



Terrain-Aware Route Planning and Risk Analysis: A Survey of GIS Least-Cost Path and A* Approaches

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ABSTRACT—

Reaching a destination over rugged ground depends on more than distance: slope, land cover, water, existing roads and restricted areas all shape what is feasible and safe. Terrain-aware routing has been studied in hiking and pedestrian modelling, forest-road and infrastructure corridor design, disaster evacuation and robotic navigation, usually as separate application-specific efforts. This survey organises that literature along a single progression: terrain representation, DEM-derived features, traversability, cost-surface generation, multi-criteria GIS routing, least-cost-path and A*/D* search, alternative-route generation, risk-aware routing and modern 2022–2026 terrain-aware A* and learning methods. From a pool of 30 studies we analyse 10 priority works that cover complementary stages of the pipeline. We compare them, identify a defensible research gap—the limited emphasis on a unified, location-independent framework with heterogeneous layers, user-defined hard constraints and preferences, alternative routes and interpretable comparisons—and position our proposed Terrain-Aware Route Planning and Risk Analysis System as an integration and generalisation of established concepts.

Index Terms—Terrain-Aware Routing, Least-Cost Path, Digital Elevation Model, Traversability, A* Algorithm, Multi-Criteria Evaluation, Risk Analysis, Evacuation Routing, GIS, Literature Review

I. INTRODUCTION

A. Motivation and Background

Search-and-rescue teams, disaster responders, forest crews, mountain logistics planners and hikers all need routes that reflect the ground they must cross. A straight line or a road-network shortest path ignores steep slopes, dense vegetation, rivers and no-go zones, and so can be slow, exhausting or unsafe. Terrain-aware routing addresses this by assigning each location a cost or traversability value and searching for the route that minimises accumulated cost [1], [2].

The idea is well established but fragmented. It appears in GIS least-cost-path (LCP) analysis [2], [13], forest-road and utility corridor planning [3], [5], [6], evacuation modelling [4], [10], [23] and robot navigation [1], [8], [9], largely in separate research communities with their own cost functions and objectives. This survey brings these strands together to clarify what is established and what remains open.

B. Evolution of Terrain-Aware Routing

Phase 1 – Graph-search foundations. Dijkstra’s shortest-path algorithm [32] and A* [33] provide the search machinery still used today; D* [34] extends it to partially known environments.

Phase 2 (2003–2010) – Terrain enters the planner. Howard et al. [1], [11] incorporated terrain difficulty into mobile-robot global planning, while GIS work modelled human movement over DEM-derived slope [2], [12], [15], building on slope-speed relations such as Tobler’s hiking function [35].

Phase 3 (2011–2019) – Multi-criteria GIS routing. Weighted overlay, AHP and environmental criteria were used for roads, power lines and corridors [3], [5], [6], [20], [21]. Anisotropic (direction-dependent) costs appeared for pedestrians [4], [16].

Phase 4 (2020–2026) – Hazards, alternatives and learning. Work expanded to evacuation and hazard-aware routing [10], [24], alternative-route generation [7], and learning-assisted or improved A* planners with richer traversability models [8], [9], [27]–[30].

DEM + elevation, slope, roughness
+ land cover, roads, water, restricted regions
+ user constraints and optimisation preference

DEM + elevation, slope, roughness
Multi-factor cost / traversability map
Hard constraints (masking)
A* / least-cost routing
Best route + alternative routes
Distance, elevation gain, terrain difficulty, risk
Explainable comparison + 2D/3D visualisation

Fig. 1. Conceptual progression of terrain-aware routing used to organise this survey.

C. Scope and Contributions

- **Pipeline-based synthesis:** the literature is organised by pipeline stage rather than summarised paper by paper.
- **Complementary coverage:** 10 priority papers spanning terrain modelling, multi-criteria cost surfaces, alternatives, risk and modern A* (Tables I–II).
- **Defensible research gap:** we do not claim terrain-aware routing is absent from the literature; the gap lies in integration and generality (Section XIII).
- **System positioning:** our system is framed as an integration and generalisation of known concepts (Section XIV). It is not a military system or a vehicle controller.

