AVIATION AND SECURITY ISSUES NO. 3(1/2023)
ISSN 2720-197X / eISSN 2956-3380

**Wojciech DAWID**
Military University of Technology
e-mail: wojciech.dawid@wat.edu.pl
ORCID: 0000-0001-7964-5706

**Krzysztof POKONIECZNY**
Military University of Technology
e-mail: krzysztof.pokonieczny@wat.edu.pl
ORCID: 0000-0001-9114-5317

**Marek WYSZYŃSKI**
Military University of Technology
e-mail: marek.wyszynski@wat.edu.pl
ORCID: 0000-0003-3264-9544

DOI: 10.55676/asi.v3i1.61

# THE APPLICATION OF THE METHODOLOGY TO DEFINE TERRAIN PASSABILITY ON A DETAILED LEVEL IN VARIOUS CONFIGURATIONS

## WYKORZYSTANIE METODYKI WYZNACZANIA PRZEJEZDNOŚCI TERENU NA POZIOMIE SZCZEGÓŁOWYM W RÓŻNYCH KONFIGURACJACH

## Abstract

The article presents a complete methodology to determine terrain passability as well as its application based on various configurations of input data. The methodology was developed with the use of the methods that had been created by the authors in their previous research projects. The determination of terrain passability consists of two stages: The first stage involves conducting the analysis of micro-relief with the aim to identify impassable spots in the area, while the second stage consists in determining the route for a specific vehicle that will avoid the existing obstacles formed by the micro-relief. Both these analyses generate results based only on a detailed digital terrain model (with a resolution of 1 m) and the traction parameters of the vehicles for which terrain passability is determined. One of the processes that are part of this methodology is the generalisation of the digital terrain model, which significantly improves the efficiency of the performed calculations. Test results demonstrated that the presented methodology enables successful automated generation of passability maps for specific vehicles and the creation of routes for such vehicles. The routes differ depending on the type of vehicle, which results directly from the fact that vehicles have different traction parameters. Nevertheless, the test results were satisfactory and demonstrated that the developed methodology may be applied by bodies that are responsible for planning military operations or crisis management activities.

**Keywords**: digital elevation model, generalisation, micro-relief, terrain passability, vehicles

## Streszczenie

W artykule zaprezentowano całościową metodykę wyznaczania przejezdności terenu, a także jej zastosowanie w oparciu o różne konfiguracje danych wejściowych. Do przygotowania metodyki wykorzystano metody, które zostały opracowane przez autorów we wcześniejszych badaniach. Wyznaczanie przejezdności terenu składa się z dwóch etapów: przeprowadzenie analizy mikrorzeźby, której celem jest wskazanie w terenie miejsc nieprzejezdnych, a także wyznaczenie trasy dla konkretnego pojazdu, która omijać będzie występujące w terenie przeszkody związane z mikrorzeźbą. Obie analizy do generowania wyników wykorzystują jedynie szczegółowy numeryczny model terenu (o rozdzielczości 1 m) oraz parametry trakcyjne pojazdów, dla których wyznaczana jest przejezdność terenu. Jednym z procesów wchodzących w skład metodyki jest uogólnienie numerycznego modelu terenu, które znacznie zwiększa wydajność prowadzonych obliczeń. Wyniki badań pokazały, że opracowana metodyka z powodzeniem automatycznie opracowuje mapy przejezdności dla konkretnych pojazdów, a także wyznacza dla nich trasy przejazdu. Są one inne dla różnych pojazdów, co wynika bezpośrednio z faktu, że posiadają one odmienne parametry trakcyjne. Niemniej jednak, zadowalające wyniki badań pokazały, że opracowana metodyka może być stosowana przez organy odpowiedzialne za planowanie operacji wojskowych czy zarządzania kryzysowego.

**Słowa kluczowe**: numeryczny model terenu, generalizacja, mikrorzeźba, przejezdność terenu, pojazdy

Artykuł wpłynął do redakcji: 28.05.2023 / Zatwierdzono do publikacji: 25.06.2023

## 1. INTRODUCTION

An effectively conducted military operation requires appropriate planning. One of the key aspects that should be taken into consideration during planning is terrain passability. Its modelling for various types of vehicles is essential in planning military operations, when the need to carry out quick and sudden manoeuvres to surprise the enemy makes it necessary to design approach paths (routes) for military vehicles outside the road network. According to military standards[1], passability is understood as the possibility to cross the area by vehicles in any weather conditions, both on roads and off-road. The process of determining passability in its simplest form is based on the division of land into 3 classes: GO, SLOW-GO and NO-GO[2]. The aim of this classification is to distinguish those parts of the area that are characterised by similar land cover and terrain formation that allow it to be crossed by specific types of vehicles. This issue is vital for land management, particularly in emergency conditions, when it is essential to reach the destination quickly. Passability is also influenced by the area where the vehicles are moving, which will also be discussed in this study.

The ability to determine the possibility to pass an area by military vehicles is a crucial aspect that allows achieving tactical and operational advantage over the enemy. Considering the above, many research centres are attempting to develop a terrain passability model that would be as close to reality as possible. Such studies are carried out, among others, at the University of Defence in Brno. The problems of modelling and creating terrain passability maps were discussed in numerous publications of this institution. The existing publications address various analyses of the key factors that influence passability, i.e., the plant cover, and more specifically, forests[3], soils[4] and even weather[5]. The next stage of their research consists in integrating soil data with data from other sources[6]. A solution, which utilizes the division of land into smaller fragments (referred to as the primary fields), was presented in the studies[7]. The key element, and, at the same time, a specific supplement to these analyses, is the influence of individual elements of the geographic environment on passability conditions, e.g. land cover[8].

The key project that refers to terrain passability modelling is the NATO Reference Mobility Model (NRMM). This model is used to model the passability for various

1 "NO-06-A015:2012, Terrain – Rules of Classification – Terrain Analysis on Operational Level."

2 "Field Manual 5-33 Terrain Analysis."

3 M. Rybansky et al., *Vegetation Structure Determination Using LIDAR Data and the Forest Growth Parameters*; M. Rybansky, *Determination of Forest Structure from Remote Sensing Data for Modeling the Navigation of Rescue Vehicles*.

4 M. Rybansky, *Soil Trafficability Analysis*; M. Hubáček, V. Kovarik, V. Kratochvil, *Analysis of Influence of Terrain Relief Roughness on DEM Accuracy Generated from Lidar in The Czech Republic Territory*.

