

Off-Road Hazard Map for Emergency Logistics in Island Regions

Ken Bruno Aono and Hiroyuki Goto

Department of Industrial and Systems Engineering
Hosei University
Tokyo 184-8584, Japan
ken.aono.4a@stu.hosei.ac.jp, goto-h@hosei.ac.jp

Taiki Otsuka

Faculty of IT and Business
Cyber University
Fukuoka 813-0017, Japan
taiki_otsuka@cyber-u.ac.jp

Yoichi Shimakawa

Department of Computer Science and Technology
Salesian Polytechnic
Tokyo 194-0215, Japan
simakawa@salesio-sp.ac.jp

Abstract

Emergency logistics in island regions presents a unique challenge due to geographical isolation and limited infrastructure resources. In such environments, natural disasters frequently sever arterial roads, resulting in conventional logistics planning based on paved networks ineffective. Furthermore, existing hazard maps primarily focus on identifying danger zones rather than evaluating post-disaster accessibility or the energy costs required for relief vehicles. To address these issues, this study proposes a novel hazard map framework to evaluate off-road travel time and fuel consumption, operating independently of vulnerable road networks. The methodology approximates terrain using Triangulated Irregular Networks (TINs) derived from high-resolution Digital Elevation Models (DEMs) to simulate vehicle performance on raw terrain. Unlike simple distance-based metrics, the study employs a physics-based fuel consumption model to account for the high rolling and slope resistances inherent to loose soil and complex terrain. A case study conducted on Izu-Oshima Island compares the simulated off-road performance against benchmark travel on existing paved roads. The results reveal a significant gap: while off-road travel time increased by factor of 1.2, fuel consumption increased by a factor of 3.1 compared to on-road driving. This finding highlights that conventional logistics metrics often underestimate energy requirements in disaster scenarios. The proposed framework successfully visualizes travel time and energy costs, offering a robust tool for resilient logistics planning under uncertain terrain conditions.

Keywords

Emergency Logistics, Off-road Pathfinding, Fuel Consumption, Hazard Map, Triangulated Irregular Network

1. Introduction

Emergency logistics in island regions presents a unique challenge due to geographical isolation and limited infrastructure. In Japan, securing a transportation network for relief supplies is a critical issue for disaster resilience. A notable example is the 2013 Izu-Oshima sediment disaster caused by Typhoon Wipha. The torrential rainfall triggered surface failures and lahars that severed arterial roads and port access, isolating interior settlements and causing a breakdown in last-mile logistics. This catastrophe highlighted the vulnerability of conventional logistics planning that relied heavily on paved road networks.

While vast research has optimized logistics and pathfinding on extant networks (Toth and Vigo 2014, Uchida et al. 2009), disaster scenarios introduce complex terrain lacking predefined paths, where standard graph-based approaches are ineffective. Existing hazard maps primarily focus on identifying danger zones, such as sediment disaster warnings areas (Guzzetti et al. 1999), rather than evaluating post-disaster accessibility (Chang and Nojima 2001) or energy costs for relief vehicles (Suzuki 2012). Furthermore, traditional mobility models such as the NATO Reference Mobility Model or Bekker's terramechanics (Laughery et al. 1990) require detailed soil parameters that are difficult to obtain during emergencies and often involve high computational costs for large-scale evaluation. Consequently, quantitative data regarding the reachability and fuel consumption of high-mobility vehicles on rough terrain remains insufficient.

Along these lines, this study devises a novel hazard map framework to visualize reachable range and fuel requirements for emergency supply transportation under severe road conditions. The target vehicle is the Suzuki Jimny (JB64W), a representative Japanese 4WD vehicle proven essential in past relief operations due to its maneuverability on damaged roads. The core contribution is a logistics evaluation method that operates independently of vulnerable road network data. By utilizing high-resolution Digital Elevation Models (DEMs) as the primary input, we simulate vehicle performance based on raw terrain characteristics rather than predefined paths. This approach enables the identification of reachable areas and energy costs from a designated origin to all accessible locations on the terrain, thereby contributing to resilient logistics planning that accounts for the potential loss of road infrastructure.