D. Organization

Section II gives the taxonomy and methodology. Sections III–V cover terrain representation, traversability and multi-criteria cost surfaces. Section VI reviews search algorithms, Section VII application domains, Section VIII alternatives and risk, and Section IX modern methods. Section X compares approaches, Section XI covers evaluation metrics, Section XII failure modes and deployment, Section XIII identifies gaps, Section XIV positions our system, Section XV outlines future work, Section XVI gives recommendations and Section XVII concludes.

II. TAXONOMY AND METHODOLOGY

A. Five-Dimensional Taxonomy

We classify terrain-aware routing studies along five dimensions:

- **Terrain input:** DEM-derived (elevation, slope, flatness), plus optional layers (land cover, roads, hydrology, soil, hazards).
- **Cost model:** isotropic or anisotropic; single-factor or multi-factor; weighted overlay, AHP or learned.
- **Search algorithm:** Dijkstra/LCP accumulation, A*, D*, valley-finding or learning-assisted heuristics.
- **Output:** single optimal route, alternatives, or Pareto-style trade-offs.
- **Application and risk treatment:** pedestrian, infrastructure, disaster or robotic; risk as cost, constraint or reported metric.

B. Survey Methodology

This is a focused narrative review rather than a PRISMA-style systematic review. We began with a pool of 30 studies from GIS, archaeology, forestry, infrastructure planning, disaster management and robotics, and selected 10 priority papers so that together they cover different pipeline stages instead of repeating the same function. One further paper on circuit theory [31] is used for limitations and future work. Recent 2024–2026 studies are retained to show current direction, while older papers are used where they supply foundational concepts.

Because the reviewed studies use different metrics, datasets and study areas, we do not attempt a quantitative meta-analysis or report pooled accuracy figures; comparisons are qualitative and based on the capabilities each study describes.

III. TERRAIN REPRESENTATION AND DEM-DERIVED FEATURES

Most terrain-aware routers represent the world as a raster grid in which each cell stores terrain attributes and connects to its eight neighbours. A Digital Elevation Model (DEM) is the primary source. Howard et al. [1] treated terrain as a map of regions with differing traversal difficulty, establishing the principle that cells should not be treated as equal.

Derived features. Slope is the most common derivative and drives cost in human-movement studies [2], [4], [15]. Rao et al. [5] combine DEM-derived slope with land-use/land-cover for corridors in Himalayan terrain. Robotic studies add flatness and elevation variation as roughness indicators [8].

Resolution and scale. Slope estimates depend on DEM resolution; Pagneux et al. [18] analysed the sensitivity of modelled trails to slope data resolution, and TerraCost [13] addressed computing least-cost surfaces over massive grid terrains. **Critical note:** DEM resolution and smoothing are rarely treated as user-visible parameters, although they directly change computed slopes and routes.

IV. TRAVERSABILITY AND COST-SURFACE GENERATION

Traversability expresses how easily terrain can be crossed. In a raster system it is converted into a cost surface. A common multi-factor form is

$$c(x) = \sum w_k \cdot f_k(x), \quad \sum w_k = 1 \quad (1)$$

where $f_k(x)$ is the normalised cost of factor k (slope, land cover, proximity to water, etc.) at cell x and w_k its weight.

Slope-to-cost mapping. Studies convert slope to cost directly [2], [15] or via speed models such as Tobler's hiking function [35]. Gowen and de Smet [17] compared LCP models using travel time and kilocalorie expenditure, showing that the choice of cost currency changes results.

Anisotropy. Movement is easier downhill than uphill or across a slope. Wood and Schmidtlein [4] model direction-dependent pedestrian cost, and the movecost package [16] provides slope-dependent anisotropic cost surfaces. Isotropic costs are simpler but cannot capture this asymmetry.

