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Environmental-friendly Pathfinding on Three-dimensional Terrain Surface Models

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Abstract

The present study deals with logistics-related pathfinding topics in hilly or mountainous areas, where roads characterized by steep slopes and curves exist. Transportation utilizing this type of road yields negative impacts by greater fuel consumption, along with greater CO_2 emissions. In recent years, increasing tourist demand in Japan has highlighted capacity limitations and safety concerns. Meanwhile, old infrastructures such as arterial roads, expressways, and sewerage systems are reaching or exceeding their designed service years. In early 2025, a large road collapse accident due to drainage aging occurred close to central Tokyo. Thus, well prioritized planning for reconstructing road infrastructures is necessitated. Along these lines, we are motivated to devise an environmental-friendly pathfinding algorithm for road (re)construction, which is beneficial for hilly or mountainous areas. This challenge involves terrain modeling and pathfinding. The former relates with a cartographic theory called Triangular Irregular Network (TIN) and Digital Elevation Model (DEM), while the latter with shortest-path algorithms. In the experiments, slope constraints and fuel efficiency are both considered. A case study on Izu-Oshima Island, an isolated island located southward from central Tokyo, was conducted. Validation was successful with savings of approximately 27% in path-length and some 10% in fuel consumption, adhering to Japan's maximum road slope standard.

Keywords
Pathfinding, slope constrained, origin-destination (O-D) transportation, geographical surface, triangular irregular network (TIN).

1. Introduction

Optimal pathfinding is an essential component in many ways of overland logistics such as freight and passenger transportation. Optimality in logistics frequently refers to the shortest path-length or shortest travel time, whereon saving or minimizing transportation cost is concerned. User-side planning addresses finding a better or best route choosing one among available services on an extant network. Decision-making in this context occasionally reduces to a shortest-path problem in a graph. Vast research and development to efficiently find a good or optimal solution have been addressed to date (Zhan and Noon 1998), (Vijayalaxmi and Pawar 2024), from which many off-the-shelf tools such as Google maps are available.

Meanwhile, another type of pathfinding occasionally becomes vital in infrastructure construction contexts. Enhancing or constructing an Origin-Destination (O–D) transportation system is common in various fields ranging from natural resources (Durmaz et al. 2019), energy (Presser et al. 2024), drainage, freight (Zweers and van der Mei 2022), to passenger transportation. Each logistics can be comprehended as either unidirectional (Swamee and Sharma 2000) or bidirectional (Collischonn and Pilar 2000). Electricity, gas, and water supplies are unidirectional logistics wherein substance is conveyed through a fixed structure such as wire or pipeline. Of these three, water supply has the strongest constraint in pathfinding as the pipeline must be laid all along downhill slopes. By contrast, electricity wire installation is flexible and can be planned irrespective of the slope.

Bidirectional logistics is occasionally tied with vehicle transportation on railway or roadway. Whether the direction is inbound or outbound, or the slope is uphill or downhill, vehicles must be continuously controlled in speed with adhesion. An underlying constraint there is that the slope must be constantly within the standard all along the path; carriages must be slowed down and occasionally stopped in the case of heavy traffic, and keep unmoved when an accident occurs. By contrast, slope constraints on energy transportation are tolerant as the substance is continuous and conveyed utilizing natural laws of gravity and pressure.

Amongst these two types, our research target lies in bidirectional logistics. The quest is to seek an optimal O–D path on a geographical surface, along which the constraint regarding the maximum slope follows. The challenge behind this is that even on a continuous surface, different paths with close lengths may pass through significantly different routes. The problem then reduces to a combinatorial optimization problem. The continuous geometrical surface is based on a common model known as Triangular Irregular Network (TIN) (van Kreveld et al. 1997). This is typically created from a Digital Elevation Model (DEM) (Li et al. 2004), (Wilson and Gallant 2000) dataset, in which elevations on a regular square or rectangular lattice are given.