5 M. Hubáček et al., *Modelling of Geographic and Meteorological Effects on Vehicle Movement in The Open Terrain*.

6 M. Hubáček et al., *Combining Different Data Types for Evaluation of the Soils Passability*.

7 M. Rybansky et al., *Modelling of Cross-Country Transport in Raster Format*; M. Rybansky, M. Vala, *Relief impact on transport*.

8 M. Rybansky, *Effect of the Geographic Factors on the Cross Country Movement During Military Operations and the Natural Disasters*.

 DOI: 10.55676/asi.v3i1.61

types of military vehicles and it includes a comprehensive planning area for the operation, which contains the data about the scenario, terrain, and vehicles[9]. It became the basis for numerous analyses of the various aspects related to military terrain passability. A comparison of the NRMM with other models in terms of the capacity of military vehicles to cross specific soils is presented in paper[10]. Furthermore, the issues related to the influence of soils on passability are discussed in study[11], whose author analyses the influence of soil characteristics on the traction parameters, such as the sink and slide of wheels, vehicle speed, and traction force.

One of the academic centres that has been researching land passability issues for many years is the Military University of Technology. Among numerous research works of the MUT team, the problems of creating passability maps based on primary fields are presented in the studies[12]. The publication[13] presents an IT system to automate the passability map generating process, while article[14] discussed the manner of generating the index of passability with the application of artificial neural networks. These studies allow for the automated creation of maps in small and medium scales, which provide a general overview of the passability conditions in large areas. Another area of interest of the MUT team is the methodology of generating high-resolution land passability maps that are created for individual vehicles based on a detailed digital terrain model and the traction parameters of the vehicles. The use of high-resolution data allows the map to reflect elements of micro-relief[15]. Similar research on the application of a high-resolution terrain model to determine passability were presented in the studies[16] where, however, a completely different terrain model and computational algorithms were applied. The authors used there a raster elevation model in resolution of 0.5 m and built a processing algorithm in ArcGIS software which computed the impassable areas in two dimensional space. The MUT team, on the other hand, created an independent procedure which computes the passability in 3D space based on vector elevation points.

The main aim of this paper is to summarise the previous research of the authors on the automation of the terrain classification process in terms of passability, taking into account elements of micro-relief. This process concerns the determination of terrain passability on a detailed level, what means that the outcome is meant to be utilized for planning the movement of single vehicles or a group of the same types of

9 M. Bradbury et al., *Next-Generation NATO Reference Mobility Model (NRMM) Development*.

10 B. Maclaurin, *Comparing the NRMM (VCI), MMP and VLCI Traction Models*.

11 P. Jayakumar, D. Mechergui, T.M. Wasfy, *Understanding the Effects of Soil Characteristics on Mobility.*

12 K. Pokonieczny, S. Borkowska, *Using High Resolution Spatial Data to Develop Military Maps of Passability*; K. Pokonieczny, A. Mościcka, *The Influence of the Shape and Size of the Cell on Developing Military Passability Maps*.

13 K. Pokonieczny, *Automatic Military Passability Map Generation System*.

14 K. Pokonieczny, *Use of a Multilayer Perceptron to Automate Terrain Assessment for the Needs of the Armed Forces*; Idem, *Methods of Using Self-Organising Maps for Terrain Classification, Using an Example of Developing a Military Passability Map*.

15 M. Hubáček, V. Kovarik, V. Kratochvil, *Analysis of Influence*…, op. cit.

16 F. Dohnal et al., *Identification of Microrelief Shapes along the Line Objects over DEM Data and Assessing Their Impact on the Vehicle Movement*; F. Dohnal, M. Hubacek, K. Simkova, *Detection of Microrelief Objects to Impede the Movement of Vehicles in Terrain*.

vehicles. As these analyses are very detailed, they may be applied in modelling passability for individual vehicles. So far, the authors have presented a study concerning the analyses of the level of detail of high-resolution digital terrain models and described an algorithm that uses these models to determine passability, taking into account the traction parameters of vehicles[17]. In publication[18], these algorithms were applied in practice to present an analysis of the methods of pathfinding in cross-country areas. Article[19] provides an example of the application of the developed algorithms for the purposes of crisis management. The authors also developed an algorithm to determine the route that takes into account passability in real time[20]. The aim of this study is to provide a synthesis and summary of the above research projects and to present them in form of a comprehensive methodology. A novelty is the fact that research was conducted for various test areas and types of vehicles, which allowed us to conduct comprehensive analyses of passability in various conditions. This enables to evaluate the usability and versatility of the proposed methodology.

## 2. MATERIALS AND METHODS

For the purposes of this study, the determination of land passability on a detailed level consists in conducting an analysis of passability for a specific vehicle (identification of impassable, NO-GO areas) and determining the route taking into account terrain conditions. The methods used were previously developed by the authors, and include:

– The method of determining passability taking into account elements of micro-relief[21];
– Pathfinding methods[22];
– The method of pathfinding optimisation by the generalisation of the digital terrain model[23].

The test areas, data used, as well as the above methods, will be discussed in detail in the following section.

### 2.1. TEST AREAS

Research was conducted on 5 test areas with different characteristics. The test areas had the shape of a square of the side length of 1000 m. They included: arable land,

[17] W. Dawid, K. Pokonieczny, *Analysis of the Possibilities of Using Different Resolution Digital Elevation Models in the Study of Microrelief on the Example of Terrain Passability*.
[18] Idem, *Methodology of Using Terrain Passability Maps for Planning the Movement of Troops and Navigation of Unmanned Ground Vehicles*.
[19] W. Dawid, K. Pokonieczny, M. Wyszyński, *The Methodology of Determining Optimum Access Routes to Remote Areas for the Purposes of Crisis Management*.
[20] W. Dawid, K. Pokonieczny, *Generalization of Digital Elevation Models for Military Passability Maps Development*.
[21] Idem, *Analysis of the Possibilities*..., op. cit.
[22] Idem, *Methodology of Using*..., op. cit.; W. Dawid, K. Pokonieczny, M. Wyszyński, *Methodology of the Iterative Route Determination Process for the Purposes of Military Passability*.
[23] W. Dawid, K. Pokonieczny, *Generalization of Digital*..., op. cit.