2. Methodology

2.1 Overall workflow

The computational framework employed in this study derives from the off-road pathfinding methodology established in our previous work (Aono et al. 2025). While the fundamental geometric processing remains consistent, the current approach extends the workflow to evaluate logistics feasibility under fuel constraints. Figure 1 illustrates the overall workflow of the proposed framework. The overall process consists of four sequential phases:

- (1) **Terrain Approximation:** Converting raw DEM data into a TIN to generate a computationally efficient surface model.
- (2) **Graph Generation via Patch Disaggregation:** Construction of a high-resolution network graph by systematically subdividing TIN elements and extracting traversable edges based on terrain properties.
- (3) **Path Optimization:** Global computation of minimum accumulated costs (time and fuel consumption) from origin to all accessible nodes using Dijkstra's algorithm.
- (4) **Hazard Map Construction:** Spatial visualization of accumulated time and fuel costs to evaluate accessibility levels and identify high-cost or unreachable areas across the terrain.

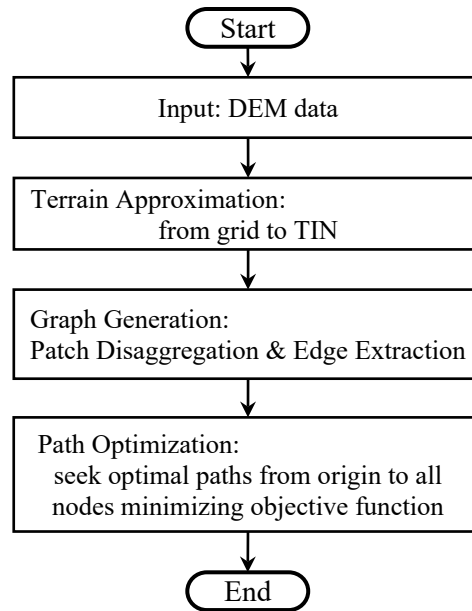


Figure 1. Overall flow of the proposed framework

2.2 Terrain surface model

Topographic representation in Geographic Information Systems (GIS) approximates the terrain as a continuous surface, typically constructed through the tessellation of piecewise elements that ensure mathematical continuity along boundaries.

Digital Elevation Models (DEMs) serves as the standard format for terrain representation, providing elevation data at regular grid intervals. While DEMs provide a consistent matrix of bare-earth elevations, the fixed grid structure entails data redundancy, particularly in areas with minimal topographic variation where uniform sampling density is unnecessary.

In contrast, the Triangulated Irregular Network (TIN) model represents terrain through a mesh of irregularly shaped triangles. This vector-based structure provides spatial adaptivity; triangle size is determined by terrain complexity, with smaller triangles allocated to steep slopes and larger triangles to flat regions. This adaptive tessellation optimizes storage efficiency while preserving topographic details. Furthermore, the conversion from a grid-based DEM to a TIN alters the spatial distribution of nodes. The resulting irregular arrangement diversifies the potential edges for graph-based algorithms, thereby facilitating more effective route optimization in unstructured, off-road environments.

2.3 Terrain Approximation

To generate a TIN from the DEM, we employ the greedy decimation algorithm (van Kreveld et al. 1997), governed by the vertical tolerance parameter $\epsilon_{\max}$. This algorithm iteratively removes vertices exhibiting the minimal vertical deviation, defined as the elevation difference between an original point and the interpolated TIN surface. This process effectively reduces data density while maintaining topographic accuracy.

The procedure consists of three phases:

- (1) Initialization: The initial vertical deviation $e(p)$ is computed for every internal point p . This value is determined by comparing the two possible triangulation patterns within the grid cell containing p and selecting the configuration that yields the smaller deviation.
- (2) Iterative Decimation: The point with the global minimum deviation $p_{\min}$, is identified and removed if $e(p_{\min}) \leq \epsilon_{\max}$. The local polygon yielded by this point removal is then partitioned into multiple triangles based on Delaunay criterion, and deviations for the immediate neighbors are updated to reflect the new surface geometry. This cycle repeats until the minimum deviation exceeds $\epsilon_{\max}$.

- (3) Finalization: Once the removal process terminates, a global Delaunay triangulation is performed on the remaining set of points. This step ensures geometric quality by maximizing minimum angles (de Berg et al. 2008), which prevents elongated triangles that could compromise pathfinding precision.