Land cover and hard constraints. Land-cover classes are reclassified into cost values [4], [5], [9]. Cells that are impassable (water, steep faces, restricted zones) are better modelled as hard constraints—removed from the search—than as very large costs, a distinction important for user-defined limits such as maximum slope.

V. MULTI-CRITERIA GIS ROUTING

Multi-criteria evaluation (MCE) combines heterogeneous layers into one cost surface. Imani et al. [3] combined slope, hydrology, geology and soil using AHP weighting [36] for forest-road alignment. Rao et al. [5] used weighted overlay of terrain and land-use layers for corridor alignment. Bagli et al. [6] and related transmission-line and pipeline studies [20], [21] combined environmental and technical criteria, and [6] tested sensitivity to different weighting scenarios. Road network planning in tropical forests [22] follows the same pattern.

Critical note: weights are usually set by experts or AHP and are inherently subjective. Few studies expose weights to the end user as adjustable preferences; sensitivity analysis [6] is the main safeguard and should be supported rather than hidden.

VI. ROUTING ALGORITHMS

A. Least-Cost Path

LCP analysis accumulates cost outward from the origin (Dijkstra-style [32]) and traces back from the destination. It underlies GIS studies of mountain routes [2], corridors [5], [12] and evacuation [23], [24]. Extensions address roadway-specific constraints [12] and scalability [13].

B. A* Search

A* [33] guides search with $f(n) = g(n) + h(n)$, where g is accumulated terrain cost and h a heuristic estimate to the goal (2). It returns the same optimal path as Dijkstra when h is admissible but explores fewer cells. Recent work applies A* to terrain cost maps [8], [10], and improves it with geometric and support-passability analysis [9] or construction-site terrain [29]. A practical point: in a weighted grid, a distance-based heuristic must be scaled by the minimum per-cell cost to stay admissible.

C. D* and Other Planners

D* [34] repairs routes as new information appears, and a terrain-based D* variant was proposed in [14]; Zhang et al. [25] plan in partially known uneven terrain. Howey [31] argues that circuit theory complements LCP by modelling multiple possible pathways rather than one optimal line.

VII. APPLICATION DOMAINS

A. Human and Pedestrian Routing

Mountain LCP work [2] and slope studies [15] compare modelled routes to real movement. Pagneux et al. [18], [19] map recreational trails and pedestrian access to the Fagradalsfjall eruptions with LCP, showing the method's value in hazard-adjacent terrain.

B. Infrastructure and Corridor Routing

Forest roads [3], [22], power lines [6], [7], [20], pipelines [21] and Himalayan corridors [5] share a raster-cost-plus-LCP pattern but optimise construction cost and environmental impact rather than traveller safety.

C. Disaster and Evacuation Routing

Wood and Schmidlein [4] assess tsunami evacuation potential with anisotropic pedestrian paths; related studies address volcanic [23] and tsunami [24] hazards. Bula and Sreenivasulu [10] combine DEM, land cover, roads and flood hazards with A*/LCP for coastal Odisha, including dynamic scenarios and detour routes—an Indian example close to our target use.

VIII. ALTERNATIVE ROUTES AND RISK-AWARE ROUTING

A. Alternative-Route Generation

A single optimal path hides near-optimal options and depends heavily on weights. Bagli et al. [6] compare routes under different weighting scenarios; Schito et al. [7] use a valley-finding algorithm to produce distinct alternatives and Pareto-optimal trade-offs for decision support; detour routes appear in [10]; and circuit theory [31] offers a connectivity-based alternative view.

B. Risk-Aware Routing

Risk is handled in three ways: as a cost term (hazard layers in [10]), as a constraint (excluded zones), or as a reported metric. Wood and Schmidlein [4] treat travel time against hazard arrival, and Gai et al. [8] include risk in a multi-objective planner. Human-demonstrated risk costs have also been learned for robots [27]. **Critical note:** risk definitions are domain-specific and seldom reported alongside distance and elevation gain in a comparable form.