 DOI: 10.55676/asi.v3i1.61

forested area, hills, swamps, and urban area. The aim of this diversification was to test the functioning of the developed methodology in various terrain conditions. The methodology was created to be versatile, i.e., so that it may be used for a specific vehicle, regardless of the terrain where the passability analysis is to be conducted. The location of test areas and their visualisation are presented in Figure 1.

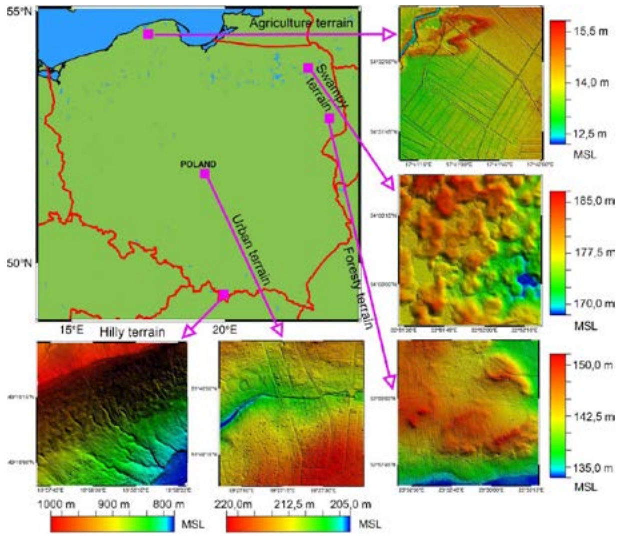



Figure 1. Location and visualisation of test areas
Source: own study.

The agricultural area is characterised by a large number of drainage ditches, which might be shown in the passability analysis as NO-GO areas. The forest and swamp areas are situated in regions which are covered, respectively, by forests and marshes that will make it significantly more difficult to determine the route for the vehicle. The hills area is located in the Polish Highlands and is characterised by large differences in height. Apart from that, there are multiple beds of mountain creeks, which might also constitute obstacles for vehicles that are moving in the area. The last analysed site was an urban area situated in the city centre of Lodz in central Poland. It contains a very high number of objects that are impassable for vehicles, such as buildings.

## 2.2. USED DATA

The research was conducted with use of the spatial vector land cover data obtained from the Topographic Objects Database, at the scale of 1:10,000. They were used to exclude areas that may be assumed to be impassable before the analysis, such as all types of buildings, surface waters, or forests. The database is maintained by the Surveyor General and it contains information about the location and attributes of such objects as: networks of watercourses; networks of roads and railways; networks of utility lines; land cover; protected areas; administrative units; buildings, structures and equipment, and land development complexes. The database is updated on an ongoing basis and is available free of charge. The whole database may be downloaded from the National Geoportal (www.geoportal.gov.pl).

Apart from land cover data, the authors used digital elevation models that are also available free of charge in the National Geoportal. These data are distributed in the ASCII Grid format in the whole territory of Poland. They contain three-dimensional coordinates of elevation points, which, in the highest resolution, are placed at a distance of 1 m from one another. This was also the resolution that was applied in the study, because previous analyses conducted by the authors had demonstrated that 1 m is the optimum resolution of a digital terrain model to conduct a passability analysis on the detailed level[24]. The detailed characteristics of the elevation data used are presented in Table 1.

Table 1. Characteristics of digital elevation models used in this research

| Kind of terrain | Recentness [year] | Resolution [m] | Mean elevation error [m] | Data source |
|---|---|---|---|---|
| Agricultural terrain | 2022 | 1.0 | 0.2 | Laser scanning |
| Forests | 2022 | 1.0 | 0.6 | Aerial photographs |
| Hilly terrain | 2022 | 1.0 | 0.5 | Aerial photographs |
| Swampy terrain | 2022 | 1.0 | 0.5 | Aerial photographs |
| Urban area | 2022 | 1.0 | 0.15 | Aerial photographs |

Source: own study.

Analyses were conducted for 3 types of vehicles that are widely used in the Polish Armed Forces: Star 266, HMMWV (High Mobility Multipurpose Wheeled Vehicle; colloquially: Humvee) and armoured personnel carrier Rosomak. These vehicles are used for different purposes (from delivery and transport to combat), so their structure is different. Their pictures are shown in Figure 2.

Figure 2. Analysed vehicles: (a) Star 266[25]; (b) HMMWV[26]; (c) Rosomak[27]
Source: own study.

[24] W. Dawid, K. Pokonieczny, *Analysis of the Possibilities*…, op. cit.
[25] J. Brach, *Star 266 – Modernization Projects*.
[26] Military.com, "High Mobility Multipurpose Wheeled Vehicle (HMMWV)."
[27] "KTO Rosomak."

 DOI: 10.55676/asi.v3i1.61

In terms of passability, the most important characteristics of these vehicles are their traction parameters, in particular ground clearance, track width, and wheelbase. These parameters are used in the developed methods of analysing passability and pathfinding to identify impassable (NO-GO) areas or access routes. The parameters for specific vehicles are presented in Table 2.

Table 2. Traction parameters of vehicles utilized in the analysis

| Parameter | Star 266 | Humvee | Rosomak |
|---|---|---|---|
| Ground clearance [m] | 0.33 | 0.43 | 0.43 |
| Track width [m] | 2.00 | 1.82 | 2.45 |
| Wheelbase [m] | 2.99 | 3.30 | 1.40<br>1.70<br>1.45 |

Source: own study.

It is worth noting, that the Rosomak vehicle is equipped with 4 axles and Table 2 shows the distances between them starting from the front of the vehicle.

## 2.3. METHODOLOGY OF DETERMINING TERRAIN PASSABILITY

As it has been mentioned before, the determination of land passability on the detailed level consists of two stages: Identifying the areas that are impassable for the given vehicle and finding paths between points for the vehicle. The methodology of the conducted analyses will be explained in detail based on the flow chart presented in Figure 3.

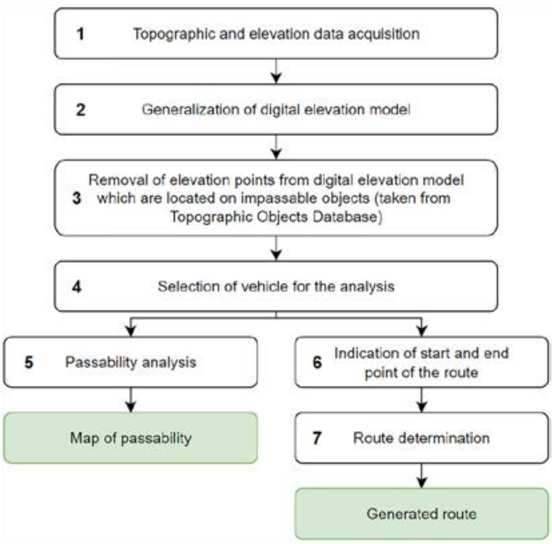



Figure 3. The flow chart of determining terrain passability on a detailed level

Source: own study.