2.4 Graph Generation via Patch Disaggregation

To construct a high-resolution network that supports flexible route selection, we employ the patch disaggregation method described in our previous work (Aono et al. 2025). Each edge of the TIN triangles is uniformly subdivided into N segments, and all resulting vertices within the patch are fully interconnected. In this study, we adopted $N=3$ to balance path resolution and computational cost. Then, edges with a slope exceeding 0.60 are removed as impassable. For the remaining edges, travel velocities are assigned according to the slope; the specific velocity profiles and their integration with the fuel consumption model are detailed in Section 3.3. This densification increases the density of passable paths, allowing for smoother trajectory selection on irregular terrain.

2.5 Path Optimization

Identifying an optimal path translates to a shortest pathfinding problem in a network, for which a solution algorithm is applied to find the optimal path. In optimization instances, each edge is weighted by one of the following two objectives:

- Estimated trip time: Calculated as the Euclidean distance of the edge divided by the travel velocity. Consistent with the graph generation phase, velocity is assigned based on the edge's slope.
- Fuel consumption: Virginia Tech Comprehensive Power-based Fuel consumption Model (VT-CPFM) proposed by Rakha et al. (2011), which is derived considering distance, velocity, and slope.

The total weight along a path is quantified using ones of the above objectives, and the optimal path is sought using a popular algorithm known as Dijkstra's algorithm.

3. Experiments

3.1 Study area and Setup

Izu-Oshima Island, located approximately 120km south of central Tokyo, was selected as the study area. The island covers an area of approximately 91.0km² and is characterized by the active volcano Mt. Mihara, which rises to an elevation of 758m at the island's center. Figure 2 illustrates the geographic location of the island. The terrain features significant elevation changes within short horizontal distances, created by historical volcanic activities. Figure 3 depicts the elevation map, highlighting the steep and complex slopes surrounding the central crater.

In this study, Motomachi Port is designated as the supply origin node. Located on the western coast adjacent to the island's largest settlement, this port serves as a central hub for the island's economy, regularly accommodating cargo vessels and passenger liners. The simulation performs a comprehensive reachability analysis from this coastal area to all accessible locations across the island. This setup, which calculates the potential supply range from the sea-level hub to the mountainous interior, allows for the identification of feasible routes to any isolated settlements and provides a critical case study for analyzing energy costs under severe topographic constraints.

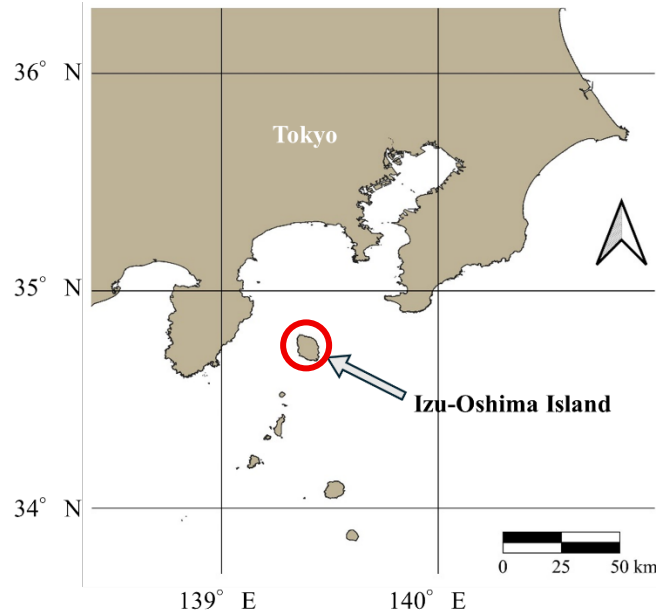


Figure 2. Location of Izu-Oshima Island.

