A Systematic Framework for Risk-Aware UAV Cargo Corridor Design

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Short summary

The large-scale deployment of UAV-based cargo delivery in urban environments is constrained by safety concerns, limited airspace availability, and complex regulatory requirements. While prior research has explored airspace structuring and risk-based routing independently, an integrated and operationally viable framework for UAV corridor planning remains lacking. This paper proposes a comprehensive, risk-aware framework for the design of fixed UAV cargo corridors in highly constrained airspace environments. The framework integrates regulatory compliance, spatial feasibility, and operational efficiency within a unified corridor-level planning methodology. UAV corridors are modelled as graph-based networks aligned with linear infrastructure and natural corridors, while considering varying ground risk. The framework is evaluated through multiple experimental case studies within the Dutch airspace. Results demonstrate that fixed UAV corridors can be feasibly designed under existing regulatory constraints, achieving substantial reductions in third-party risk with limited efficiency loss.
Keywords: AV cargo delivery; airspace design; risk-aware routing; UAV corridors

1 Introduction

Unmanned Aerial Vehicles (UAVs), widely known as drones, have emerged as a promising technology to contribute to last-mile delivery. UAVs are gaining traction in logistics for their ability to reduce costs, increase delivery speed and precision, and operate independently of ground-based congestion (Politi et al., 2021). The integration of UAVs into national airspace systems requires navigating a complex web of spatial, regulatory, and operational constraints that are particularly pronounced in densely populated countries like the Netherlands. The European regulatory framework provides essential safety standards through the U-space concept, which defines digital traffic management services to enable safe and scalable UAV operations, particularly in dense urban areas (EASA, 2020; Single European Sky ATM Research 3 Joint Undertaking, 2017). Current regulations prohibit UAV flights over highly populated areas, critical infrastructure, and numerous other sensitive locations, effectively eliminating direct point-to-point delivery for freight transport in most urban contexts. In this context, a critical gap persists: regulations specify safety standards but not how to design networks that are simultaneously safe, operationally efficient, and spatially feasible.

The central challenge is thus one of spatial design and optimisation. UAV corridors must navigate the complex constraints of airspaces while remaining economically competitive with ground-based delivery, requiring a careful balance between risk mitigation and efficiency. Avoiding populated areas increases safety but often results in longer routes with substantial altitude variation, reducing operational viability. Current approaches fail to integrate the full spectrum of these requirements within a single implementable model. While existing literature addresses individual aspects such as conceptual airspace structures, risk-based routing, or regulatory compliance, it does not combine these into an integrated framework suitable for deployment in highly constrained environments. This study addresses this gap by developing and validating a comprehensive framework for risk-aware UAV corridor planning that integrates regulatory requirements, spatial constraints, and operational considerations to support practical implementation. To the best of the authors' knowledge, this study is the first comprehensive framework that simultaneously addresses regulatory compliance, spatial feasibility, and operational viability for UAV corridor planning in highly constrained airspace environments.

2 Methodology

This section develops the spatial design methodology for constructing UAV freight corridors. First, we argue which structure is most suitable for UAV airspace design. Second, we describe the approach taken to represent an airspace as a graph. Third, we describe the semi-quantitative risk assessment framework used to assign risk values to geographic areas. Fourth, we present the corridor planning framework, which is applied to the constructed graph by assigning risk values to arcs based on their corresponding geographic areas. Due to space limitations, we provide only a high-level description here; the complete algorithm and implementation details are included in the full version.

UAV airspace structuring

Sunil et al. (2015) introduced four conceptual designs for UAV airspace structuring, ranging from unstructured free-flight configurations to fully structured networks based on fixed routes:

- *Full mix*: An unstructured airspace design, where traffic is only subject to physical constraints such as weather, obstacles, and terrain. UAVs follow direct point-to-point routes, optimizing for fuel or battery efficiency.
- *Layers*: In this concept, airspace is segmented into vertically stacked bands, each assigned to a range of horizontal headings. While horizontal routing remains flexible, the vertical position is constrained by heading direction, promoting traffic alignment and segmentation.
- *Zones*: In this approach, traffic is segmented based on similarities in driving direction. However, unlike the layer concept, the zone concept also takes into account the layout of the city when designing the structure. Here, two main types of zones are used: circular and radial zones. Both types of zones segment the airspace in the horizontal plane.
- *Tubes*: The final concept of tubes proposes a maximally structured design for fixed routes in airspace. This design makes use of graph theory (Rodrigue et al., 2016), with nodes as connection points for one or more routes, and edges connecting the two nodes as tubes. The tubes never intersect horizontally beyond the nodes and are sized to allow a UAV to fly.

