell is its value (attribute), which is specified by a particular or continuous character of the represented terrain area. It may be a landform, a terrain slope, weather effects, the enemy activity, or the time of its covering in a predetermined manner. The raster format of the network graph allows the layers of individual situation variables to be flexibly updated and mathematically combined; the layers of the individual situation variables affect the process of creating the movement route. Depending on the importance or the character of information, each raster cell acquires an attribute from a minimum value to  $\infty$ , which represents the time of covering the raster cell in hundredths of a second. The algorithm of the optimal movement route model then searches for the path between the two selected points with the lowest total sum of attribute values on the route; this allows the estimated total time of covering the route to be obtained. The TDSS uses the combination of Floyd-Warshall and Dijkstra's principle, described in [1, 10].

The model processes and evaluates tactical geographical information for three methods of troop movement:

- Dismounted movement
- Wheeled vehicles
- Tracked vehicles

Each method of the movement is influenced by specific characteristics of speed, terrain passability, and weather. The resulting movement route, evaluated by the model, is calculated with respect to the real terrain passability, the shortest time between the start and end points, and the safety. The enemy activity is the worst predictable part of the model due to its uncertainty and variant design.

## 2. Model concept

The concept of the optimal movement route model uses rasterized geographic data of the Digital Terrain Model and the Digital Relief Model for its work. The structure of the model is composed of several matrix layers that represent individual groups of horizontal (HF) and vertical (VF) factors of the passability (movement demands) of the area and safety. Each raster cell contains a numerical value of the difficulty of its covering ( $P_{np}$ , cost surface of passability), derived from the current state of the effects of task variables at a given position in the area. These are represented by HF and VF related to the difficulty of movement, which depend on the criterion evaluation of their occurrence characteristics, described in [11, 12].

When designing a movement route of forces and equipment, the model evaluates the following layers:

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<sup>1</sup> The TDSS is an experimental platform for testing of mathematic algorithmic models, using raster representation of data, having been developed at the Department of Tactics at the University of Defense since 2006 by Lt-Col. assoc. prof. Petr Stodola, PhD, and Lt-Col. assoc. prof. Jan Mazal, PhD.

1. Ground surface layer ( $P_{np1}$ ,  $HF_1$ )
2. Elevation layer ( $VF_2$ )
3. Weather layer ( $HF_3$ )
4. Enemy situation layer ( $HF_4$ )
5. Friendly forces and equipment layer of ( $HF_5$ )

The metrics of criterion evaluation are different for each layer in relation to its character and composition. The basic data for its calculation are cell dimensions, the average movement speed of a selected element on a given type of the ground surface that moves across the cell, and the resistance of the factor under consideration. The value calculated through the combination of  $P_{np1}$  and all layers of the model indicates the combined time of covering a given cell, influenced by all terrain and situation factors, in the form of the combined cost surface of passability ( $SP_{np}$ ), shown in **Figure 1**.

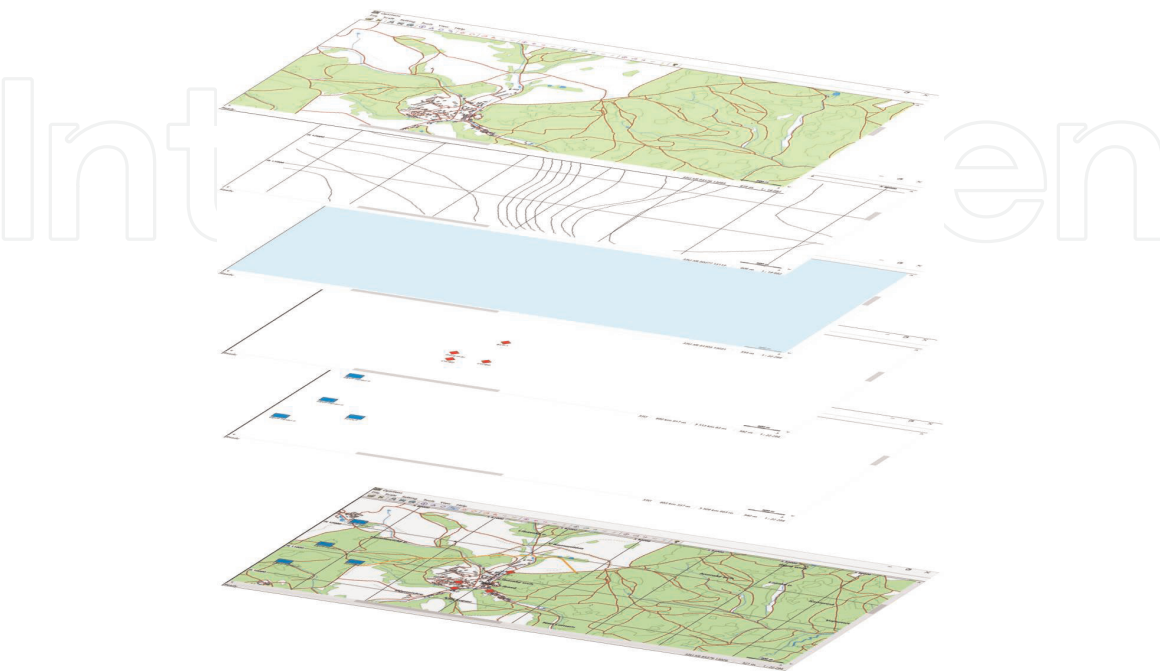
## 2.1 Model layers

The calculation of the model combined cost surface of passability consists of several layers of the task variables that are defined in the following text:

1. Ground surface layer

The ground surface layer forms a basis for further analysis of the model. Its cost surface of passability ( $P_{np1}$ ) consists of sublayers representing the types of ground surface as follows, described in [11–13]:

- a. Plant and soil cover



**Figure 1.**  
*The creation of the combined cost surface of passability (source: own).*



- b. Watercourses and water areas
- c. Communication over land and buildings
- d. Urbanized area

Based on its  $P_{np1}$ , the effects of other layers of the model are derived.