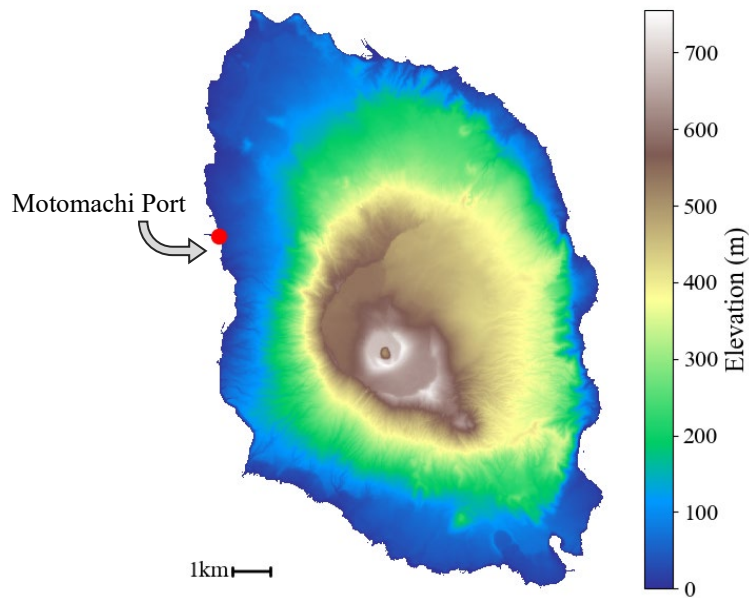


Figure 3. Elevation map of Izu-Oshima Island.

3.2 Datasets

The study utilizes two primary datasets centered on Izu-Oshima Island.

- **Elevation Data:** A 10m grid Digital Elevation Model (DEM) provided by the Geospatial Information Authority of Japan (2024) serves as the basis for terrain modeling. We calculated the effective metric resolution based on the island's centroid coordinates. The resulting mesh dimensions are approximately 10.16m in the latitudinal direction (N-S) and 12.33m in the longitudinal direction (E-W).
- **Road Network Data:** To serve as a benchmark for comparative analysis, the existing road network was extracted from OpenStreetMap (2025). These road vector data are overlaid onto the DEM to assign elevation values to each node, thereby enabling the calculation of road slopes required for fuel consumption estimation.

3.3 Fuel consumption model

We adopt the Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT-CPFM) to estimate energy costs. Unlike simple empirical models that rely solely on slope categories, the VT-CPFM calculates instantaneous fuel consumption based on the vehicle power required to overcome resistance forces, enabling a physics-based representation of vehicle traversal on three-dimensional terrain.

The instantaneous fuel consumption rate $FC(t)$ [L/s] is expressed as a quadratic function of the vehicle power $P(t)$ [kW]:

$$FC(t) = \begin{cases} \alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2 & : \text{if } P(t) \geq 0, \\ \alpha_0 & : \text{if } P(t) < 0, \end{cases}$$

where $\alpha_0, \alpha_1, \alpha_2$ are vehicle-specific coefficients. In this study, these coefficients were calibrated for the Suzuki Jimny (JB64W), a representative cross-country 4WD vehicle, replacing the standard passenger car parameters used in typical on-road studies. The vehicle power $P(t)$ required to maintain velocity $v(t)$ [km/h] is computed from the sum of aerodynamic, rolling, and grade resistance forces:

$$P(t) = \frac{R(t)v(t)}{3600\eta_d},$$

$$R(t) = \frac{\rho}{25.92} C_D C_h A_f v(t)^2 + mg \frac{C_r}{1000} (c_1 v(t) + c_2) + mgG(t).$$

According to the model definition by Rakha et al., the rolling resistance parameters C_r , c_1 and c_2 vary as a function of road surface type, road condition, and vehicle tire type. While C_r is typically set to 1.75 for standard paved roads, the target environment in this study consists of loose volcanic soil, which imposes significantly higher resistance. Therefore, based on the experimental data for off-road conditions provided by Schreiber and Kutzbach, we adjusted C_r to 32.0 to represent the specific surface characteristics. The coefficients c_1 and c_2 , governing the speed dependence and vehicle tire type, remain unchanged.

Since the simulations assume constant cruising travel within each segment, the acceleration term is omitted. Consequently, the vehicle velocity $v(t)$ becomes the dominant factor influencing fuel consumption. It not only determines the duration of travel per segment but also directly scales the power required to overcome the significant rolling and slope resistances, thereby acting as the primary driver of energy costs in the simulation.