Their analysis indicates that some degree of structuring is necessary to maintain safety at scale, as unstructured designs lead to excessive separation violations. However, overly rigid designs, such as tube-based networks, significantly reduce capacity and operational flexibility. For unconstrained airspace, layered configurations were found to provide the most effective balance between safety and efficiency. Various other studies later evaluated these airspace designs (Zhang et al., 2023; Doole, 2022; Bauranov & Rakas, 2021), all suggesting that structured airspace designs improve safety but introduce trade-offs with operational efficiency.

Graph-based network representation

To model the spatial structure of these corridors, a graph-based representation was constructed based on geospatial data. Once the geographic data have been retrieved from OSMnx and preprocessed for analysis, the construction of a graph-based network representing all feasible UAV routes within the study area can be initiated. The graph construction process consists of several key steps. Nodes are initialized as origins and destinations of freight requests. Then, edges are constructed for all linear infrastructure in the OSM dataset (e.g., roads, waterways). Connector nodes are constructed where necessary. All polygon-based areas suitable for UAV routing are integrated into the corridor network. These areas, which include open land-use zones and other spatially contiguous regions defined in the GeoDataFrame, are modelled differently from linear infrastructure by employing grid-based internal structures combined with sampled boundaries. Edges and connector nodes are constructed throughout the grid. Strict no-fly zones are then removed from the graph to ensure compliance with airspace restrictions.

The resulting network captures all feasible paths along both linear infrastructures and polygon-based natural corridors, providing a spatially consistent basis for subsequent routing, risk assessment, and corridor evaluation.

Risk assessment framework

Having established the spatial design and graph-based structure of the UAV corridor network, this section focuses on the integration of third-party ground risks into the corridor planning framework. To differentiate between corridors based on safety and societal risk exposure, we deploy an SQRA framework. SQRA offers the structured reasoning of qualitative assessments with the comparability and transparency of numerical scoring systems. In this study, the following three steps are applied, based on the SQRA framework of Majka (2024):

1. **Risk Identification:** Identify potential hazards or risk factors using expert input, brainstorming sessions, and historical incident data.
2. **Risk Analysis:** Evaluate each identified risk by assessing its likelihood and potential consequences. Use predefined qualitative categories and assign a corresponding numerical score to each (typically on a 1–5 scale).
3. **Risk Rating Calculation:** Calculate the risk rating for each hazard by multiplying its likelihood and consequence scores. Use a risk matrix to classify the overall risk level (e.g., low, medium, high).

The focus of this study is therefore on five spatially-defined external risk factors, adapted from the comprehensive hazard identification conducted by Allouch et al. (2019): Obstacles, interference, communication, navigational environment, and electrical environment. Each identified external risk factor is evaluated along two dimensions: likelihood of occurrence and severity of consequences.

To assess the likelihood of different external risk factors, each area type is assigned a likelihood score reflecting the estimated frequency of occurrence. In order to enhance objectivity and consistency, a standardized scoring procedure is applied. This structured approach ensures that likelihood estimations remain transparent, replicable, and systematically grounded in the spatial characteristics of each corridor segment.

Severity is assessed in terms of the potential consequences for human safety and the surrounding environment. To ensure consistency with the UAV safety literature, this study adopts the three most commonly applied consequence domains in third-party risk models: fatality risk, property damage risk, and societal impact. This structure mirrors the widely used frameworks proposed by Pang et al. (2021), Zhou et al. (2024), and Tang et al. (2023), each of which operationalizes these dimensions in grid-based or area-specific risk models.