While potential applications include both roadway and railway transportations, we are mainly concerned with the former one, i.e. pathfinding for O–D roadway planning. The target scale of the problem is approximately up to some ten kilometers, which is popular in ward- and city-level infrastructure plans. Gentle roadways may enhance safety, while they usually increase the path length and construction cost. Because Japan is a mountainous country, (local) governments have historically taken decisions on minimizing the construction cost. The consequence is that there are a host number of narrow and steep roadways even around major sightseeing spots. Some spots have been registered as World Heritages, where many tourists rush into in recent years. The number of visitors surpasses the carrying capacity in several spots, for which construction of a new transportation system is under survey by several local governments; Mt. Fuji is a famous example among others.

Along these lines, our motivation was induced by this recent social problem. Constructing short and gentle roadways would contribute to reducing fuel consumption as well as enhancing safety, which also accompanies environment-friendliness. The technical goal is to construct a pathfinding framework on a three-dimensional geographical terrain. Given a DEM dataset, a continuous terrain spline surface is first determined. The surface is then approximated by a polyhedron called a TIN. Several triangles in the network may be disaggregated to enhance approximation by discretization, while several edges may be eliminated to prohibit accessibility on steep locations. The optimal path is sought using a popular shortest-path algorithm. The selected path would achieve low fuel consumption as well as low risk of traffic accidents.

2. Terrain Manipulation

The terrain of the region of interest is modeled by continuous spline surface. In Geographic Information Systems (GISs) contexts, a spline surface comprises a set of piecewise objects accompanying continuity across borders. Each object is typically a planar triangle or a non-linear function, the whole collection of which composes a tessellation.

2.1 Surface model

DEM datasets are commonly used in terrain representation. A typical dataset consists of elevations at regular intervals on a mesh, representing the bare-earth surface eliminated the impacts by natural or artificial objects such as vegetation and buildings. Common DEM datasets contain elevation values at regular intervals, the values of which are stored in a real matrix. While this format is suited for direct analyses of topographic structures, this may be redundant around locations where the change of elevation is small.

Another major terrain representation is called TIN. A TIN stores elevations on irregularly shaped triangles, comprising a three-dimensional network. Smaller triangles are employed around areas with a steep slope or complex terrain, reflecting detailed topographic variations. Conversely, larger triangles are employed around flat areas with lower variations, to achieve storage efficiency. Such adaptivity in the triangles' size and density attain efficient preservation of terrain features, namely enabling reduction in storage size.

Conversion of a DEM-based terrain into a TIN-based has diversified patterns in the elevation points. This variety accompanies flexibility in path selection, rendering TIN-based representations effective in route planning and optimization.

2.2 TIN surface construction

To generate a TIN, we employ an algorithm proposed by van Kreveld et al. (1997). The key concept is a user-defined maximum error for vertical distances between the original DEM points and TIN surface. It iteratively removes elevation points that contribute the smallest vertical distance error. This is repeated until the resultant by further removal exceeds the maximum error threshold. This method reduces the elevation points in constructing a TIN, and preserves the essential terrain shapes. Figure 1 illustrates the role of the vertical distance error during TIN generation, where the arrow explicitly depicts the maximum error threshold. This limits the allowable vertical deviation between the original DEM points and the surface of the generated TIN. Points are iteratively removed based on their vertical distance errors as follows:

- Temporarily remove a point from the current TIN surface, and reconstruct the surface using a Delaunay triangulation without the point.
- Calculate the vertical distance error at the removed point's location, which is the absolute elevation difference between the original DEM point and the reconstructed TIN surface.
- Identify and permanently remove the point that impacts the smallest vertical distance error, provided this error does not exceed the predefined maximum threshold.
- Repeat the above steps iteratively until the removal of any further points results in a vertical distance error greater than the maximum threshold.

Figure 1 illustrates the vertical distance error during the TIN construction. The red arrows indicate the vertical distance error at the point. If this error is not greater than the user-defined threshold, then the point is removed (Figure 1).