To ensure safety and physical feasibility on steep, unpaved gradients, we applied a step-wise speed constraint model based on the slope. The speed limits for relatively gentle slopes (≤ 0.08 and ≤ 0.12) were determined by adjusting the maximum speeds defined in the Japanese Road Structure Ordinance (40km/h for ≤ 0.08 and 20km/h for ≤ 0.12). Considering the increased resistance and safety risks of off-road driving, these were slightly reduced to 30km/h and 15km/h, respectively.

For steeper gradients (≤ 0.60), the speed limit of 5.5km/h was derived from the mechanical specifications of a representative off-road vehicle using the following powertrain equation:

$$V = \frac{R \cdot C \cdot 60}{G_{total} \cdot 1000},$$

where V is the vehicle speed (km/h), R is the engine speed (2500 rpm), C is the tire circumference (0.686π m), and G_{total} is the combined gear ratio ($5.809 \cdot 2.643 \cdot 3.818$) based on the manufacturer's catalog values. The limit for intermediate slopes (≤ 0.40) was set at 10km/h to ensure a logical transition between these empirical and mechanical constraints. Slopes exceeding 0.60 are classified as impassable.

The total fuel consumption F along a path is then computed as:

$$F = \sum_i FC_i \cdot \frac{d_i}{v_i}.$$

where d_i is the segment length and v_i is the assigned speed on segment i .

4. Case Study

The simulation conducted using the Suzuki Jimny (JB64W) as the target vehicle, adhering to the modified VT-CPFM and speed constraint models described in Section 3.3. The specific parameter values used for the calculation are summarized in Table 1.

The vehicle mass m was based on the manufacturer's catalog. Other parameters (A_f, C_D, η_d) were calculated following (Rakha et al. 2011) or estimated using representative values for similar off-road vehicles to ensure the simulation quality.

Table 1. Simulation Parameters for Suzuki Jimny.

Parameter	Symbol	Value
Vehicle mass (kg)	m	1,310
Drag coeff	C_D	0.48
Frontal area	A_f	2.16
Driveline efficiency	η_d	0.90
Rolling coefficient	C_r	32.0
	c_1	0.0328
	c_2	4.575
Air Density (kg/m ³)	ρ	1.2256

4.1 Hazard Map Generation

Figure 4 shows the Travel Time Map (One-way). The isochrones are distorted by the steep terrain; while coastal areas are reached relatively quickly, the route to the mountainous interior and the southeastern area requires significantly more time. The simulation indicates that reaching the furthest southeastern settlement takes approximately 35 minutes one-way under off-road constraints.

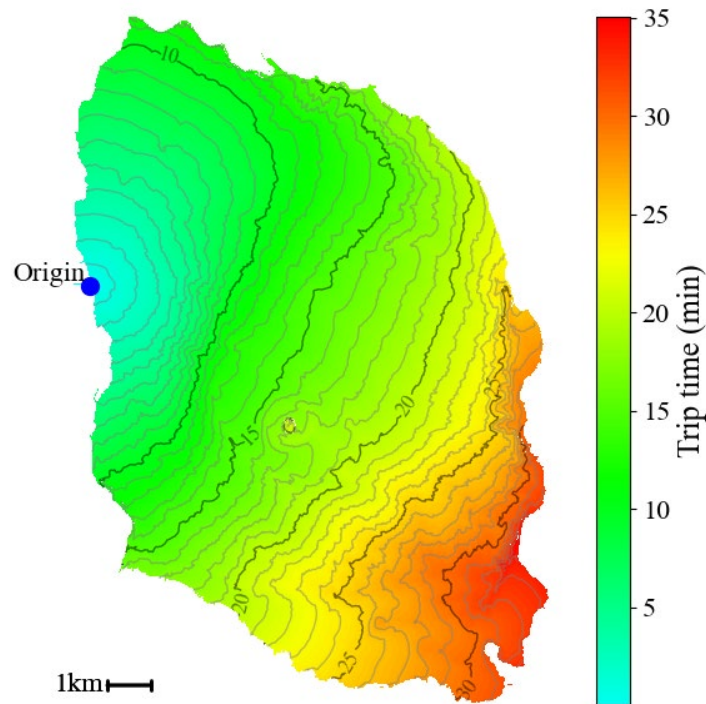


Figure 4. Travel Time Map (One-way)