The total risk per corridor segment is computed by combining severity and likelihood scores through weighted aggregation. Importantly, severity scores are assigned at the area level, independent of individual external risk factors. This reflects the assumption that the severity of a UAV crash or presence is primarily driven by the characteristics of the area itself, rather than by the specific external hazard that triggers the event. For example, a UAV crash over a densely populated residential street will consistently yield more severe consequences than a crash over an open field, regardless of whether the failure was caused by obstacles, interference, or navigation errors.

Corridor planning framework

To find the optimal UAV corridors between pickup and delivery points, Dijkstra's algorithm is applied to the weighted network graph. Dijkstra's algorithm computes the shortest path by minimizing a cumulative cost across the network. Instead of minimizing distance alone, each edge in the network is assigned a composite cost that integrates both third-party safety risk and energy consumption. First, the cost of each edge is calculated based on the risk-energy trade-off parameter α, after which the optimal route is identified using Dijkstra's algorithm on the resulting weighted graph.
The cost c_{uv} for a given edge (u, v) is defined as:

$$c_{uv} = \alpha \cdot (r_{uv} \cdot \ell_{uv}) + (1 - \alpha) \cdot \left(e_{uv}^{\text{hor}} + e_{uv}^{\text{vert}}\right)$$

where:

- $\alpha \in [0, 1]$ is a weighting factor that balances safety versus energy efficiency;
- r_{uv} is the risk score associated with the edge;

- ℓ_{uv} is the horizontal length of the edge in meters;
- $e_{uv}^{\text{hor}} = \ell_{uv} \cdot \varepsilon$, with $\varepsilon = 0.025$ Wh/m representing the horizontal energy cost;
- e_{uv}^{vert} is a fixed vertical energy penalty depending on ascent or descent.

3 Results

The use cases involve parcel delivery from PostNL distribution centres (origins) to designated PostNL pick-up points (destinations). To capture variation in geography, infrastructure, and ground-based risk exposure, three representative regions were selected: one urban (Breda), one rural (Borsele), and one suburban (Alphen aan den Rijn and Waddinxveen). The suburban case is of particular interest, as it includes two distribution centres within operational range. This configuration enables an assessment of how corridor behaviour changes when multiple origin points are available.

Efficiency-oriented versus risk-averse design

For each region, a range of α values is tested in the single-objective optimization function, where α governs the trade-off between risk aversion and route efficiency. This enables an evaluation of how corridor designs vary depending on whether operational efficiency ($\alpha = 0$) or risk minimization ($\alpha = 1$) is prioritized, and whether the framework can generate both efficient and risk-averse routes across diverse geographic contexts.

All three regions experience substantial risk reductions between $\alpha = 0$ and $\alpha = 0.1$, with diminishing returns thereafter. This finding indicates that significant risk mitigation can be achieved with only modest sacrifices in operational efficiency. The relative impact varies across contexts, with Alphen–Waddinxveen achieving the largest reduction (77%), while Breda (71%) and Borsele (70%) demonstrate similar patterns. These results suggest that the proposed framework can successfully generate low-risk yet reasonably efficient corridor networks across all tested geographic contexts.