The whole process of determining terrain passability may be divided into several stages. Some of them are common for creating a passability map and determining the routes for the vehicle. Every stage presented in Figure 3 is described in detail in the sub-points below.

1. Acquiring topographic and elevation data

The first step consists in obtaining the data for the analysis. For the purposes of this project, both topographic and elevation data were obtained from the National Geoportal (www.geoportal.gov.pl), where they are available free of charge. The topographic data were obtained from the Topographic Object Database at the scale of 1:10,000, and elevation data were digital terrain models of the resolution of 1 m.

2. Generalisation of the digital terrain model

Digital terrain models that are used in passability analysis and pathfinding take the form of evenly distributed elevation points, here, located at 1 m intervals. The aim of this step was to perform a reduction of these points, with the aim to, firstly, accelerate the processes that are performed at the subsequent stages, i.e., passability analysis and pathfinding, and secondly, to maintain the nature of the formation of the analysed terrain.

For the purposes of generalisation, it was assumed that areas with less diversified relief, e.g., flatlands, may be presented with the use of fewer elevation points that areas that are characterised by more diverse relief, such as hills, drainage ditches, or slopes. In the previous studies, the authors developed a method to perform such generalisation based on local terrain inclinations, or, more precisely, on their standard deviation. The specific stages of this method are presented in Figure 4.

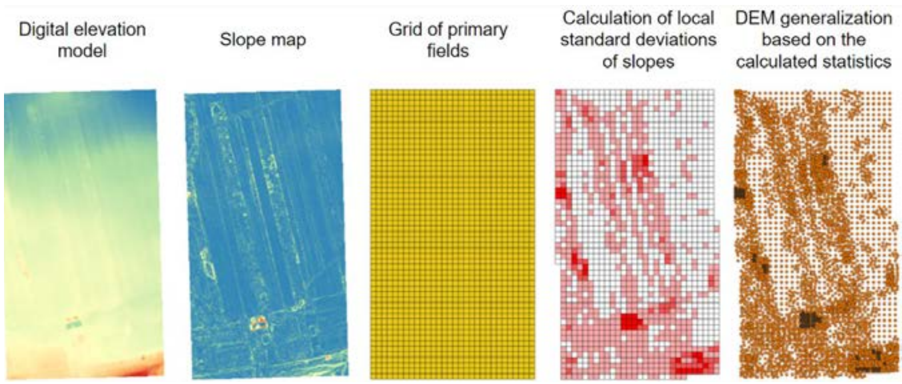



Figure 4. The process of generalisation of the digital terrain model (from left to right)
Source: own study.

The process of generalisation of the digital terrain model begins with creating a map of slopes based on the model. Then, a regular grid of primary fields is generated in the same resolution as the Digital terrain Model. For each primary field, the value

 DOI: 10.55676/asi.v3i1.61

of standard deviation of the slopes in the given field is calculated. Based on these statistics, in the next step, the reduction of points of the digital terrain model is performed. The number of elevation points will be higher in areas where the slopes are more diverse. Such generalisation allows us to obtain a reduced number of elevation points, which enables to accelerate further analyses while maintaining the nature of the relief of the analysed area at the same time, as it was proven in the previous publication of the authors[28]. The cited article also provided a detailed description of the whole process of generalisation of the digital terrain model for the purposes of determining land passability.

3. Removing points situated on impassable objects from the model

The previous research conducted by the authors demonstrated that in the determination of passability on a detailed level it is pointless to perform the calculations for areas where impassable objects are situated[29]. As a result, analyses are not conducted in areas that vehicles cannot cross anyway, which may significantly shorten the time of the analysis. For the purposes of this study, some of the layers from the Topographic Objects Database were used to exclude impassable areas. The list of all these layers, together with the reasons why they were qualified for exclusion from the analysis, is provided in Table 3.

Table 3. Layers from the Topographic Objects Database that were assumed to be impassable

| Layer code | Layer | Reason for excluding the layer as impassable |
|---|---|---|
| OT_BUBD | Building | They represent buildings that are permanently fixed to the ground, separated from the surrounding space with building partitions that cannot be passed by vehicles. |
| OT_BUSP | Sports building | |
| OT_BUZT | Technical tank | |
| OT_KUMN | Residential estate | They represent areas where various types of buildings are located. They represent complexes of buildings and structures, facilities and internal communication systems, usually surrounded by fences. Due to that, they were excluded from further analysis. |
| OT_KUPG | Industrial and commercial complex | |
| OT_KUKO | Transportation complex | |
| OT_KUSK | Sports and leisure facility | |
| OT_KUHO | Hospitality services complex | |
| OT_KUHU | Street market | |
| OT_KUOS | Educational facility | |
| OT_KUOZ | Healthcare facility | |
| OT_KUZA | Historical complex | |
| OT_KUSC | Sacral facility and cemetery | |
| OT_OIMK | Wetland | It represents land that is periodically or permanently swampy, flooded, or covered with a layer of water as well as areas with a high level of ground waters. As the passability conditions in such areas strongly depend on the weather conditions, which are not taken into account in the study, all these areas were excluded from further analysis. |

[28] W. Dawid, K. Pokonieczny, *Generalization of Digital*..., op. cit.
[29] W. Dawid, K. Pokonieczny, M. Wyszyński, *The Methodology of Determining*..., op. cit.

| | | |
|---|---|---|
| OT_OISZ | Rushes | It represent areas that are overgrown with tall grassy vegetation, which is present both in the coastal areas of waters and on land. Rushes are also often situated in wetlands. Due to the fact that such areas may significantly hinder the movement of vehicles, they were excluded from further analyses. |
| OT_PTLZ | Forests or wooded areas | It represents areas with dense tree cover, such as forests, wooded areas of parks and cemeteries, and other areas overgrown with trees. Due to the fact that it is impossible to quickly and precisely define such parameters as the distance between trees or girth at breast height, the authors assumed these areas to be impassable. |
| OT_PTWP | Surface waters | It represents areas covered by the waters of the sea, lakes, rivers, channels, and artificial water reservoirs, which prevents the movement of vehicles. |

Source: own study.