## 2. Elevation layer

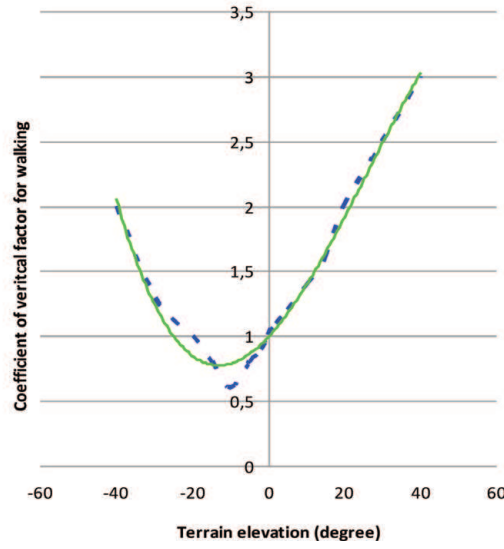
The hypsometry layer is formed by topography, which enters the calculation of  $SP_{np}$  through the vertical factor ( $VF_2$ ) of the terrain slope. Its definition can be formulated as a measure of demanding movement in the elevated terrain.  $SP_{np1,2}$  is created by a multiple of  $P_{np1}$  with a value of  $VF_2$ . It varies according to the type of movement as a vertical factor of the terrain slope for vehicles ( $VF_{2V}$ ) and for dismounted units ( $VF_{2C}$ ). The calculation of these factors is expressed by mathematical formulas (1) and (2). In the case of the movement of tracked or wheeled vehicles, it is possible to refer to the so-called linear influence of the terrain slope on the average speed of a given type of a vehicle. The vehicle engine load increases evenly with the rise in the terrain slope, and, under unchanged operating conditions, it causes a steady drop in speed. On the contrary, when driving downhill, the vehicle speed increases steadily. However, its gravity increase, given by the downhill driving and the pull of gravity, is usually broken by the driver using the braking system of the vehicle. The vertical factor of the terrain slope for vehicles ( $VF_{2V}$ ) is expressed by the mathematical formula as follows:

$$VF_{2V} = K_{V2V} \times \omega + 1 \qquad VF_{2V} = \frac{1}{K_{V2C}} \qquad (1)$$

The limiting passable terrain slope is set for tracked vehicles in the range of  $-30^\circ$  to  $+30^\circ$  and for wheeled vehicles of  $-30^\circ$  to  $+20^\circ$ , derived from [14–16]. Out of the range of these values, the terrain slope in the model is assessed as impassable, with  $VF_2 = 0$ . The course of  $VF_{2V}$  has a linear character given by constant value  $KV_{2V} = -0.004$ .

The difficulty of the movement of a dismounted element in the field has a nonlinear course as opposed to vehicles. The terrain slope ( $\omega$ ) affects the dismounted movement downhill or uphill differently depending on the topography and the safe movement controllability. Its difficulty in walking uphill increases exponentially as the slope increases. When walking downhill, it drops down up to  $20^\circ$ , when it is equal to the difficulty of movement on the flat ground. When walking downhill with the angle of slope of more than  $20^\circ$ , the difficulty increases again with the increasing slope. Such a course is caused by a degree of gravity that facilitates the movement at first. However, when the terrain slope is more than  $20^\circ$ , it forces the dismounted movement of individuals to brake in order to maintain a safe control over their movement. The influence of the terrain slope on the dismounted movement is expressed by the vertical factor of the terrain slope for dismounted movement ( $VF_{2C}$ ). The coefficient of the vertical factor for dismounted individuals ( $KV_{2C}$ ) is included in its calculation shown in **Figure 2**, which represents the degree of difficulty of the dismounted movement for a given terrain slope. Its values have been borrowed from the thesis developed by Lenka Mezníková, described in [17]. The limiting passable terrain slope for the dismounted movement is set in the range of  $-50^\circ$  to  $+50^\circ$ .

**Coefficient of vertical factor for walking( $K_{V2C}$ )**



**Figure 2.**  
Coefficient of vertical factor for dismounted movement (source: own).

The  $K_{V2C}$  curve, shown in the graph in **Figure 2**, has been put through the third degree polynomial curve to generate a regression equation as follows:

$$K_{V2C} = -0.0121\left(\frac{\omega}{10}\right)^3 + 0.0968\left(\frac{\omega}{10}\right)^2 + 0.3156\frac{\omega}{10} + 0.9933 \quad (2)$$

The value of the regression equation reliability is 0.9875.

### 3. Weather layer

In the weather layer, snowfall and rainfall are taken into account as direct effects on the terrain passability. Both of these effects are characterized by the overall impact of its occurrence in [18], which can be defined in the model based on the weather forecast or meteorological radar outputs. Snowfall limits the terrain passability on the entire terrain area. On the roads, it reduces the adhesion of their surface to the chassis of moving vehicles, even on a thin layer of snow.

To calculate the possibilities of passability in the field with a zero slope, the coefficients of the snow layer influence ( $K_{3.1}$ ) related to particular types of moving elements were mathematically derived, as follows:

- For tracked vehicles:  $K_{3.1P} = 0.01205$
- For wheeled vehicles:  $K_{3.1K} = 0.0192$
- For the dismounted movement:  $K_{3.1C} = 0.008$

The combination of the influences of the terrain slope and the snow layer thickness implements the coefficient of the snow-covered topography ( $O_{3.1}$ ) in the calculation of  $HF_{3.1}$ , which is differentiated according to the type of a moving element.  $O_{3.1}$  attains the following values:

- For tracked vehicles:  $O_{3.1P} = 0.034$
- For wheeled vehicles:  $O_{3.1K} = 0.0576$

- For the dismounted element:  $O_{3.1C} = V_{F2C}$

For the movement of tracked and wheeled vehicles, the derived mathematical formula is used as follows:

$$HF_{3.1P/K} = 1 - (K_{3.1P/K} \times L_{3.1}) - (O_{3.1P/K} \times \omega) \tag{3}$$

For the movement of the dismounted element, the derived mathematical formula is used as follows:

$$HF_{3.1C} = 1 - (K_{3.1C} \times L_{3.1}) - (1 - O_{3.1C}) \tag{4}$$

The limiting passable snow thickness for the dismounted element is set for 90 cm of snow since a thicker layer of snow is negotiable with great difficulties or even impassable for the dismounted element.

The model of the movement route for forces and equipment evaluates the effects of rainfall only for tracked and wheeled vehicles that move off the paved roads. The limitation of the terrain passability due to rainfall is generally assessed in four steps based on the precipitation amount for the purpose of creating a movement route in the model. The degree of limitation of individual steps is derived from the reduction in vehicle climbing performance, which defines the approximated reduction in vehicle climbing performance up to 50% when moving on a muddy soil surface. The muddy soil surface is defined generally as a precipitation amount larger than 40 mm in 3 days. Based on the meteorological forecast or the measurement of the abovementioned precipitation amounts, the model user can set a horizontal rainfall factor ( $HF_{3.2}$ ), which attains the values listed in **Table 1**.