IX. MODERN TERRAIN-AWARE A* AND LEARNING APPROACHES

Recent work, mostly in robotics and unmanned ground vehicles, enriches traversability and accelerates search. Mobility prediction supports global UGV planning in off-road environments [26]; learned human-demonstrated risk cost maps improve traversability estimation [27]; semantic segmentation with uncertainty rejection supports terrain-aware planning [28]; NNPP learns a heuristic to accelerate optimal planning on uneven terrain [30]; and improved A* variants serve construction sites [29]. Gai et al. [8] combine slope, flatness and elevation variation with kinematic constraints, balancing path length, risk and smoothness. The 2026 off-road method [9] integrates DEM, land cover and support passability into an improved A*.

Observations. (i) Traversability models are richer than GIS slope-and-land-cover costs. (ii) Learning-based methods often need sensor data or training sets and target a specific platform. (iii) Vehicle kinematics are outside our scope. These methods mark the modern direction but are not directly location-independent route-planning tools for general users.

X. COMPARATIVE ANALYSIS OF EXISTING APPROACHES

Study	Domain	Terrain / layers	Method
[1] 2003	Robotics	Terrain maps, difficulty	Traversability-cost global planning
[2] 2004	Human movement	DEM, slope	Slope cost surface, LCP
[3] 2012	Forest roads	Slope, hydrology, geology, soil	AHP cost map, shortest path
[4] 2012	Evacuation	DEM/slope, land cover	Anisotropic cost, pedestrian paths
[5] 2019	Corridors	DEM, slope, LULC	Weighted overlay, LCP
[6] 2011	Power lines	Environmental criteria	MCE, LCP, alternatives
[7] 2021	Transmission	Cost surfaces	Valley-finding, Pareto
[8] 2026	Ground vehicles	Slope, flatness, elevation variation	A*, multi-objective
[9] 2026	Off-road	DEM, land cover, slope	Improved A*
[10] 2026	Flood evacuation	DEM, land cover, roads, hazards	GIS A*/LCP, dynamic

TABLE I. Priority studies compared by domain, inputs and method.

Study	Terrain	Env. layers	Multi-factor cost	Altern-atives	Risk	Human
[1]	•	–	•	–	●	–
[2]	•	–	●	–	–	•
[3]	•	•	•	–	–	–
[4]	•	•	●	–	•	•
[5]	•	•	•	–	–	–
[6]	●	•	•	•	●	–
[7]	●	–	•	•	–	–
[8]	•	–	•	–	•	–
[9]	•	•	•	–	●	–
[10]	•	•	•	•	•	●

TABLE II. Capability matrix (• covered, ● partial/implicit, – not a stated focus; based on our reading of each study's described scope).

Key findings. (1) Terrain and slope costs are universal. (2) Multi-factor cost surfaces are standard in GIS and infrastructure work. (3) Alternatives appear mainly in corridor [6], [7] and evacuation [10] studies. (4) Risk is treated inconsistently. (5) Only one study [10] combines most capabilities, and it targets a specific region and hazard. No single study combines user-defined hard constraints, adjustable preferences, alternatives and interpretable comparison in a general framework.

XI. EVALUATION METRICS AND VALIDATION

A. Route-Level Metrics

A terrain-aware router should report more than cost. Based on the reviewed studies we identify metrics that make routes comparable:

- **Distance (D):** planimetric or slope-corrected 3D length of the route.
- **Elevation gain (E):** cumulative ascent, a proxy for effort [17].
- **Terrain difficulty (T):** mean or maximum cost along the route, or the share of path on steep or difficult classes [1], [8].
- **Risk (R):** exposure to hazard or hazardous classes, e.g., flood or hazard-zone cells traversed [4], [10].
- **Travel time or energy:** from speed models such as Tobler's [35] or kilocalorie models [17].