At this stage, the elevation points that are situated in the layers listed above are removed from the digital terrain model so that they are excluded from further analyses.

4. Selection of the vehicle for analysis

The next stage consists in selecting the vehicle, for which further analyses will be conducted. The traction parameters of the vehicle will become the basis both for pathfinding and for generating a terrain passability map. As it has been already mentioned, in the present study the passability was determined for 3 types of vehicles (Star, Humvee, and Rosomak). Their traction parameters are presented in Table 2. After the vehicle has been selected, the rest of the process consists in either conducting the passability analysis or finding a route between points. These stages will be described in the further sub-sections.

5. Passability analysis

The first described process is the passability analysis that results in creating terrain passability maps for a specific vehicle. In general terms, the method used to determine passability checks if there is a possibility that the chassis will get stuck on the ground at any point. This method will be described based on Figure 5.

The method to determine passability for individual vehicles was described by the authors in their previous studies[30]. It works in this way that the points of the elevation model are, consecutively, attributed to the centre of the chassis of the analysed vehicle. Based on its parameters and depending on the direction of movement, horizontal coordinates of the wheels are calculated and terrain elevation is determined with the use of inverse distance weighting interpolation (IDW)[31]. The calculated heights determine the contact point of the wheels with the terrain (step 1, Figure 5). Then, a plane is fitted into the determined points and the parameters of its general

[30] W. Dawid, K. Pokonieczny, *Analysis of the Possibilities*..., op. cit.

[31] G.A. Achilleos, *The Inverse Distance Weighted Interpolation Method and Error Propagation Mechanism – Creating a DEM from an Analogue Topographical Map*.

 DOI: 10.55676/asi.v3i1.61

equation are calculated (step 2, Figure 5). They enable to move the calculated plane vertically by the value of ground clearance of the analysed vehicle. As a result, a model of the chassis plane is obtained (step 3, Figure 5).

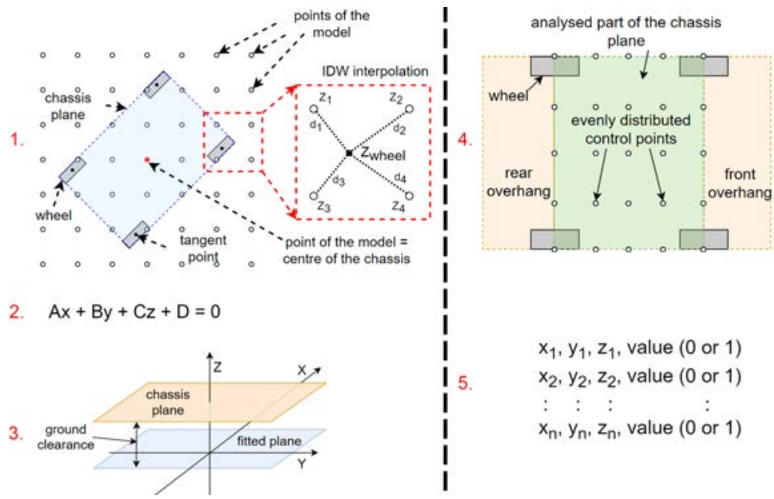



Figure 5. Workflow of the passability analysis
Source: own study.

In the next step, evenly distributed control points are generated on the chassis plane, and tests are conducted to check whether at any of these points the interpolated terrain elevation might exceed the elevation of the control point located on the chassis plane (step 4, Figure 5). If yes, it means a possibility that the vehicle's chassis will hit the terrain, so the analysed point of the digital terrain model is classified as impassable.

As a result of the calculations, a passability map is created that presents areas that are impassable for the specific type of vehicle. Examples of such maps are provided in Figures 7–11 in Section 3. As it has been mentioned above, the detailed description of this process is provided in the previous publications by the authors[32].

6. Determination of the start and end points of the route

The next type of analysis that is conducted as part of determining the passability consists in generating a route for a specific type of vehicle. This process requires defining the start and end points for which the route will be determined.

7. Route determination

The method that allows for the determination of a route for the vehicle based only on the generalised digital terrain model after the removal of impassable areas and on the traction parameters of vehicles was developed by the author in their previous

[32] W. Dawid, K. Pokonieczny, *Analysis of the Possibilities*..., op. cit.

research projects[33]. The general principle of functioning of this method will be described based on Figure 6.

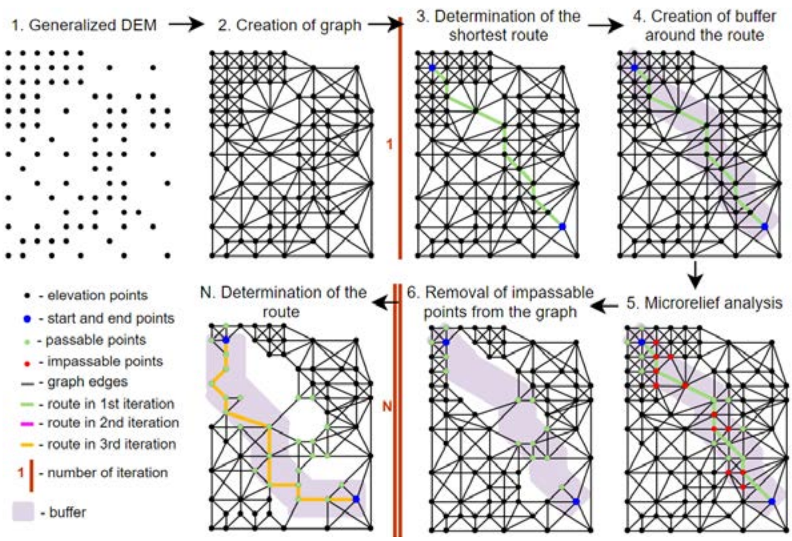



Figure 6. Workflow of the route determination process
Source: own study.