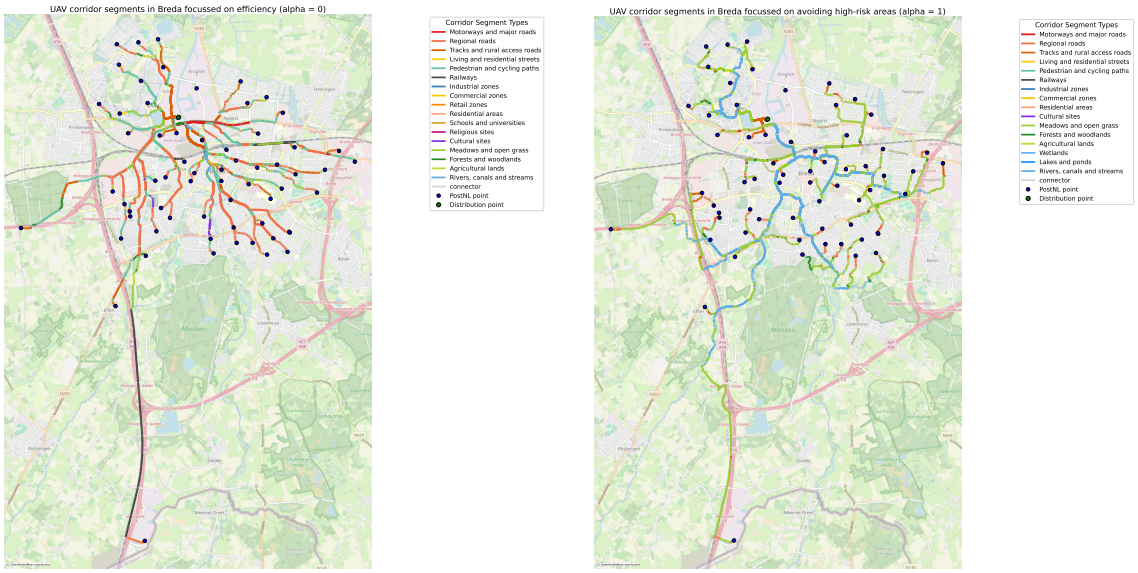
The topological differences between efficiency-based networks (Figures 1a, 2a, and 3a) and risk-averse configurations (Figures 1b, 2b, and 3b) clearly illustrate how risk considerations fundamentally reshape corridor structures. Efficiency-based path planning generates predominantly direct trajectories between origin and destination points, prioritizing minimal distance and energy consumption. In contrast, risk-averse routing produces notably circuitous paths characterized by systematic deviations around high-risk zones, accepting increased path length as a trade-off for enhanced ground safety.

Effect of risk on infrastructure utilization

To further quantify this effect, we consider the utilization of different infrastructure types under varying values of risk. Each geographic context exhibits characteristic infrastructure preferences under risk-averse planning, particularly evident in the transition from $\alpha = 0$ to $\alpha = 0.1$. Nevertheless, substantial differences are observed between urban, suburban, and rural areas, given the different underlying infrastructures in those areas.

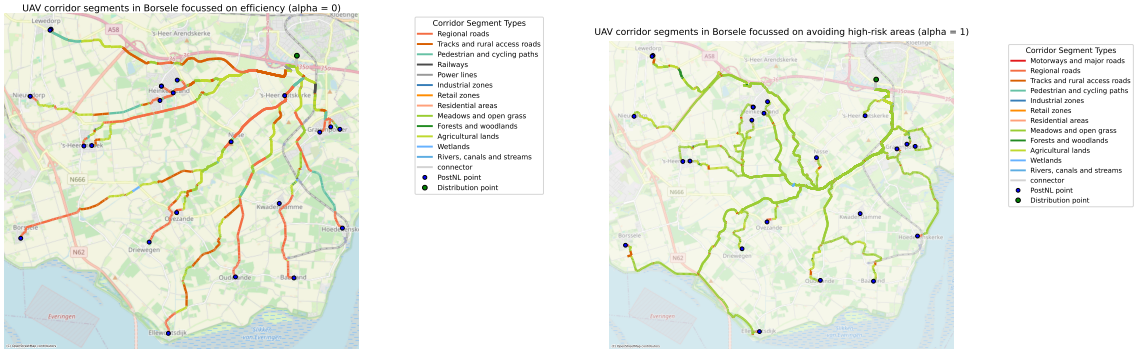
Figure 4 demonstrates that efficiency-based planning in urban areas (Breda) heavily utilizes pedestrian/cycling paths and regional roads. The introduction of risk considerations triggers a dramatic modal shift toward the city's extensive waterway network and open green spaces, achieving substantial risk reduction through systematic infrastructure substitution. Tracks and rural roads maintain consistent utilization across both planning paradigms, suggesting their balanced risk-efficiency profiles in the urban context.