Figure 5a and Figure 5b illustrate the Fuel Consumption Maps for one-way (outbound) and round-trip scenarios, respectively. In the Outbound Map (Figure 5a), the consumption is directionally biased and heavily influenced by uphill climb towards the central volcano. However, Round-trip Map (Figure 5b) exhibits a relatively concentric pattern similar to geographic distance. This suggests that the elevation effects (ascent and descent) are averaged out over the round trip. While the spatial pattern resembles standard distance-based concentric circles, the overall fuel consumption

is significantly higher than on paved roads. The simulation indicates that a round trip to the southeastern settlement consumes approximately 4.6L of fuel.

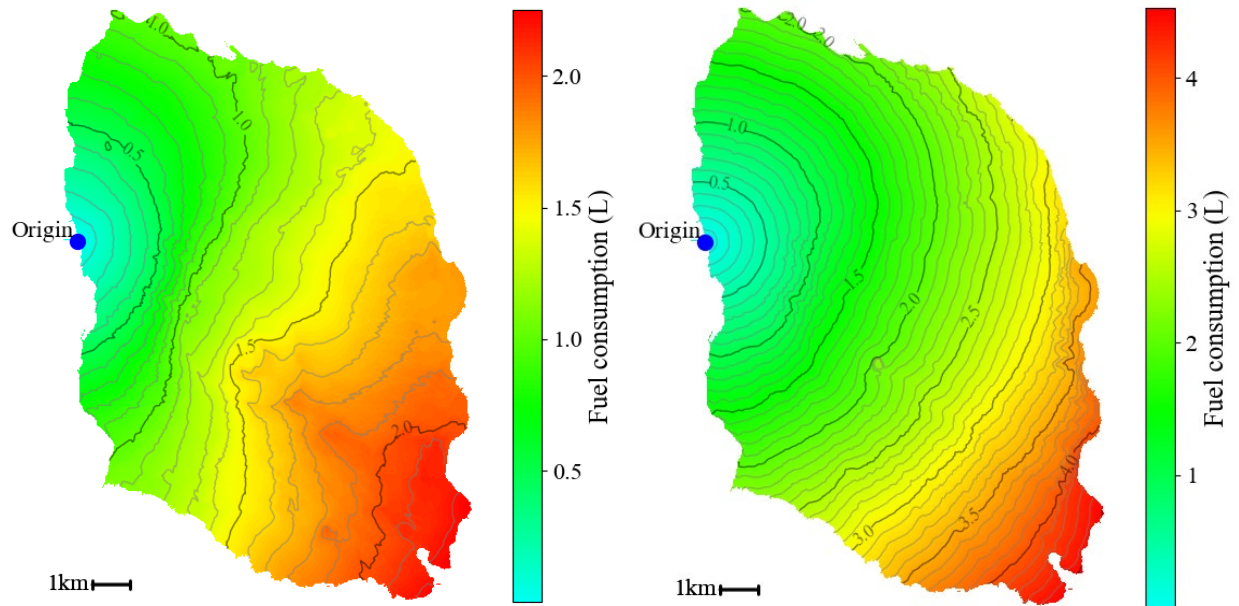


Figure 5a (left) and Figure 5b (right). Fuel Consumption Maps for outbound(left) and round-trip(right).

4.2 Comparative Analysis and Discussion

To evaluate the impact of infrastructure loss and the necessity of the proposed hazard map, we compared the simulation results with a standard driving scenario on existing paved roads. Figure 6 illustrates the benchmark route from Motomachi Port to the southeastern area using the existing road network. Under normal conditions, a round trip to this specific location (approx. 30km total) typically consumes 1.5L of fuel and takes 27 minutes one-way.