Initially, based on the elevation points (step 1, Figure 6) a graph is created, consisting of nodes and edges, where the nodes are the elevation points, and the edges are the sections that join them (step 2, Figure 6). After that, the first iteration begins: first, the shortest route between the start and end points is created (step 3, Figure 6). At the next stage, a buffer is created around that route (step 4, Figure 6). The default size of the buffer is set to 10 m, but the user of the tool may change it before starting the procedure of determining the route. The next stage consists in conducting the passability analysis for elevation points that are located inside the buffer (step 5, Figure 6). This analysis was characterised above, in the description of step 5. At the subsequent stage, elevation points that were determined to be impassable are removed from the graph (step 6, Figure 6). The iteration ends with checking whether a connection between the points exists within the buffer. If there is no such connection, the programme starts another iteration, and if a route exists, it is the result of the operation of the process (step N, Figure 6). The number of iterations depends, to a large extent, on the type of the analysed terrain. If the terrain contains many obstacles connected to micro-relief, which are impassable for the given vehicle, then the algorithm will try to find a path that will avoid these obstacles, therefore the number of iterations will increase. Due to the fact that it is impossible to define the

33 Idem, *Methodology of Using*..., op. cit.

 DOI: 10.55676/asi.v3i1.61

total number of iterations that are required to determine the route, the last stage is marked with the letter N in Figure 6.

A detailed description of the presented pathfinding method is provided in article[34].

## 3. RESULTS

The results of the application of the methodology presented in the previous section are passability maps and routes between points. All these products were generated for 5 test areas. As far as pathfinding is concerned, the start and end points were located, approximately, in the opposite corners of the areas, to make the determined routes as long as possible. All the results are visualised in Figures 7–11.

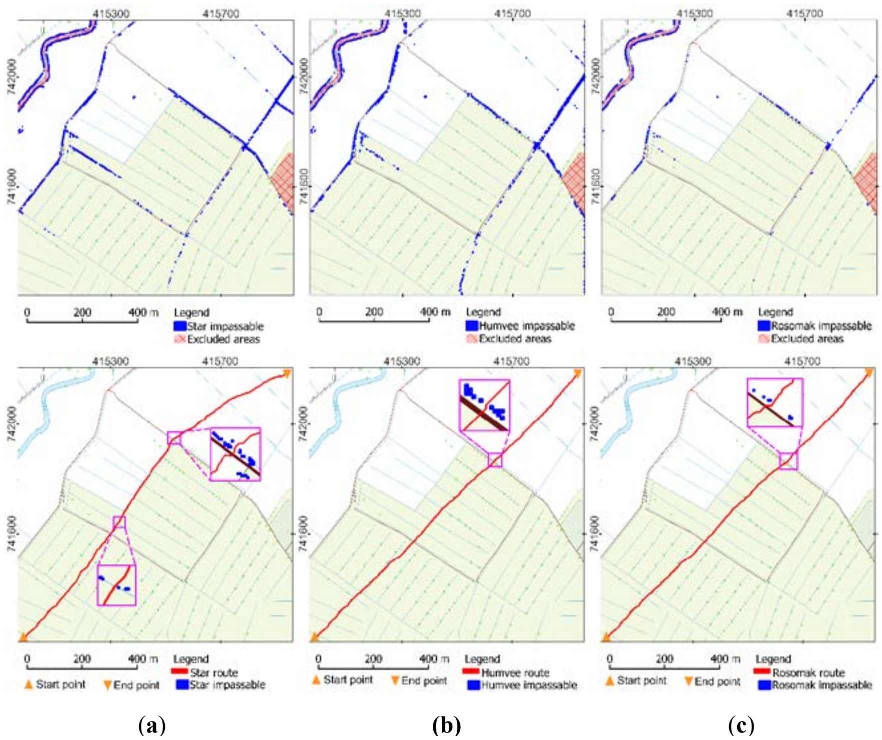



Figure 7. Agricultural terrain. Maps of passability (first row) and determined routes (second row) for: (a) Star vehicle; (b) Humvee vehicle; (c) Rosomak vehicle. Projection ETRF2000-PL / CS92 (EPSG:2180)

Source: own study.

[34] W. Dawid, K. Pokonieczny, M. Wyszyński, *Methodology of the Iterative*..., op. cit.

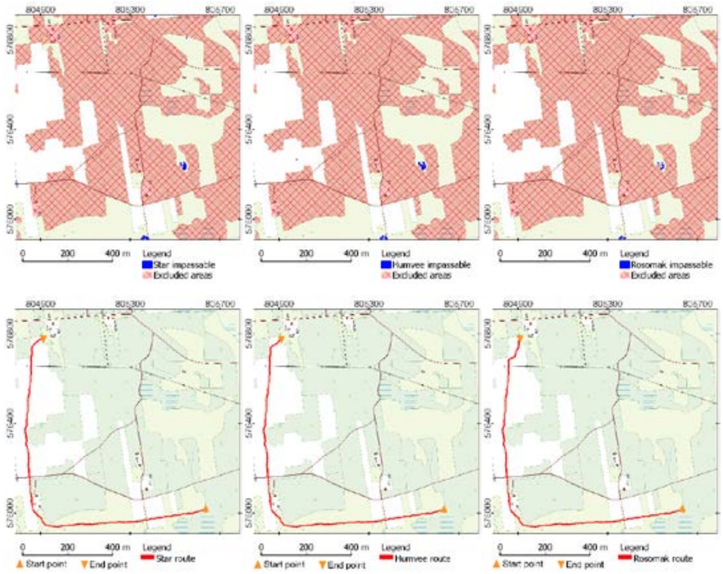



Figure 8. Forested terrain. Maps of passability (first row) and determined routes (second row) for: (a) Star vehicle; (b) Humvee vehicle; (c) Rosomak vehicle. Projection ETRF2000-PL / CS92 (EPSG:2180)

Source: own study.