4. The enemy situation layer

The enemy situation layer evaluates the safe passability of the area, depending on the possibilities of effective fire of his main weapons. It is created by the results of collecting the information on the enemy forces and equipment, which are defined in the model by their geographical position and the attributes of the tactical and technical characteristics of his weapons. From the location of their deployment, the area that is visible within the effective range of enemy weapon systems is then evaluated. Further, the model evaluates the danger area (which is impassable) of detected unexploded ammunition, improvised explosive devices (IEDs) or mine-fields, which is set based on the weight of detonating charge and the type of ammunition. The degree of danger expresses the degree of difficulty of covering the given area in the form of horizontal factor of the enemy situation ( $HF_4$ ). The database of forces and equipment enables the rapid editing of enemy forces and equipment.

$HF_{3.2}$	Rainfall amounts
0 impassable	Larger than 80 mm
0.25	Larger than 60 mm
0.5	Larger than 40 mm
0.75	Larger than 20 mm
1 without an effect	Smaller than 20 mm

**Table 1.**  
*The value of  $HF_{3.2}$  with different rainfall amounts.*



## 5. Friendly forces and equipment layer

The model of the optimal movement route evaluates the influence of availability of fire support executed by friendly forces and equipment based on their current position and effective range of the main weapon system. The model evaluates these facts as a supporting factor for the ability to pass through the area affected by the enemy activity via  $HF_5$ .  $HF_5$  expresses the degree of reduction in the impact of the enemy activity in terms of supporting the passage of the danger area of the task performance. The layer of friendly forces and equipment does not affect the passability of the area as a whole. It expresses only the ability or capabilities of friendly forces and equipment to support the maneuvering element by eliminating security risks. Thus, the combined cost surface of passability includes layers 1.4 and 5 only. The calculation of  $SP_{np1,4,5}$  is then expressed by formula (5):

$$SP_{np1,4,5} = \frac{P_{np1,4}}{\min(1, HF_4 \times HF_5)} \quad (5)$$

In the areas where any combat activity of the enemy is not and even was not detected in the past, its influence on the passability in the model is not evaluated.

## 2.2 Combined cost surface of passability

The model of combined cost surface of passability ( $SP_{np}$ ) is created by  $P_{np1}$  as a basis for its calculation and then by mathematical operations (division) of  $P_{np1}$  with  $HF$  and  $VF$  of individual layers. The  $SP_{np}$  calculation is then expressed by the mathematical formula as follows:

$$SP_{np} = \frac{P_{np1,i}}{VF_2 \times HF_3 \times \min(1, HF_4 \times HF_5)} \quad (6)$$

The result of the  $SP_{np}$  calculations is the difficulty of covering a given area in time affected by all the factors of the situation in the operation area shown in **Figure 1**.

## 3. Possibilities of the enemy activity influence

The enemy activity in the area of operation has the greatest influence on the planning of the movement route of forces and equipment along with the terrain passability. Estimating the future activity of the enemy is always a very complicated and intuitive matter for the analyst who processes it. Due to its uncertainty and variant implementation, it is impossible to create a mathematical algorithm that would accurately identify the intention of the enemy. However, it can be visualized based on the real terrain passability, including the weather attack, known deployment of enemy forces and equipment, and their activities in the past. The greatest deviations in the measurements were achieved outside paved roads, where hardly predictable impact of the microrelief, a driver's caution, and the dense vegetation of the terrain were evident.

### 3.1 Influence of detected enemy combat activity in the past

The past activity of the enemy includes the activity of his forces and equipment over the last 6 months, which can be divided according to the observed type of activity (laid minefields, barriers, IED, IDF, SAF, SVEST attacks, demonstrations, and other incidents). The geographical position, the type of activity or attack and its development, the frequency of repetition in the same areas, and the description of surroundings are critical for this kind of evaluation.

The degree of threat to the safe movement through the area can be expressed by the horizontal factor of enemy activity in the past  $HF_{4.2}$ , which can acquire the following average values:

- $HF_{4.2} = 0$ , an impassable area, at a distance of 500 m from the site of the enemy activity, active minefields and barriers, and the repeated occurrence of attacks and incidents over the last 3 months
- $HF_{4.2} = 0.5$ , at a distance of 1000 m from the site of the enemy activity and the repeated occurrence of attacks and incidents over the last 3 months
- $HF_{4.2} = 1$ , without affecting the passability, at a distance of more than 1000 m from the site of the enemy activity, attacks, and incidents older than 3 months

### 3.2 Influence of the current deployment of enemy forces and equipment

This evaluation has already been described in a simplified fashion in the enemy situation layer. The model evaluates danger areas of the potential enemy conduct of effective fire depending on the visibility and effective range of the main weapons.

The degree of threat to the safe movement through the area may be expressed by horizontal factor of the enemy firepower  $HF_{4.1}$ , which attains the following values:

- $HF_{4.1} = 0$ , impassable, enemy-observable area of an effective range of his weapon systems
- $HF_{4.1} = 0.5$ , an area at a distance of 1 to 1.5 multiple of the effective range of the enemy weapon systems in a strip of the area observable by the enemy
- $HF_{4.1} = 1$ , a passable area with minimal predictable threat, at a distance of 1.5 multiple of the effective range of the enemy weapon system in the area observable by the enemy

### 3.3 Databases of system information

The system input information must be structured and stored in thematic databases so that they can always be used quickly.

The information databases can be divided into:

- The TTD of friendly military equipment and weapon systems (including width, length, clearance height, weight, maximum range, terrain passability, carried weapon systems, and their effective range)
- The characteristics of performance parameters of the dismounted element (including the speed of movement at different slopes and on different terrain surfaces)

- An urbanized area (including location, population, livelihood, ethnic groups and their leaders with photographs, layout and characteristic of infrastructure, structure of state and municipal authorities, facilities, and important buildings)
- The TTD of enemy military equipment and weapon systems (including width, length, clearance height, weight, maximum range, terrain passability, carried weapon systems, and their effective range)
- Land mines and barriers
- IED attacks (date, time, location, type, description of the surrounding situation)
- IDF attacks (date, time, location, type, description of the surrounding situation)
- SAF attacks (date, time, location, type, description of the surrounding situation)
- Incidents (date, time, location, type, description of the surrounding situation)

Editing the new types of military equipment and weapon systems in the database, as well as creating a completely new database, is apparent.