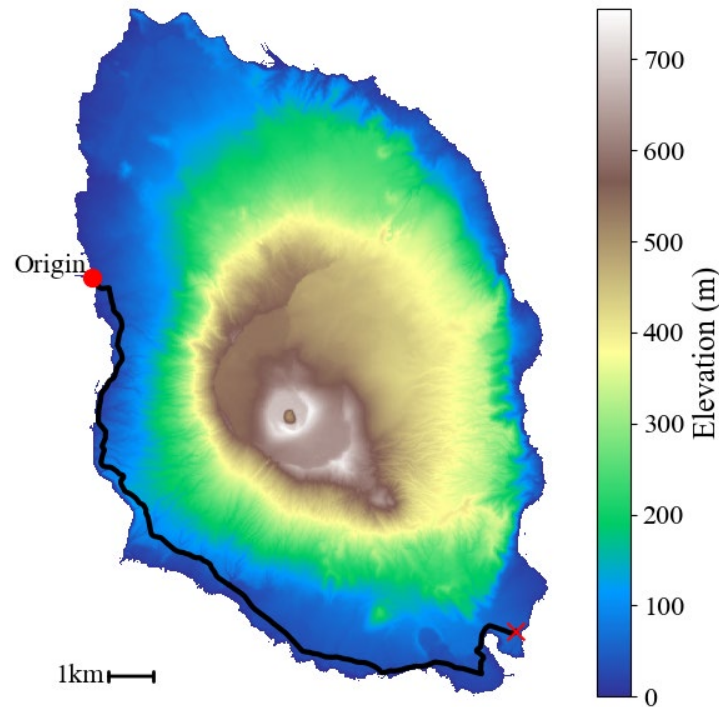


Figure 6. Benchmark route from Motomachi Port to the southeastern area.

A significant contrast is observed in the increase ratios of travel time and fuel consumption. While the travel time shows a moderate increase of approximately 1.2 times (from 27 to 32 minutes), the fuel consumption exhibits a 3.1-fold increase (from 1.5L to 4.6L). This discrepancy implies that logistics planning based solely on conventional time-distance metrics, which are often used in standard navigation systems, would result in a severe underestimation of fuel requirements. Consequently, providing an energy-based hazard map becomes a requisite for feasibility planning to prevent vehicle stranding during relief missions.

Furthermore, the proposed TIN-based method offers adaptability to topological changes. In the event of infrastructure severance, such as landslides, the reachability analysis can be instantly updated by eliminating the corresponding edges from the network. This feature demonstrates the practical effectiveness for resilient logistics planning under uncertain terrain conditions.

5. Summary and Conclusion

This study proposed a hazard map construction framework to evaluate off-road reachability and fuel consumption, assuming road network severance in island regions. By integrating a physics-based fuel model (VT-CPFM) with a high-resolution TIN terrain model, the proposed method quantifies movement costs independent of existing infrastructure. A case study on Izu-Oshima revealed that off-road travel consumes approximately 3.1 times more fuel than on-road driving, despite only a 1.2-fold increase in travel time. This significant disparity indicates that conventional time-based logistics planning may drastically underestimate fuel requirements. The resulting maps successfully visualize high-cost areas based on raw terrain data. The framework offers high adaptability to infrastructure loss; since it operates on terrain geometry rather than predefined road networks, reachability can be instantly re-evaluated by eliminating edges affected by landslides, thereby enhancing the robustness of relief operations.

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Biographies

Ken Bruno Aono is currently an undergraduate student in the Faculty of Science and Engineering, Hosei University, Japan. His research interests include operations research and geographic information science.

Hiroyuki Goto is Professor in the Department of Industrial and Systems Engineering, Hosei University, Japan. He received his B.S. and M.S. degrees from The University of Tokyo in 1995 and 1997, respectively. He received his D.E. degree from Tokyo Metropolitan Institute of Technology in 2004. His research interests include operations research, geographic information science, and high-performance computing. He was elected as an IEOM Society International Fellow in February, 2025.

Taiki Otsuka is an Assistant Professor in the Faculty of IT and Business at Cyber University, Japan. He received his B.Sc. and M.Sc. degrees from Chuo University in 2003 and 2005, respectively. His research and teaching interests include algorithms, operations research, and their applications.

Yoichi Shimakawa is a Professor and Director at the Department of Computer Science and Technology, Salesian Polytechnic Japan. He received his B.S. and M.Sc. degrees from Chuo University in 1990 and 1996, respectively. In 1998, he joined Chuo University as a research assistant on the research project "Integrated Geographic Information Systems." He received his D.E. degree from Chuo University. He received paper awards from the Operations Research Society of Japan in 2002.