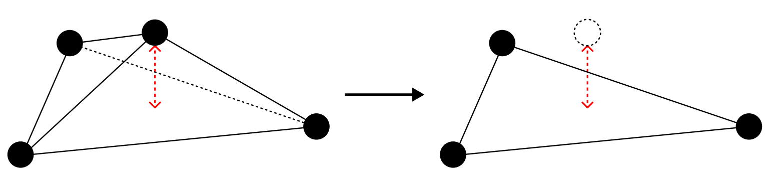

Figure 1. Vertical distance error during a TIN construction. The red arrow is the error at the point.

2.3 Patch disaggregation

To enhance flexibility of route selection in the network, each edge of a triangle in the TIN is uniformly subdivided into N segments. As an outlet, all the original and auxiliary vertices within the triangle are fully interconnected. In this study, N=3 is adopted considering the trade-off between the network resolution and computation cost. The inserted auxiliary vertices enrich the internal connectivity of a triangle.

This disaggregation process increases the number of potential paths in a single triangle, which is especially effective around steep or irregular terrains when fine-grained slope control is required. Figure 2 illustrates a simple example of a triangle disaggregation for N=2, while N has other choices considering the trade-off between the desired resolution and computational cost.

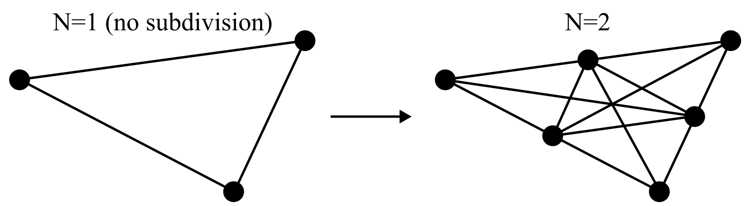

Figure 2. Triangle disaggregation in a TIN-based network

2.4 Finding an optimal path

Finding an optimal path translates into a shortest pathfinding problem in a network. To contain the maximum slope into a standard, the entire disaggregated TIN network is modified to eliminate edges whose slope exceed the allowed maximum value. Then a solution algorithm to seek the shortest path is applied.

The Japanese Road Structure Ordinance regulates the maximum slope of 12% to roads designed for a maximum speed of 20 km/h. However, the fuel consumption model used in this study assumes a constant driving speed of 35–42km/h. We hence relax the constraint by limiting the maximum slope to 12%. Reachability is validated across the network by ensuring every path from the origin to destination complies with this standard. Edges that violate this requirement are removed from the network.

In the path selection, the following two criteria are experimented:

- Shortest distance: Euclidean distance between two endpoints, weighted on each edge.
- Minimum fuel consumption: a metric considering both Euclidean distance and slope, weighted on each edge.

The path length is computed using the abovementioned weights, while the optimal path is sought using a popular algorithm called the Dijkstra's algorithm.

2.5 Path refinement

Since the obtained optimal paths comprise polylines, they should be refined to render them more realistic. The cubic spline interpolation is applied to smoothen two-dimensional (x, y) paths. To estimate the elevation z, linear interpolation is applied using the elevation values along the original paths corresponding to each interpolated (x, y) coordinate.

3. Experiments

3.1 Study area

Izu-Oshima Island is chosen as a study area. The island is located approximately 120km to the south from central Tokyo Metropolitan, and has an area of approximately 91.0km^2. Figure 3 clarifies the geographic location of the island. There is an active volcano named Mt. Miharayama at the center, whose elevation of the summit is 758m. There are steep slopes formed by repeating volcanic activities in the past, resulting in significant elevation changes within short horizontal distances. Figure 4 depicts the elevation map, revealing complex terrains spread out around Mt. Miharayama. These features have an affinity for case study of slope-constrained road route planning.