#### **4. Simulation of movement executed by enemy forces and equipment**

The movement variant of the detected or predicted enemy units can be visualized in the terrain using the optimal route model and the TDSS. The editing and evaluation of the information related to all five layers identify the possibilities for performing the movement of the enemy. The specification of how to perform the movement to the system will complement the capabilities of a particular unit. The system, after selecting the initial deployment area and the projected objective area of the movement, will calculate the movement route optimized in terms of time and safety. However, an integral part of the simulated enemy movement will still be a qualified intelligence estimate of the enemy future intention, which will have to include the objective area or at least the direction of the enemy movement. Further, it will be necessary for the enemy to predict the deployment of particular friendly units so that the model could also include this factor in the calculation of the enemy movement route. Another suitable direction for the development of the TDSS will be a spatially specified and coordinated group movement of several units with the same goal. It will be necessary to specify the visualizations of movement routes of a larger concentration of enemy units with the same goal. It can provide commanders with an idea of a possible variant of the enemy activity in the whole area of responsibility of friendly forces and equipment.

#### **5. Testing and verification of model functions**

For the practical verification of the basic function and correctness of the mathematical processing and criterion evaluation of input geographical tactical information implemented in the TDSS, practical measurements have been made. The measurements have been focused on the correctness of the movement route

identification meeting the criteria of optimality in terms of the minimum time spent when covering and the calculation of the total time needed for its covering. In its implementation, most of the types of movement considered have been verified. Tracked vehicles were represented by BVP-2, wheeled vehicles by Tatra T815 (4×4), and the dismounted element by soldiers. The mean deviation of verified model results and the practical measurements besides the abovementioned extremes reached 2.74%, described in [11].

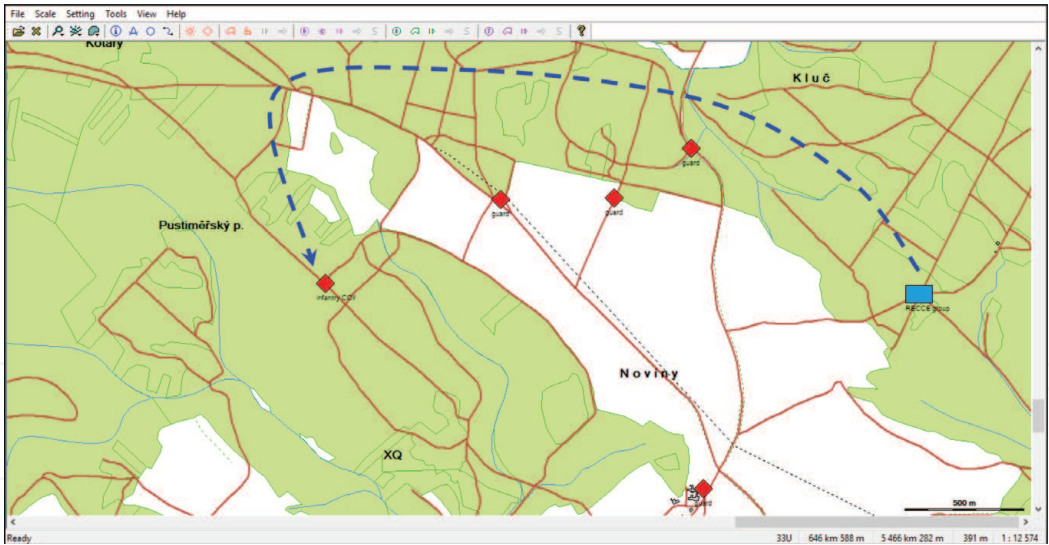
Supplemental measurements were carried out in experiments No. 1 and No. 2 relating to the movement of a reconnaissance group for the purpose of a concealed approach and the tracking of the object of interest. The same method of maneuver and approach was used in the experiment with a ground autonomous vehicle, the execution of which was calculated for the passability of wheeled vehicles. An off-road four-wheeler with a driver was simulating the vehicle, which solved the problems with the direct control of the vehicle, and the requirements for the terrain passability of wheeled vehicles were fulfilled. Experiment No. 3 was aimed at using the flanking maneuver model implemented in the TDSS. In all the cases, the enemy was made up of groups of individuals armed with hand weapons, taking up a fire position. For performing experiments No. 1 and No. 3, two groups were selected; each one consisted of four soldiers with comparable experience and skills. The commanders of both groups were soldiers who had the same level of experience in the decision-making process, terrain analysis, and leadership. All the experiments were carried out in daylight conditions in January when the temperature ranged from 2 to −2°C, without precipitation, on a frosted surface with a layer of snow cover of about 2 cm.

### **5.1 Experiment No. 1: Reconnaissance group movement**

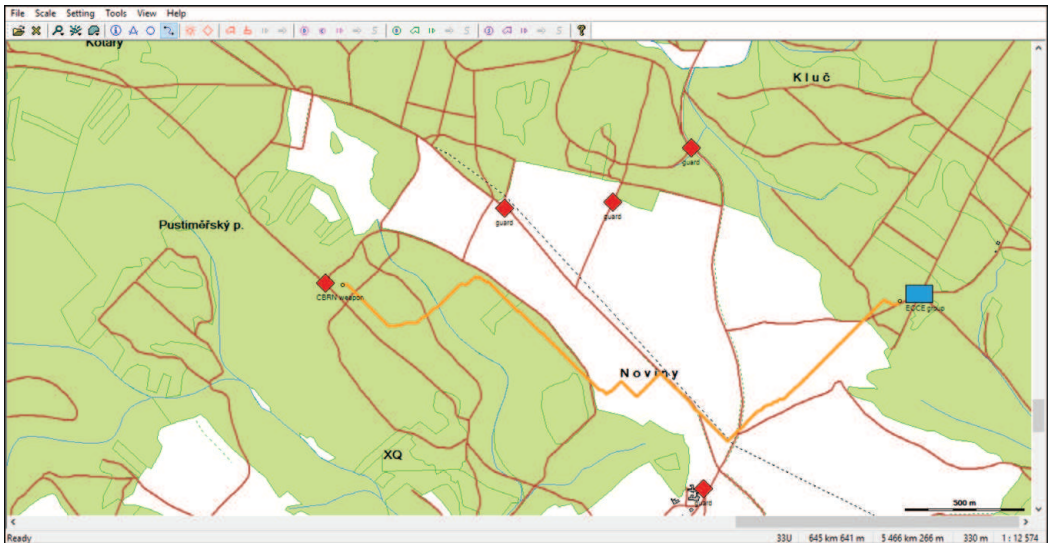
Both reconnaissance groups were given a task to move unnoticed and as quickly as possible to the object of interest to monitor it. The load carried by each group member included a personal weapon, individual protective equipment, and a backpack of a total weight of 20 kg. Both groups were given the task mentioned at the same time and in the same initial area. Then, their decision-making and planning process to accomplish the task followed; they planned the fastest and safest movement route to the object of interest. In the phase of approach to the object, both groups should have used the route concealed from the identified enemy units' observation in the area of maneuver and should have begun the immediate monitoring of the object. The ALFA reconnaissance group used only a printed topographic map, compass, and GPS receiver to plan and cover the movement route. The planning process of this group lasted 16 minutes. The ALFA group commander tried to estimate the conditions of the terrain passability, the visibility of the enemy, and protecting terrain features. The result of his rapid assessment was a movement route along the edge of the forest, which protected the group from the observation over a distance of more than 50 m. The route was 4190 m long (see **Figure 3**). The group covered the route in 113 minutes. During this movement, the group was not observed by the enemy soldiers. In the time of 118 minutes, the group took up positions in the vicinity of the object of interest and started its observation.