Figure 5 reveals that risk-averse planning in rural environments (Borsele) relies predominantly on agricultural corridors and open grasslands, systematically avoiding regional roads and pedestrian/cycling infrastructure that feature prominently in efficiency-based routing. While aggregate statistics indicate minimal railway and motorway usage even under $\alpha = 0$, their strategic exclusion from risk-averse routes significantly impacts network topology at the individual path level, as evidenced by the structural differences between Figures 2a and 2b.



(a) Efficiency-focused planning ($\alpha = 0$) (b) Risk-averse planning ($\alpha = 1$)

Figure 1: Comparison of corridor networks in Breda under efficiency-oriented and risk-averse planning.



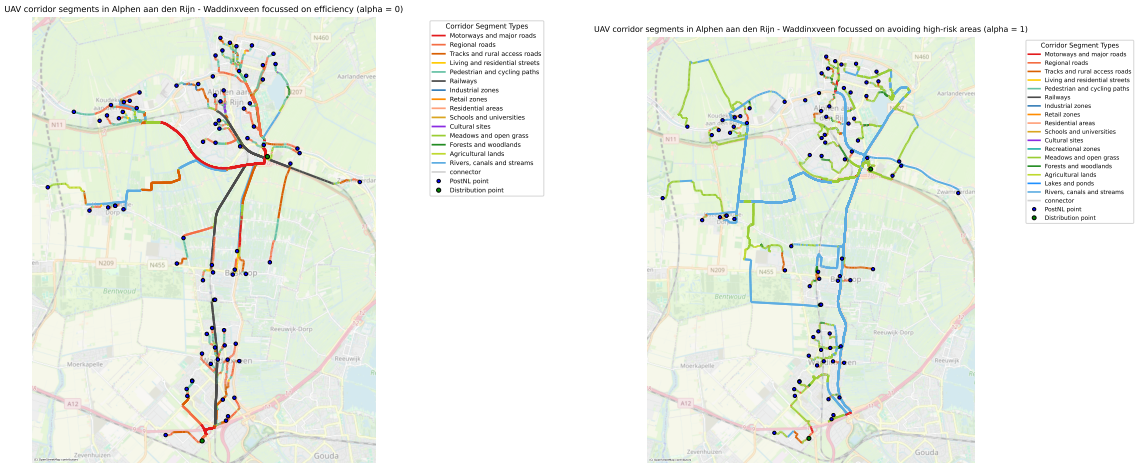
(a) Efficiency-focused planning ($\alpha = 0$) (b) Risk-averse planning ($\alpha = 1$)

Figure 2: Comparison of corridor networks in Borsele under efficiency-oriented and risk-averse planning.

Figure 6 illustrates a pronounced reduction in high-risk corridor utilization, encompassing motorways, major roads, pedestrian/cycling paths, railways, regional roads, and residential streets. The suburban context of Alphen-Waddinxveen compensates for these restrictions by leveraging natural and semi-natural infrastructure, including meadows, open grasslands, waterway networks (rivers, canals, and streams), and forested areas. This substitution pattern demonstrates how suburban environments can exploit their heterogeneous land-use characteristics to maintain network connectivity while minimizing ground risk exposure.

Pareto analysis of risk-efficiency trade-offs

The primary objective of the proposed framework is to determine whether fixed UAV corridors are feasibly designed within the spatial, operational and regulatory constraints of Dutch airspace, while balancing ground risk and energy efficiency. Central to this objective is the identification of acceptable trade-offs between risk reduction and efficiency loss, using a weighting parameter α. Although the framework implements a single-objective optimization using a weighted sum of risk and energy, the set of solutions obtained with different α values can be interpreted as an empirical approximation of a Pareto frontier. Although this set is not strictly Pareto optimal in the multi-objective sense, it illustrates how risk and energy interact for different policy priorities. The resulting trade-off curves for the three case study regions are shown in Figure 7.



(a) Efficiency-focused planning ($\alpha = 0$)

(b) Risk-averse planning ($\alpha = 1$)

Figure 3: Comparison of corridor networks in Alphen aan den Rijn and Waddinxveen under efficiency-oriented and risk-averse planning.