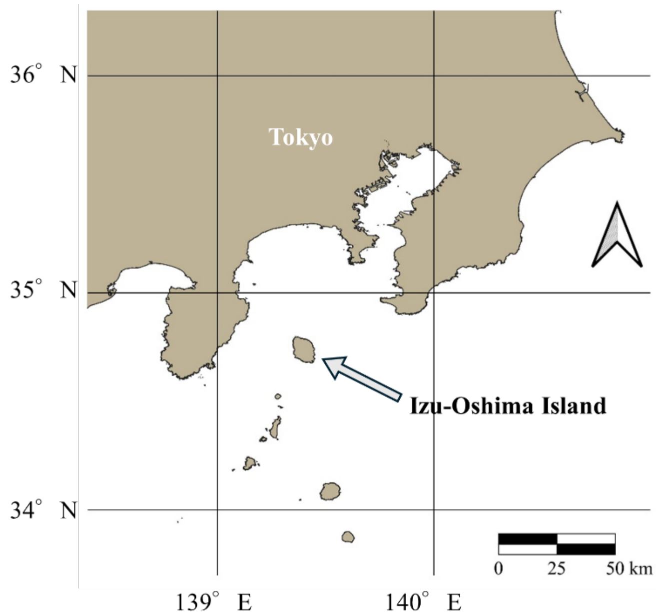

Figure 3. Location of Izu-Oshima Island

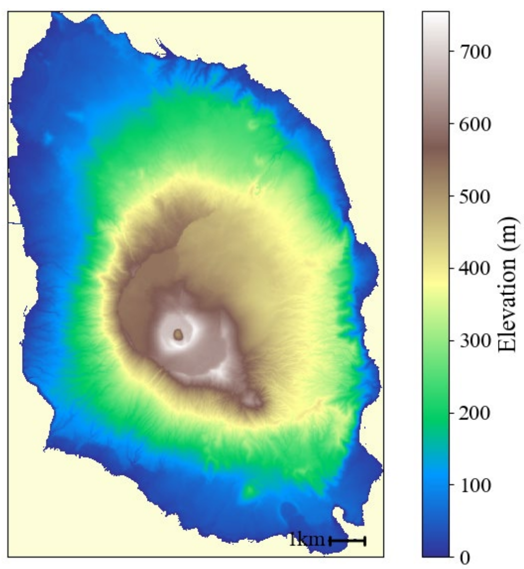

Figure 4. Elevation map of Izu-Oshima Island

3.2 Datasets

The following two datasets are used in this study.

- DEM data:
  A 10m grid elevation dataset of Izu-Oshima Island provided by the Geospatial Information Authority of Japan (2024) is utilized. Because the actual length of each grid cell varies according to latitude and longitude, we computed mesh sizes of approximately 10.16m (in latitude, N-S) and 12.33m (in longitude, E-W), the mesh-size of which is adjusted based on the coordinates at the island's centroid (latitude 34°44′N, longitude 139°24′E).
- Road network data:
  Existing road network data on Izu-Oshima Island retrieved from OpenStreetMap (2025) is used as a benchmark instance.

The road network data are overlaid on the DEM data to estimate the elevations on the nodes, enabling the estimation of fuel consumption according to the slope of the roads.

3.3 Benchmark path

Because of the repetitive eruptions in the past, more than half of the overland is rocky and only small portions of flat areas exist. The largest town of the island is located on the westernmost, where approximately 1/3 of the total population reside, along with a ferry port there. There is a larger flat area on northwest of the island, where there is a small airport. The majority of the tourists visit the island via either the airport or ferry port. To seek better path from the airport to the most popular sightseeing spot of Caldera vent at the summit, we take an extant hilly road from the bottom area to the sightseeing spot. This road includes significant elevation differences all the way to the summit, which would be ideal for comparison with our algorithm.

Figure 5a designates the area of interest in the island, and Figure 5b magnifies the existing benchmark road in the interested area. The starting and goal points are designated as the origin and destination, respectively.