As a support for the decision-making process to create a movement route, the BRAVO reconnaissance group used the optimal movement route model, implemented in the TDSS, the possible application of which is described in [19]. The planning process of the BRAVO reconnaissance group took 7 minutes, including entering the identified enemy positions into the TDSS and the minimum necessary preparation to accomplish the task. Its route designed by the model is shown in **Figure 4**. When designing the optimal movement route, the TDSS calculated the





**Figure 3.**  
*The movement route of the ALFA group (source: TDSS).*



**Figure 4.**  
*The movement route of the BRAVO group (source: TDSS).*

terrain passability characteristics, in which the system also included the possibilities of the enemy visibility. The priority was to lead the movement route off roads for safety reasons, which was achieved by the deliberate suppression of variable speeds on the routes in the TDSS. Through linking the calculations together, the system calculated the areas concealed from the identified enemy's observation. Subsequently, it used the areas identified in this way to create the fastest and safest movement route. The group covered the route (2963 m long) in 75 minutes. The time calculated using the TDSS to cover this route was 68 minutes. During this movement, the group was not observed by the enemy soldiers. In the time of 78 minutes, the group started observing the object of interest.

## 5.2 Experiment No. 2: Movement of an autonomous vehicle

Experiment No. 2 was carried out using the simulation of an autonomous vehicle in the form of a Yamaha Grizzly off-road four-wheeler (**Figure 5**) driven by one person and powered by a gasoline engine. The four-wheeler was selected due to similar terrain passability characteristics as a modern UGV. The need for direct



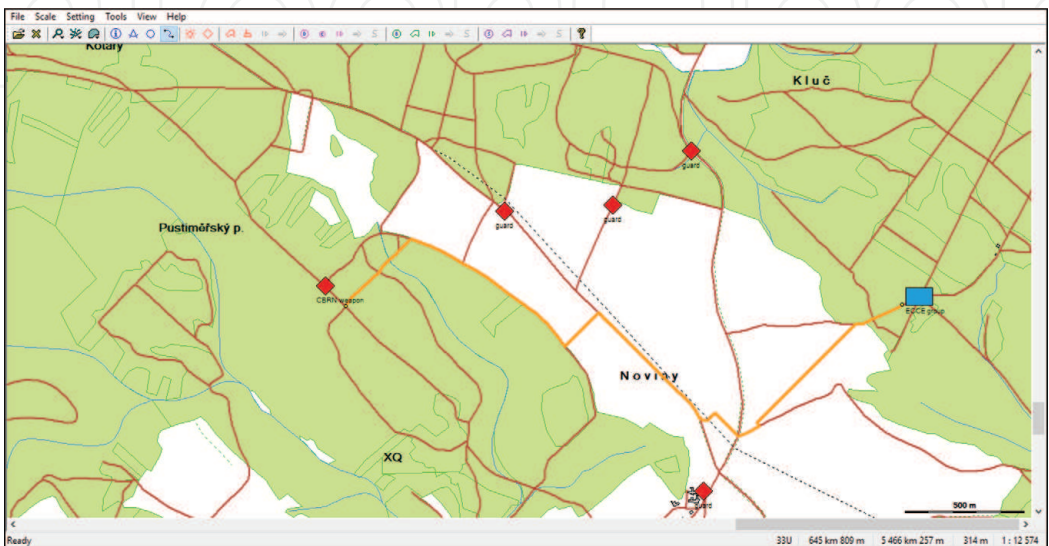


**Figure 5.**  
*The Yamaha Grizzly four-wheeler (source: own).*

control and the influence of microrelief were eliminated thanks to the four-wheeler driver. The optimal movement route model implemented in the TDSS was used to plan and cover the UVG movement route. Entering the identified enemy positions in the TDSS and the minimum necessary preparation for the movement took 3 minutes. The UGV route was designed in the passability mode “for wheeled vehicles,” and its course can be seen in **Figure 6**. As in the BRAVO reconnaissance group, the TDSS assessed the passability possibilities of the vehicles in the field and calculated the areas concealed from the observation and fire of the identified enemy. Covering the proposed fastest and safest route (3419 m long) of the four-wheeler took 7 minutes and 25 seconds. During the movement, the vehicle at 124 cm high was not observed by the enemy. However, its engine running was audible, which could be replaced by a silent electric motor. The time calculated by the TDSS to cover this route was 7 minutes and 4 seconds.

**5.3 Evaluation of experiments No. 1 and No. 2**

As for the movement of reconnaissance groups in experiment No. 1, a noticeable difference in time required for planning the movement route was observed. When planning the movement route, the ALFA group commander used mainly his knowledge and experience and a printed military topographic map. He was not able



**Figure 6.**  
*Autonomous vehicle movement route (source: TDSS).*

to accurately estimate the areas endangered by the enemy fire (by observation). Therefore, he directed the movement route through the forest vegetation, which provided the group with an estimated cover from observation from the ground. For planning the movement route, the BRAVO group commander took advantage of the optimal movement route model in the TDSS, which accurately calculated the areas concealed from the enemy's observation. Subsequently, the TDSS used these areas for planning the fastest and safest movement route, provided that the enemy does not significantly change his deployment or that he patrols the area. Its practical realization can be considered in terms of the necessity to fulfill the task as quickly as possible, with the acceptance of the abovementioned risk. In the case of an autonomous vehicle (four-wheeler), the route designed by the TDSS was the fastest and safest one for wheeled vehicles with variable speeds adapted to the type of vehicle (see **Figure 7**). The terrain passable for the Yamaha Grizzly off-road four-wheeler includes especially roads and open areas by the reason of its wheel undercarriage. Its height of 1240 mm is comparable to the height of the UGV, developed or used in modern armies (compare) [20]. The lower silhouette of the vehicle and the unmanned control make it possible to use even less concealed areas for the movement. The driver of the four-wheeler followed the proposed route and eliminated the impact of the microrelief on the terrain passability using the control mechanisms of the vehicle. In none of the experiments mentioned, the reconnaissance group or the four-wheeler was observed by the enemy. The movement of all elements was stopped in the area of the target object at a maximum distance of visibility. An additional change of the position of the observation post was subsequently done with the utmost care and minimum movement. In the case of four-wheeler approach, the guard of the target object would hear the sound of the vehicle engine but without locating the exact position. At that time, the four-wheeler appeared approximately 200 m from the object.