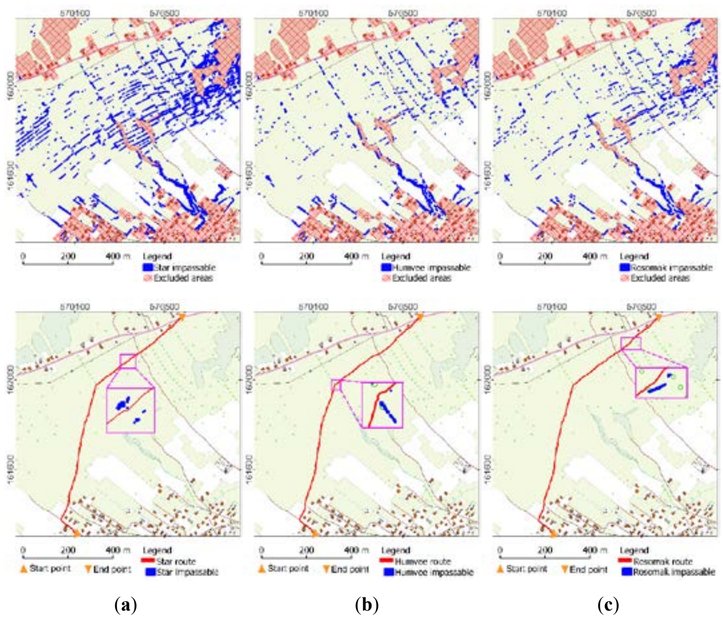
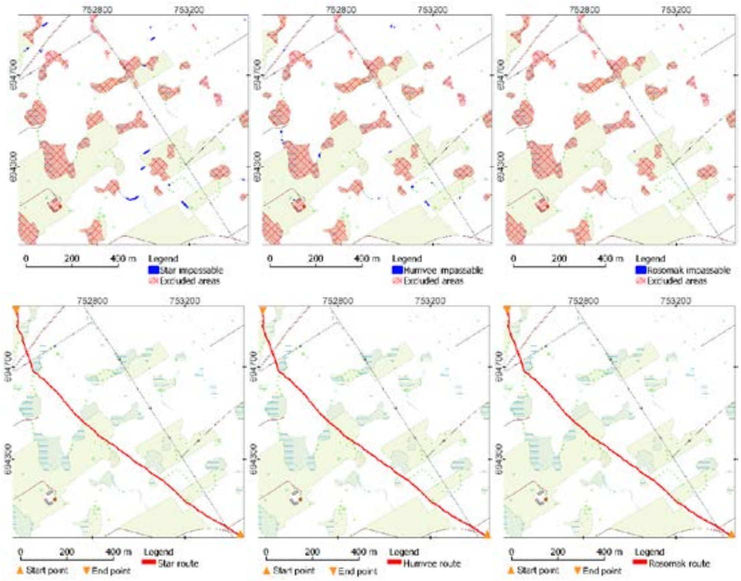



Figure 9. Hilly terrain. Maps of passability (first row) and determined routes (second row) for: (a) Star vehicle; (b) Humvee vehicle; (c) Rosomak vehicle. Projection ETRF2000-PL / CS92 (EPSG:2180)

Source: own study.

 DOI: 10.55676/asi.v3i1.61




(a) (b) (c)

Figure 10. Swampy terrain. Maps of passability (first row) and determined routes (second row) for: (a) Star vehicle; (b) Humvee vehicle; (c) Rosomak vehicle. Projection ETRF2000-PL / CS92 (EPSG:2180)

Source: own study.


(a) (b) (c)

Figure 11. Urban terrain. Maps of passability (first row) and determined routes (second row) for: (a) Star vehicle; (b) Humvee vehicle; (c) Rosomak vehicle. Projection ETRF2000-PL / CS92 (EPSG:2180)

Source: own study.

The length of the determined routes and the straight-line distance between the start and end points are presented in Table 4.

Table 4. Determined route lengths in various configurations

| Kind of terrain | Start – end point distance [m] | Star [m] | Humvee [m] | Rosomak [m] |
|---|---|---|---|---|
| Agriculture | 1375.47 | 1448.52 | 1415.10 | 1416.98 |
| Forest | 1054.40 | 1643.36 | 1644.53 | 1645.80 |
| Hilly | 1076.82 | 1247.91 | 1245.83 | 1245.46 |
| Swampy | 1383.72 | 1481.68 | 1480.31 | 1480.31 |
| Urban | 1261.84 | 1693.65 | 1715.83 | 1709.10 |

Source: own study.

The share of excluded impassable objects and areas that are impassable for specific vehicles based on the analysis are presented in Table 5.

Table 5. Percentage of impassable terrain

| Kind of terrain | Excluded area due to land cover [%] | Impassable for Star [%] | Impassable for Humvee [%] | Impassable for Rosomak [%] |
|---|---|---|---|---|
| Agriculture | 1.84 | 0.38 | 0.36 | 0.11 |
| Forest | 59.16 | 0.23 | 0.23 | 0.06 |
| Hilly | 19.37 | 2.06 | 0.75 | 0.70 |
| Swampy | 10.94 | 0.03 | 0.01 | 0.00 |
| Urban | 79.36 | 0.21 | 0.12 | 0.07 |

Source: own study.

An important aspect of the conducted analyses is their efficiency. All analyses were conducted in the multiprocessing mode on a computer with the following parameters:

– CPU: 2 x Intel® Xeon® Gold 6230;
– Base speed: 2.10 GHz;
– RAM: 192 GB;
– Number of cores: 40.

The times required to generate the results are presented in Table 6. Additionally, for pathfinding, the table shows the number of iterations that were required for the algorithm to determine the route.

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Table 6. Performance of the analysis (no. of iterations concerns only the route determination time)

| Kind of terrain | Duration of: | Star [h:mm:ss] (no. of iterations) | Humvee [h:mm:ss] (no. of iterations) | Rosomak [h:mm:ss] (no. of iterations) |
|---|---|---|---|---|
| Agriculture | Passability analysis (avg) | 1:13:47 | | |
| | Route determination | 2:55:50 (22) | 0:22:10 (1) | 0:22:10 (1) |
| Forest | Passability analysis (avg) | 0:28:18 | | |
| | Route determination | 0:23:52 (1) | 0:23:05 (1) | 0:23:51 (1) |
| Hilly | Passability analysis (avg) | 1:32:42 | | |
| | Route determination | 0:54:08 (4) | 0:37:14 (3) | 0:37:03 (3) |
| Swampy | Passability analysis (avg) | 0:59:55 | | |
| | Route determination | 0:23:16 (1) | 0:22:37 (1) | 0:23:22 (1) |
| Urban | Passability analysis (avg) | 0:24:06 | | |
| | Route determination | 0:48:03 (6) | 0:35:05 (3) | 0:35:32 (3) |

Source: own study.