B. Algorithm-Level and Validation Metrics

Studies also report computation time and explored cells (relevant to A* heuristics [9], [30]), path smoothness [8], and agreement with real routes. Mountain LCP work [2] compared modelled and actual paths, and recreational-trail studies compare against mapped trails [18], [19]. Where ground truth is unavailable, **sensitivity analysis** under varied weights [6] or DEM resolution [18] is the more defensible alternative to a single reported score.

Recommendation. A general system should report all route-level metrics for every candidate route, not only the optimised quantity, so that users can see what each preference profile gains and sacrifices.

XII. FAILURE MODES AND DEPLOYMENT CONSIDERATIONS

A. Failure Modes

Failure mode	Effect on routes	Mitigation
Coarse or noisy DEM	Misestimated slope; missed cliffs or ravines [18]	Resolution check, smoothing options
Subjective weights	Different routes from different weightings [6]	Preset profiles, sensitivity runs
Isotropic cost	Ignores uphill/downhill asymmetry [4]	Directional cost models [16]

Failure mode	Effect on routes	Mitigation
Outdated layers	Stale land cover, roads, hazards [10]	Layer dating, user updates
Hard-constraint over-restriction	No feasible route	Report binding constraint, suggest relaxation
Single-path output	Hides near-equal options [7], [31]	Alternative generation

TABLE IV. Failure modes of terrain-aware routing and mitigation strategies.

B. Deployment Considerations

Data availability. A location-independent system relies on users supplying a suitable DEM and optional layers; layers must be reprojected to a common grid and resolution, and missing layers should degrade gracefully rather than block routing.

Computation. Raster size affects search time; A* with an admissible heuristic reduces explored cells, and scalability techniques for massive grids [13] become relevant for large regions.

Safety and responsibility. In rescue and disaster settings a computed route is decision support, not a guarantee. Outputs should state data limitations and encourage human review, particularly where risk layers are incomplete.

Usability. Non-expert users benefit from named preference profiles, clear constraint feedback and visual explanations, which are rarely a focus of the studies reviewed here.

XIII. CHALLENGES AND RESEARCH GAPS

Existing research demonstrates terrain-aware route optimisation across several specialised domains, including hiking, forest-road planning, infrastructure corridor design, disaster evacuation, ecological movement and robotic navigation. However, these approaches are generally developed for a specific application and rely on domain-specific cost functions, constraints or route objectives. There is comparatively less emphasis on a unified, location-independent framework that accepts heterogeneous terrain and environmental layers, allows user-defined hard constraints and optimisation preferences, generates alternative routes, and provides interpretable comparisons of route distance, elevation, terrain difficulty and risk.

Specific open challenges include:

- **Generality:** cost functions are tuned per application and region.
- **User control:** weights and constraints are fixed by the analyst, not the end user.
- **Explainability:** few studies explain why a route was selected over alternatives.
- **Validation:** ground truth (GPS traces, expert routes) is limited and study-specific [2].
- **Data quality:** DEM resolution sensitivity [18] and subjective weighting [3], [6].
- **Model limits:** isotropic costs ignore direction [4]; single paths ignore multiple pathways [31].

XIV. POSITIONING OF THE PROPOSED SYSTEM

The proposed Terrain-Aware Route Planning and Risk Analysis System integrates established concepts into one location-independent pipeline (Fig. 1). The user supplies a DEM; the system derives elevation and slope, optionally integrates land cover/forest, roads, water and restricted regions, and converts them into a weighted cost/traversability map (Section IV). User-defined hard constraints, such as maximum slope or no-go regions, mask cells before search (Section IV). A*/least-cost routing then generates a recommended route (Section VI).

Preferences. Optimisation preferences map to weight profiles in the objective $J = \alpha D + \beta E + \gamma T + \delta R$ (3), where D is distance, E elevation gain, T terrain difficulty and R risk (Table III). The values shown are illustrative starting points to be tuned, not validated results.

Profile	Emphasis	Typical use
Shortest	High α	Quick access
Safest	High γ, δ	Rescue, evacuation
Lowest gain	High β	Load carrying, hiking
Balanced	Even weights	General planning

TABLE III. Planned preference profiles.