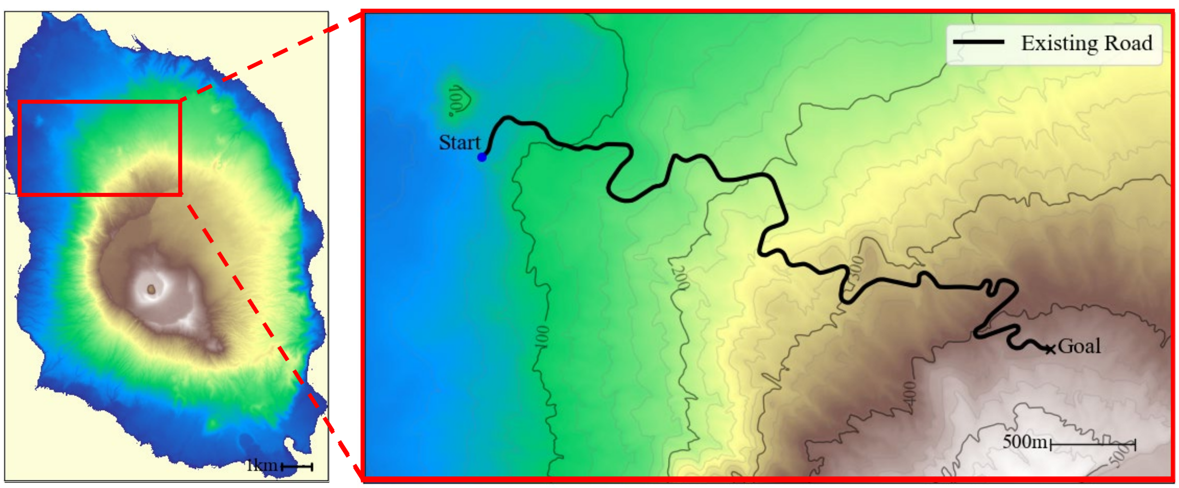

Figure 5a (left), Figure 5b(right). The left map shows the entire Izu-Oshima Island with the target area highlighted in red, while the right map provides a close-up of the selected road including the start and end points.

4. Experiments and Validation

We generate two different TINs from the same DEM data to investigate the impact of the maximum error on path generation. The maximum error is set to 1.0m and 2.0, which we call TIN1.0 and TIN2.0, respectively. To increase candidate routes in path selection, each edge of the TINs is subdivided into three segments of equal length. As a consequence, all vertices including both the original and auxiliary points are fully interconnected in each triangle. Unless otherwise mentioned, the path will be sought using the subdivided networks.

To evaluate paths taking into account fuel consumption, we adopt a fuel consumption model proposed by Li et al. (2010). This was derived from a driving test data using Toyota Corolla, which is one of the most popular passenger vehicles in Japan. The data provides a simple yet practical evaluation of fuel consumption assuming constant velocity and acceleration, which considers solely a road slope as a variable.

The total fuel consumption F(cc) is calculated along road segment i on the path, using the segment distance d_i(km), road slope s_i(%), and corresponding instantaneous fuel consumption $f(s_i)$ (cc/km) according to:

$$F = \sum_i f(s_i) \cdot d_i$$

The instantaneous fuel consumption $f(s)$ is computed by multiplying the instantaneous fuel consumption on flat terrains f_0[cc/km] and the instantaneous fuel consumption change rate $r(s)$ [%], as follows:

$$f(s) = f_0 \cdot \left(1 + \frac{r(s)}{100}\right)$$

The rate $r(s)$ as a function of the road slope g is detailed in Table 1. Although this model is simple, it effectively reflects the impact of road slope to fuel consumption. It is thus straightforward to incorporate the model into constant-speed conditions, and would be suited for path evaluation. To validate and assess the applicability of the proposed method, the following metrics are compared between the TIN-based paths and the extant road-path:

- Total path length
- Total fuel consumption
- Maximum slope
- Average slope

The road data used as a benchmark for comparison were extracted from OpenStreetMap (2025). Elevation data was retrieved from Geospatial Information Authority of Japan (2024). The former data is overlaid on the latter map, enabling calculation of horizontal slopes and fuel consumption for comparative analysis (Table 1).

Table 1. Instantaneous fuel consumption model.