## 4. DISCUSSION

The obtained results revealed certain patterns that should be referenced and discussed. Table 5 presents the size of the area that was considered to be impassable. This area was excluded from the analysis generating the route. The table shows clearly that the main part of the excluded area consists of areas that were identified as impassable based on the land cover. In other areas the micro-relief revealed immeasurably smaller areas that were inaccessible for vehicles. The largest share of such areas was found in mountainous regions (0.7 - 2%), while the fewest were found in flatlands, which are practically free from terrain inclinations. In the conducted analyses, these were swampy areas (0.03% of the excluded area). These results are completely consistent with the assumptions (mountainous areas mean larger inclinations), and so are the sizes of areas that were excluded due to obstacles being elements of land cover. The largest surfaces were excluded in forest (59%) and urban areas (79%), as they contained the largest number of terrain obstacles. On the other hand, in uncovered areas, such as agricultural or swampy areas, only small parts (respectively less than 2% and 11%) were excluded as impassable areas.

As a result of the fact that certain areas were excluded based on the analysis of micro-relief, the routes differ both in shape and in length. Although these differences are small and range from several to several dozen meters, depending on the case, they affect the course of the generated routes and confirm the assumption that taking micro-relief into account allows for improved modelling of passability conditions. Although the impassable areas that were determined in the analysis of micro-relief are relatively small, they form consistent parts, often of a linear shape (see Fig. 9), which must be avoided in order to cross the terrain without encountering obstacles that result from land inclinations. The generated routes do not differ significantly depending on the type of the analysed vehicle, either. These differences result mainly from the individual properties of the analysed areas, but also from the fact that the analysed vehicles are suitable for cross-country movement.

What is worth noting are the results that are presented in Table 6 that refer to the time of generating passability analyses. Although the analyses were conducted for relatively small areas, the whole process of generating passability maps lasted from 24 minutes to over 1.5 hours. This time depends mainly on the number of elevation points that must be analysed by the algorithm in order to check the passability conditions at the given point. Due to the fact that certain areas had been excluded based on land cover and thanks to the generalisation of the digital terrain model, the times were significantly shorter than without these procedures. What is more, for each type of terrain, determining the route for the Star truck took the longest time. This results from the fact that this type of vehicles has the worst traction parameters among all three analysed vehicles, so the most impassable areas were found during the determination of the route. This was also reflected in the number of iterations performed by the algorithm. For agricultural, hilly, and urban areas, Star needed more iterations than the other vehicles in order for an optimal route to be determined. Nevertheless, if no terrain obstacles preventing mobility were detected (the number of iterations was 1), the duration of the determination of the route was close to 23 minutes.

However, the factor that has a decisive influence on the efficiency of the analysis is the enormous number of input data in form of hundreds of thousands of elevation points in the digital terrain model that were the basis for conducting the micro-relief analysis. It should be strongly emphasised that the time of route determination may be significantly shortened by using more efficient computational infrastructure.

The maps in Figures 7–11 present the distinguished impassable areas and the generated routes for the analysed test areas:

1. Agricultural area (Fig. 7) – this area is characterised by a relatively low number of exclusions resulting from land cover elements and it is generally an open area. Areas that are impassable based on micro-relief include mainly drainage ditches, which, however, do not constitute obstacles for the vehicles with the best traction properties, i.e., Rosomak and Humvee. It is worth noting that the algorithm correctly identified the culvert that enabled the Star vehicle to cross this area.
2. The forested area (Fig. 8) is characterised by the presence of a vast impassable area. This is caused by the predominance of the forest, which was automatically and correctly (pursuant to binding standards) classified as impassable. This area practically does not contain any terrain obstacles that result from the micro-relief, so all routes follow the same path, avoiding the forest.
3. The hilly area (Fig. 9), contains numerous inclinations and steep slopes, so it is characterised by the largest area excluded based on micro-relief (in particular for the Star truck). It is worth noting that, in spite of these exclusions, the

 DOI: 10.55676/asi.v3i1.61

courses of the routes are very similar. The noticeable curve in the route marks a culvert, which the algorithm used to create the path, as the areas situated near the creek proved to be impassable for all vehicles.

4. In Poland, swampy areas are situated in flatlands. This is why in the area that is presented in Figure 10 the impassable areas are almost only swamps. After passing by the swamps, the routes generated for all three analysed vehicles are almost identical.
5. Very interesting results were noted for the urban area (Fig. 11). Developed areas were marked as impassable by the algorithm. However, in the remaining part of the region, the only impassable area was the steep embankment of the water course that flows through the analysed town. Nevertheless, the generated route follows existing roads, which is characteristic for movement in areas with dense development.

## 5. CONCLUSIONS

The conducted research revealed that the presented methodology is fully automatic and that it allows for the determination of impassable areas for various vehicles in various types of terrain. The process of generating passability maps was divided into two stages. The first stage involves the analysis of land cover elements that form natural or anthropogenic terrain obstacles. Adopting this assumption allowed the analysis to become more efficient, because only the remaining areas were qualified to be analysed in the second phase, which consists in analysing the micro-relief. This is the most demanding process from the computational point of view or in terms of determining the routes. Considering that, in areas with diverse land cover, the parts that are excluded at the first stage of the process may cover even as much as 80% of the whole surface area, this prevents us from conducting pointless micro-relief analysis in the whole area of interest. This approach to the issue of modelling land passability takes into consideration the situation where an area that is open and apparently easy to pass still contains terrain obstacles in form of elements of micro-relief. It should be emphasised very strongly that the developed algorithms are fully configurable and that they allow both changing the traction parameters of the vehicles (in order to adapt them to other types and models of vehicles) and the data that are used for passability analysis. In the present methodology, the data used originated from the Topographic Objects Database. However, nothing prevents the user from applying data obtained from military databases (such as Vector Map Level 2[35]) or other data sources (e.g., OpenStreetMap[36]). The versatility of sources of spatial data that may be use is extremely important considering the possibility of using the described algorithms in areas located outside the territory of Poland. A limitation of the proposed solution may be the relatively long time of generating the ultimate route. However, this disadvantage will be reduced by optimising the data processing

35 “Military specification MIL-V-89032 Vector Smart Map (VMAP) Level 2.”
36 J. Jokar Arsanjani et al., *An Introduction to OpenStreetMap in Geographic Information Science*.

algorithms and increasing the computational power of the hardware platform used. It is worth noting that, thanks to the application of simultaneous processing techniques, the described methodology is scalable and very sensitive to increasing computational power of the platform used.

A noticeable disadvantage of the research is the lack of field verification of the obtained results. In further research projects, the authors are planning to verify the results on site, with the use of real vehicles and compare them with results obtained from other methods.

Apart from improving the efficiency, the described system will be further developed with the aim to include other factors that influence passability (such as weather or soil conditions) in the analysis.

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