The experiments performed have proven the usefulness of the optimal maneuver model, especially when solving the situations requiring the fastest maneuver,

Optimal route

Initial location

X: 647 km 533 m  
Y: 5 467 km 164 m  
Z: 392.1 m

Edit initial location

Destination

X: 645 km 69 m  
Y: 5 467 km 209 m  
Z: 404.0 m

Edit destination

Distance

By air: 2 464 m  
Real: 3 419 m  
Time: 0:07:04

Swap points

Model parameters

Type of vehicle: Wheeled vehicle

Geodata precision: Extra high

Load parameters

Save parameters

Surface: roads

Highway: 90.00 km/h

1st class road: 90.00 km/h

2nd class road: 70.00 km/h

3rd class road: 60.00 km/h

Street: 40.00 km/h

Unsurfaced: 25.00 km/h

Other: 25.00 km/h

Surface: vegetation

Forest: 0.00 km/h

Pasture: 5.00 km/h

Field: 10.00 km/h

Other: 0.00 km/h

Surface: other

Water surface: 0.00 km/h

Build-up area: 0.00 km/h

Close

Compute

**Figure 7.**  
*Speeds of Yamaha Grizzly on individual types of surface in the TDSS (source: TDSS).*

14

even at the price of the risk of revelation on the account of the enemy's unpredictable movement or the use of a hostile air reconnaissance. The reconnaissance of an important target, e.g., command posts or the location of fire support means, can be mentioned as examples. Using the TDSS optimal maneuver model in experiment No. 1, the total time from the receipt of the task to the attainment of readiness to fulfill it was reduced to 9 minutes. The calculation of the time to cover the movement route had a difference of 38 minutes from the real time of the ALFA group movement.

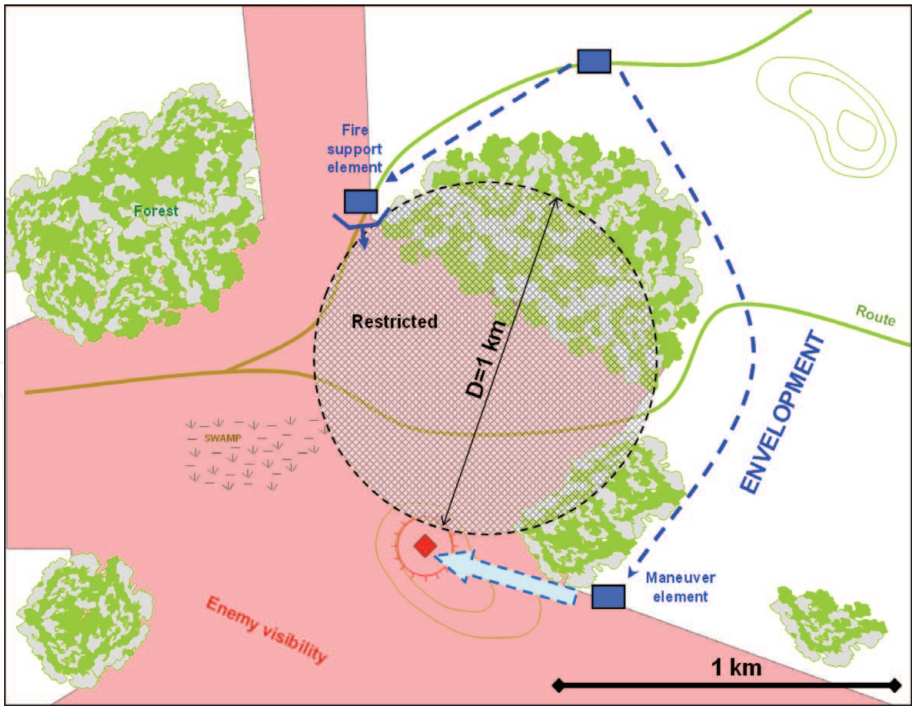
## 6. Maneuver control system

The optimal maneuver route model described in [11] represents the basis for optimizing the maneuver between the starting point and the target point of the maneuver. It can be used for dealing with different tactical situations and tasks on the battlefield including the UGV maneuver. One of them is an offensive maneuver performed by military forces and equipment; its technical term is flanking maneuver. The flanking maneuver represents an offensive maneuver of a part of the military unit, in which the detached forces attack on the flank and the rear of the enemy in the firing and tactical cooperation with the units attacking from the frontal direction. It is defined in [21].