Slope	Road slope (%)	Fuel consumption rate
Uphill	$0 < s < 7$	$r(s) = -1.16 \cdot s^3 + 14.42 \cdot s^2$
	$s \geq 7$	$r(s) = 33.6 \cdot s + 72.0$
Downhill	$0 < s < 2.7$	$r(s) = -16.5 \cdot s$
	$s \geq 2.7$	$r(s) = -45.0$

4.1 Impact of the approximation error

Figures 6a and 6b illustrate the comparison between the generated paths and the existing road overlaid on a map. The former result is based on TIN1.0, while the latter on TIN2.0, enabling visual comparison of the differences from the existing road. In both TINs, the maximum slope is set to 12% along with N=3 for the subdivisions.

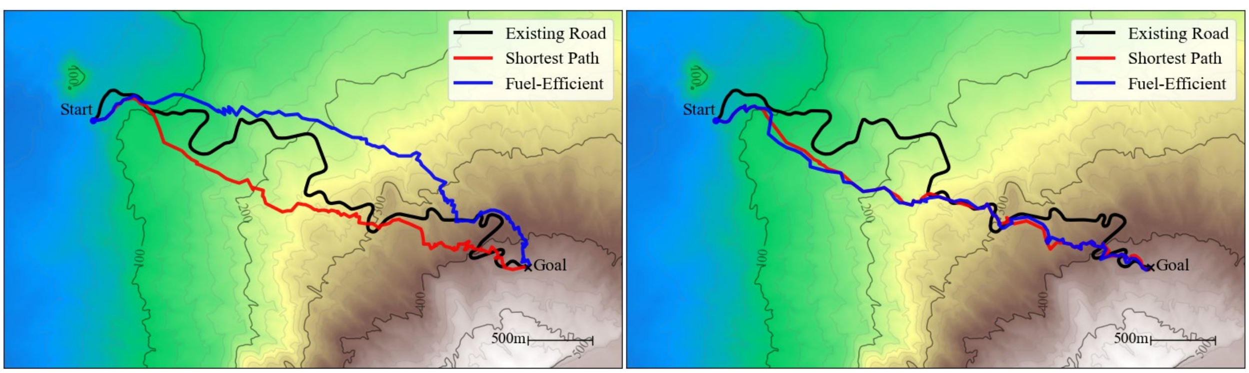

Figure 6a (left), Figure 6b(right). Comparison of the efficient paths generated by TIN1.0 (6a) and TIN2.0 (6b).

Although there seem to be notable differences between the paths generated using TIN1.0 and TIN2.0, a common feature is observed around the areas close to the goal; the slope around there is steep. To climb steep slopes, both generated paths are apt to incorporate multiple curves.

The TIN approximation accuracy would significantly impact the path's shapes. Even with the same pathfinding constraints, the resulting paths are not necessarily similar in shape. On the other hand, in terms of quantitative characteristics such as path length, fuel consumption, and slope paths, the values obtained from TIN1.0 and TIN2.0 result in similar ones. This indicates a diversity in potential path selections, providing multiple viable routing options.

4.2 Path smoothing

Figure 7 demonstrates a comparison of two paths generated from TIN1.0. The red path traces amenably on the TIN edges, while the yellow one is a smoothed curve in which a cubic spline smoothing is applied. It can be observed that the smoothed curve suggests a more realistic and practical path than the raw one.

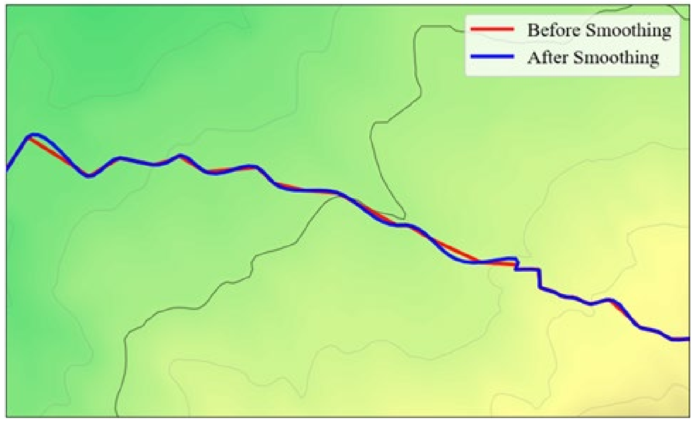

Figure 7. Comparison of the raw and smoothed paths generated by TIN 1.0.