Alternatives and explanation. Alternative routes are generated by re-running the search under different profiles or penalising the recommended path, following [6], [7]. The system reports distance, elevation gain, terrain difficulty and risk for each, and uses 2D/3D visualisation and per-route explanations (e.g., which layers or constraints drove the selection).

Design Mapping and Formulation

Pipeline stage	Grounded in	Planned implementation
DEM features	[1], [2], [8]	Elevation, slope, roughness from user DEM
Cost surface	[3], [5], [6]	Weighted overlay of normalised layers, Eq. (1)
Hard constraints	[2], [4]	Max-slope and restricted-zone masks (infinite cost)
Search	[8]-[10], [33]	A* on 8-connected grid, scaled heuristic
Alternatives	[6], [7], [10]	Multi-profile runs, path penalisation
Risk / difficulty	[4], [8], [10]	Per-route aggregation of cell costs
Explanation	This work	Layer-wise cost breakdown, 2D/3D view

TABLE V. Mapping of surveyed concepts to the proposed system.

For a cell pair (i, j), the step cost is the mean of the two cell costs scaled by step length and a slope-length correction, and cells violating a hard constraint receive infinite cost:

$$c(i,j) = \frac{1}{2} (c_i + c_j) \cdot L_{ij} / \cos \theta_{ij}; \quad c = \infty \text{ if slope} > s_{\text{max}} \text{ or cell} \in R \quad (4)$$

A* then minimises $f(n) = g(n) + h(n)$ with $h(n) = c_{\text{min}} \cdot d(n, \text{goal})$, where c_{min} is the smallest per-unit cost in the grid so that h remains admissible. The planned procedure is: (1) load and align layers; (2) derive terrain features; (3) build the cost surface; (4) apply constraints; (5) search for the preferred route; (6) generate alternatives under other profiles or penalised cells; (7) compute D, E, T and R per route; (8) render and explain the results. If no feasible route exists, the system reports which constraint blocks the search instead of failing silently.

Scope. The system targets search and rescue, disaster response, mountain logistics, forest operations and hiking. It is not a military system, autonomous vehicle controller or vehicle-control system. Its contribution is **integration and generalisation** of known ideas, not the invention of terrain-aware routing. Current limitations include symmetric (isotropic) costs and static layers.

XV. FUTURE RESEARCH DIRECTIONS

- **Anisotropic costs** using slope-direction-dependent models [4], [16].
- **Multiple pathways** via circuit theory or Pareto methods [7], [31].
- **Dynamic hazards** with D*-style replanning [14], [34] and scenarios as in [10].
- **Learning-assisted heuristics and traversability** [27], [30], where data allow.
- **Sensitivity and uncertainty analysis** for weights and DEM resolution [6], [18].
- **Validation** against GPS traces, expert routes and user studies with responders.

XVI. BEST PRACTICES AND RECOMMENDATIONS

For researchers:

- Report distance, elevation gain, terrain difficulty and risk together, and state the DEM resolution used.
- Publish cost-function parameters and weights, and include sensitivity analysis [6].
- Validate against real routes or expert judgement where possible [2], [18].

For practitioners and system builders:

- Treat impassable terrain as hard constraints and everything else as weighted cost.
- Offer preference profiles with adjustable weights, and generate alternatives rather than a single route [7].
- Explain each recommendation by naming the layers and constraints that influenced it.

- Keep human review in the loop for rescue and disaster use.

XVII. CONCLUSION

Terrain-aware routing is mature within specialised domains: DEM-derived slope, land-cover costs, multi-criteria weighting, least-cost and A* search, alternatives and hazard-aware routing are all demonstrated. Recent 2024–2026 work adds richer traversability and learning, mainly for robots. What is less emphasised is a unified, location-independent framework combining heterogeneous layers, user-defined hard constraints and preferences, alternative routes and interpretable comparison of distance, elevation, difficulty and risk. Our proposed system addresses this by integrating and generalising established concepts, and its next step is empirical validation.

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