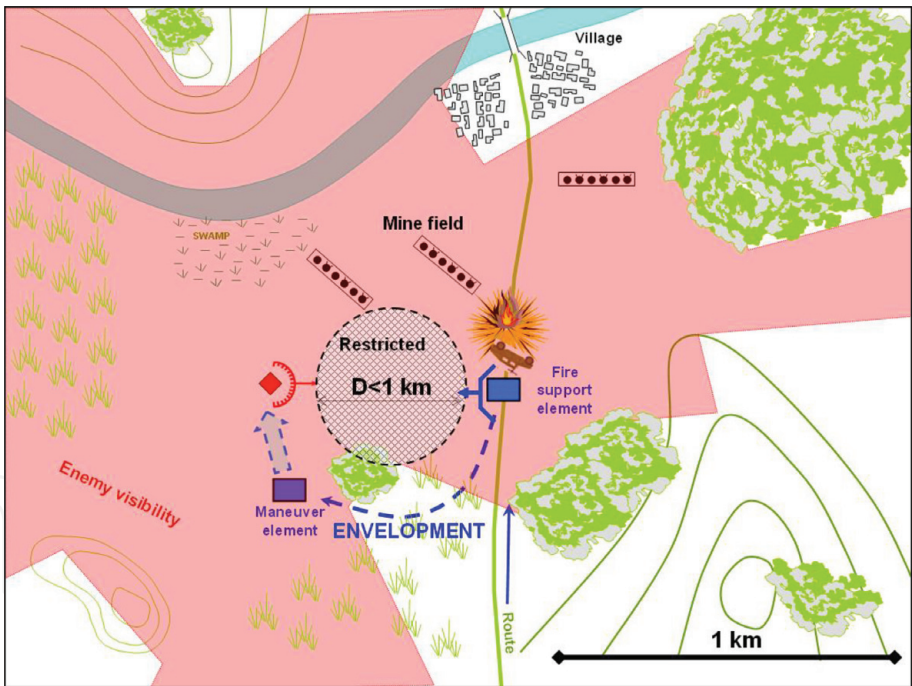
One of the most significant benefits of this chapter is the flanking maneuver model, which represents the complement to the TDSS [11] in the form of the Maneuver Control System CZ application program. It is specified by the so-called invisible layer of the cost surface of passability in the form of an impassable (forbidden) area. This impassable area is in the form of a circle with a diameter equal to the distance "d" between the position of a friendly unit and an attacking unit of the enemy, but not more than 1 km. The attacking unit is divided into two independent elements, i.e., a firing group and an assault group. The TDSS suggests the maneuver route of the firing element to the nearest edge of the visibility area of the target enemy, but not more than 1 km from his position. The 1 km distance is specified in the model due to the expected maximum distance of the direct fire by handguns and mounted weapons. The firing group of the unit should be able to hold the enemy under fire at this maximum distance. Then, depending on the terrain, the assault group should be able to bypass this circular distance to the enemy and cover it. In the case of planning the offensive activity at a distance greater than 1 km, the TDSS will plan the movement route of the firing group to the nearest area with the direct visibility of the enemy (see **Figure 8**). Subsequently, it will plan the maneuver route of the assault group maintaining 1 km of the circular forbidden area. The reason is a real feasibility and success rate of the offensive maneuver in the direction of the enemy at a distance of 1 km or more while the firing group attacks on the identified enemy.

The maximum usability of the flanking maneuver in the TDSS can be considered when dealing with a response to attacking the unit by a weaker enemy, in the case of its inability to leave the attacked area completely (see **Figure 9**). Such a situation can occur, for example, in the case of multiple injuries of friendly forces or during the movement using combat vehicles. The solution of this situation can provide the enemy with the time, which he will probably use to change his position or to perform a direct attack without a direct pressure on his forces and equipment. The route of the flanking maneuver will be created outside the impassable circle, without including the layer of influence (the maximum effective range) of the target enemy. The reason for not including the target enemy's maximum effective range may be the absence of the fastest and safest route of movement to the area of his occurrence.





**Figure 8.**  
*The planned flanking maneuver route at a distance of more than 1 km (source: own).*



**Figure 9.**  
*The flanking maneuver route in response to the attack (source: own).*

### 6.1 Experiment No. 3: Response to the attack

The experiment was carried out in a broken and partially forested terrain. The motorized unit was moving along the paved road. When passing through a partially open area, it was attacked by shooting handguns from an almost perpendicular direction to the paved road from a distance of approximately 230 m. The incapacitated vehicle with a severely injured driver remained at the scene of the incident. The attacker was interpreted as a group of men armed with handguns. During the

response to the attack, the unit had to provide the primary emergency treatment to the injured driver.

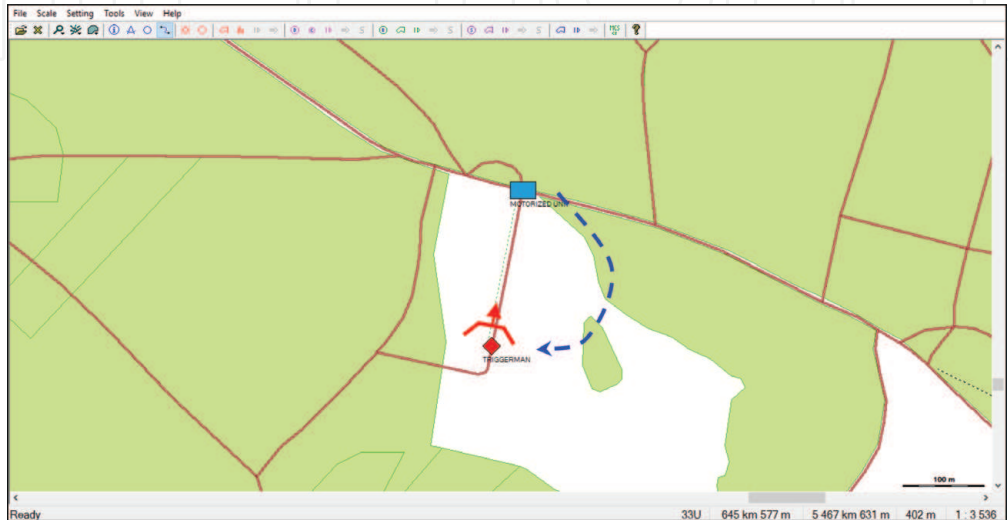
The commander of the attacked ALFA unit, using standard means to support decision-making (radio station and map), began to create an overview of the situation at the scene of the incident. He identified the position of the enemy based on the reports from his subordinates. He was well versed in the space distribution of his attacked unit, the attacking enemy, the open space in the shooting direction, the forest vegetation, and the relief of the terrain. The decision-making process to respond to the attack took him approximately 60 seconds. Its result was the approach maneuver of the assault group through a forest area to take up an advantageous fire position and to eliminate the enemy (see **Figure 10**). Executing the maneuver (428 m long) took 6 minutes and 50 seconds, including destroying the enemy and securing his positions.

Using the TDSS and its maneuver control system application, the commander of the attacked BRAVO unit defined the enemy's position and entered the calculation of the flanking maneuver approximately 30 seconds after the attack. Subsequently, the TDSS calculated the cost surface of passability in the area of the attack and proposed the fastest and safest route of the flanking maneuver to the position of the attackers with the use of mathematical algorithm. These calculations did not include visibility and the attackers' weapon range so that the system could plan the route in their position. Approximately 40 seconds after attack, the assault group started the flanking maneuver along the route in the direction of the enemy's position.

The route led to the position of the attackers through the forest vegetation passing into the open plain (see **Figure 11**). At the edge of the forest, the assault group took a hastily prepared firing position and almost immediately started destroying the enemy by fire. Then, it destroyed the enemy and secured his positions. The time to cover the route (369 m long) was calculated by the TDSS for 5 minutes and 3 seconds, which represented the difference of 36 seconds compared to the actual time of BRAVO unit. The delay of the real maneuver was caused by the destruction of the attackers by fire, which preceded the occupation of the target position itself.