4.3 Storage efficiency of TINs

To confirm the effectiveness of the conversion of a DEM data into TIN, Table 2 shows the number of vertices used in the original DEM and generated TINs. The DEM consists of regularly gridded points with approximately 726,000 vertices. After converting it into a TIN, the number of points is significantly reduced but depends on the maximum error; TIN1.0 contains about 98,000 points, and TIN2.0 about 52,000 points. This indicates that a TIN effectively simplifies the terrain representation retaining key topographic features.

Table 3 reports the reachability from the origin to destination with slope constraints, comparing the cases of original and subdivided TINs. With the original TINs, i.e. without the edge subdivision, we failed to find a reachable path to the goal point with the slope constraint of 12%. Along with this, relaxed constraints are applied with an increasing interval of 1%, and a feasible path was found with a slope constraint of 13%, while it inadvertently violates the road construction regulation in Japan.

On the other hand, along with stricter slope constraints with a decreasing interval of 1%, the instances subdivided into three segments (i.e. N=3) were able to reach the destination even with stricter slope constraints. TIN1.0 and TIN2.0 were reachable with the maximum slope constraints of 8% and 7%, respectively. These results imply the benefit of edge subdivision to seek more candidate paths.

We further sought shortest-path and fuel-efficient paths on TIN1.0 and TIN2.0, with the maximum slope of 12% and N=3. Figures 8a and 8b reports the path length and fuel consumption obtained for the two TINs comparing with the existing road.

Table 4 compares the results obtained with the four TINs, reporting the path length, fuel consumption, maximum slope, and average slope. The reduction effects on the path length and fuel consumption are reported. The maximum slope of all the generated paths was contained to 12%, which complies with the road design standards in Japan. In addition, fuel-efficient paths exhibit lower average slopes, highlighting their significance in fuel-efficient road design.
Finally, the cubic spline smoothing was applied to the fuel-efficient path based on TIN1.0. The effectiveness of the smoothing is evaluated in Table 5. After the smoothing, the number of vertices was increased from 191 to 350, which reflects a more detailed path representation. The path length was slightly increased from 4,902m to 4,917m, and fuel consumption showed a minor increase from 808cc to 812cc.

However, the maximum slope was increased saliently from 12% to 31%. This indicates that cubic spline smoothing introduced steep elevation changes in some segments. The average slope remained through the smoothing. These results suggest that while the cubic spline smoothing effectively smooths the path shapes, while it also accompanies a risk of exceeding slope constraints. Hence, further refinements for the smoothing procedure are necessitated.

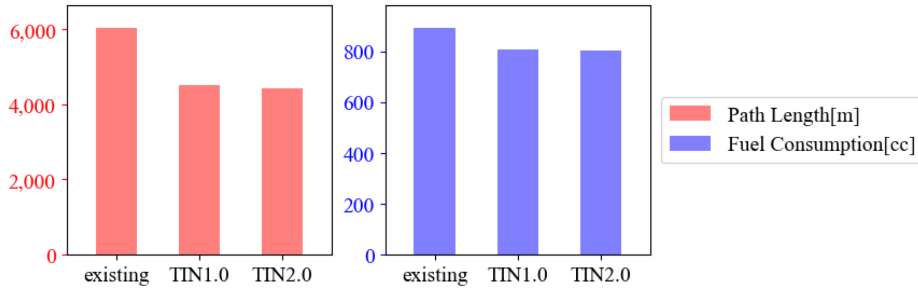

Figure 8a (left), Figure 8b (right). Path lengths and fuel consumptions along the existing road, TIN1.0, and TIN2.0

Table 2. Number of vertices used in the original DEM and two generated TINs.

Model	Number of vertices	Reduction effect (vs. DEM)
DEM	725,958	-
TIN1.0	98,442	86.4%
TIN2.0	51,805	92.9%

Table 3. Reachability between the origin and destination with slope constraints

Model	Edge subdivision	Reachable with slope 12% slope ?	Minimum reachable slope (%)
TIN1.0	No (N=1)	No	13
	N=3	Yes	8
TIN2.0	No (N=1)	No	13
	N=3	Yes	7

Table 4. Comparison of the path length, fuel consumption, and slope for the four TINs

Model	Edge weight	Path length reduction effect (%)	Fuel consumption reduction effect (%)	Maximum slope (%)	Average slope (%)
Extant	-	(0)	(0)	33	6.2
TIN1.0	Shortest	25	8.7	12	8.3
	Fuel-efficient	19	9.2	12	7.6
TIN2.0	Shortest	27	8.0	12	8.5
	Fuel-efficient	22	9.9	12	8.0

Table 5. Comparison of the original optimal and smoothed paths (TIN1.0 fuel-efficient path)

Smoothing	Number of vertices	Path length (m)	Fuel consumption (cc)	Maximum slope (%)	Average slope (%)
(Original)	191	4,902	808	12	7.6
Cubic spline	350	4,917	812	31	7.6

4.4 Further improvements

Based on the results and limitations observed in this study, the following improvements are identified for future research. First, the proposed pathfinding method does not take into account curvature constraints. In practical road designs, a minimum curve radius is mandated since sharp curves negatively impact safety and drivability. The comparison between the generated paths and existing road revealed that the generated routes exhibited excessive bending and winding, resulting in unnatural geometries. Such outlets primarily arose from the absence of curvature constraints. Introducing curvature restrictions into the pathfinding algorithm is therefore crucial to achieve more realistic and practical road designs.

Secondly, the relationship between the horizontal slopes and vehicle speeds requires more rigorous consideration. The current model assumes a constant vehicle speed (35–42km/h), yet in real-world road design, the maximum permissible slopes depend on the vehicle speeds. Future studies should incorporate variable-speed models to allow for more flexible and realistic evaluation.

Furthermore, issues of localized steep slopes emerged following cubic spline smoothing of the generated paths. To address this, integrating slope constraints directly into the smoothing process, or adjusting the selection of segments and the distance between interpolation points, should be considered. This would ensure a smoothing technique that better accounts for safety and realistic driving conditions. In summary, future developments should integrate the curvature constraints, speed variability, and slope control into the path-generation framework.

5. Conclusion

This study addressed path optimization that relies on a TIN generated from DEM data. By subdividing edges of a TIN, the flexibility of pathfinding was enhanced, allowing seeking of more efficient routes. The method integrates the slope constraints based on the road construction regulation and fuel consumption, which is aimed at environment-friendly road design. Furthermore, cubic spline smoothing was applied to render the chosen path smoother and more realistic.

Applying the proposed method to a terrain data of an isolated island close to Tokyo Metropolitan, we generated both shortest-distance and fuel-efficient paths, and compared with an existing road. The results indicated that the shortest-distance paths achieved a reduction of approximately 25-27% in path length, while the fuel-efficient paths reduced fuel consumption by about 9.2-9.9%. Worth noting is that the generated paths observed the 12% maximum slope constraint all the way from the origin to the destination.

Based on these outcomes, all the research objectives established in this study have been successfully achieved. The key contribution includes enhanced flexibility in route exploration, which was achieved by TIN subdivision along with cubic spline smoothing. Incorporating a fuel consumption model that depends on local slope rendered the proposed framework more practical. This study along these lines introduces a novel approach to balance both fuel efficiency and slope safety.

There remain issues to be addressed in future work. Issues such as curvature constraints, variable vehicle speed, and localized slopes raised by cubic spline smoothing, must be taken into account. These will be addressed in future research. While some of them would be challenging, all are essential to establish more comprehensive and practical road planning methodologies.

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