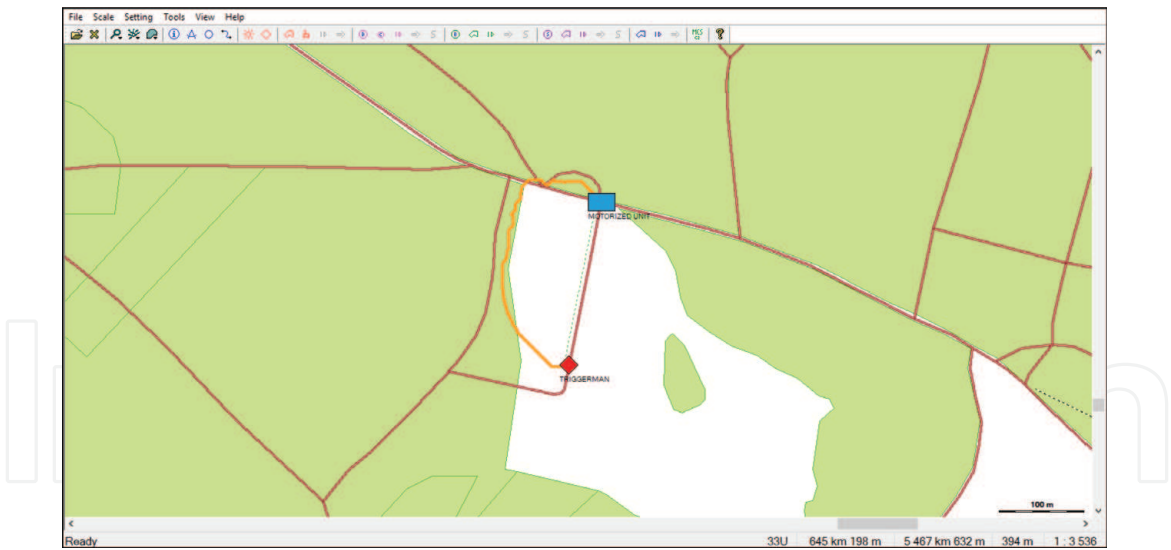
### 6.2 Evaluation of experiment No. 3

When comparing both variants of experiment No. 3, a significant difference can be observed in both the speed of orientation and the decision-making process of the



**Figure 10.**  
*The movement route of the ALFA group (source: TDSS).*





**Figure 11.**  
*The movement route of the BRAVO group (source: MCS CZ, TDSS).*

attacked unit commander, as well as in the mode of maneuver execution. The difference in time of the commencement of the flanking maneuver to the enemy's position shows that the assault group of the BRAVO unit started more than 20 seconds earlier than the ALFA unit.

The terrain in the attacked area did not enable executing the direct attack, and, therefore, both units used the flanking maneuver. The maneuver route of the ALFA unit was displaced to the area where the commander expected the most advantageous and safest fire position. On the contrary, the BRAVO unit carried out the flanking maneuver using the fastest and safest route. The maneuver speed of the BRAVO unit created an effective pressure on the enemy's activity; he had to partially switch his attention to the damaged vehicle. At approximately 5 minutes and 40 seconds, after the commencement of the attack, the assault group of the BRAVO unit began firing on the enemy's position. The comparison of both responses to the attack shows that the BRAVO unit destroyed the attackers by 71 seconds faster than the ALFA unit. From the abovementioned facts, it can be stated that if the enemy did not abandon its position immediately after the commencement of the attack, he would be completely destroyed by rapid response of the BRAVO unit.

## 7. Conclusion

The abovementioned text has described the structure of the optimal movement route model implemented in the TDSS and its further possible use within the Maneuver Control System application. The practical benefit is a total of three experiments, in which two groups of soldiers and an autonomous vehicle simulation have been used. The results of the experiments have shown that the optimal movement route model is functional and very effective from the viewpoint of time demands for creating a movement route and the method of deploying military forces.

The optimal movement route model, implemented in the TDSS, has proven its usefulness even when planning the movement route of autonomous vehicles. In its calculations, it combines the assessment of all terrain and safety characteristics of the operational area; it also focuses on the possibilities of the passability of wheeled vehicles in the terrain. The passability of the routes calculated has been verified and confirmed during the experiments. Nevertheless, in the case of autonomous

vehicles, there is still a need for direct control in the terrain due to the accidental occurrence of microrelief forms and obstacles. The implemented model represents a basis for planning the movement route before the task fulfillment itself. The experiments realized have verified the function of the optimal movement route model when neither the reconnaissance group nor the autonomous vehicle was observed by the enemy. The total time of the UGV with the use of the TDSS to cover the route of maneuver was 67 minutes shorter than the real time of the BRAVO group movement with the use of the TDSS and 105 minutes shorter than the real time of the ALFA group without the use of the TDSS.

The TDSS calculation results are available in the order of seconds from the definition of all the tactical situation variables and the commencement of the calculation. This speed of calculation significantly minimizes time demands of the unit commanders' decision-making process. The functionality of the system has been verified in response to the enemy attacking a moving unit, the consequence of which was one incapacitated vehicle with a severely injured driver. The tactical situation of experiment No. 3 has been created precisely for the situation that demonstrates the most appropriate use of the TDSS. These are especially the situations with great time demands for creating an optimized decision, when friendly forces are endangered by the enemy. To achieve a successful solution with minimal death toll and loss of material, the decision must be taken as soon as possible after the attack of the enemy. The comparison of responses to the attack shows that the BRAVO group using the Maneuver Control System (MCS CZ) as part of the TDSS destroyed the attackers by 71 seconds faster than the ALFA group without the use of the TDSS. The optimal maneuver route model and the MCS CZ implemented in the TDSS represent the appropriate support tools for the command and control process in the military operation. They can also be used for planning a maneuver route of logistic support units and equipment if these units use UGVs for their activities in a military operation. Another possibility for using other types of autonomous vehicles is in military amphibious operations. The MCS CZ can be easily adapted to amphibious operations by adding a layer of the water surface. The standard part of the MCS CZ analyzes the terrain passability during the approach of the vehicle to the water surface. The added layer of the water surface will evaluate the character of the bottom along the coast as an approach route to the sea or to the river. The influence of direction and power of a water stream as a passability factor for amphibious vehicles as well as the standard or planned shipping lanes would also be included in this special water layer. The abovementioned MCS CZ update will reduce the risks of autonomous amphibious vehicles during the approach to the water surface and shipping.

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