In all cases, the curves show a clear "hockey-stick" pattern: significant risk reductions can be achieved with relatively modest increases in energy consumption at low values of the α, while decreasing returns occur at higher levels of the α. For example, in the urban case of Breda, average risk reduces with 71% between $\alpha = 0.0$ and $\alpha = 0.1$, while energy consumption rises modestly from 114 Wh to 130 Wh (14%). This shows that a relatively small concession in efficiency yields significant safety gains. Beyond $\alpha = 0.3$, however, further increases in α produce only marginal improvements: risk decreases by merely 5.0% from $\alpha = 0.3$ to $\alpha = 1.0$.

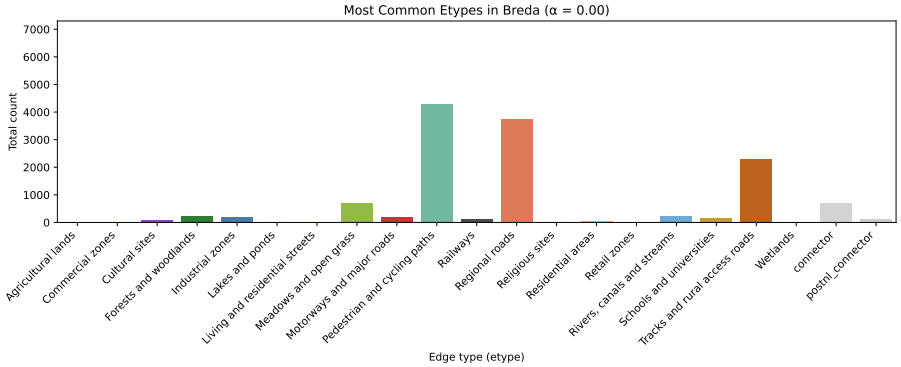
A comparable dynamic is observed in Alphen–Waddinxveen, where risk decreases with 77% between $\alpha = 0.0$ and $\alpha = 0.1$, with energy rising only 10.5%. From $\alpha = 0.4$ to $\alpha = 1.0$, the additional risk reduction amounts to only 8.1%, confirming the presence of diminishing returns. Finally, the rural case of Borsele shows a similar pattern. Here, risk decreases from approximately 70% as α increases from 0.0 to 0.1, while energy consumption rises with 9%. Between $\alpha = 0.5$ and $\alpha = 1.0$, risk declines by only 7.3%, despite a further energy increase of over 50 Wh (18% increase).

These findings confirm that the trade-off structure is consistent in urban, suburban and rural contexts, although the inflection points at which diminishing capital gains occur vary slightly. In the urban context of Breda, a value around $\alpha = 0.10$ seems to offer an efficient compromise. In suburban or rural areas, slightly higher values, closer to $\alpha = 0.20$, may be more appropriate (Figure 7). Ultimately, the preferred option remains a policy decision that reflects the acceptable balance between risk exposure and operational efficiency in a given deployment scenario.

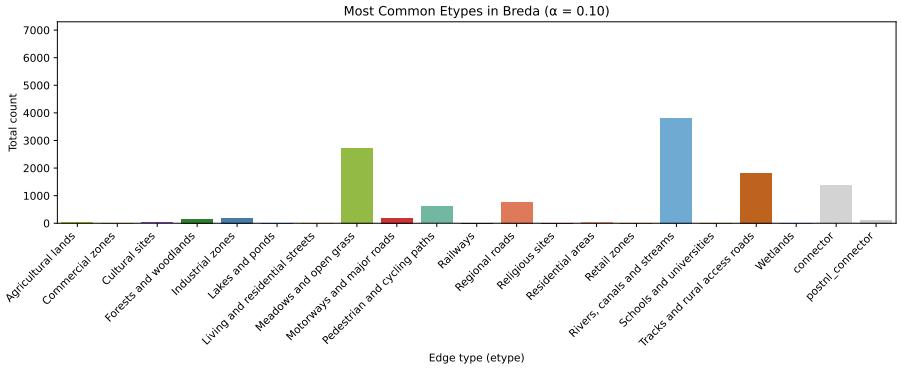
4 Conclusions

This paper presents a comprehensive methodological framework for the design of risk-aware UAV cargo corridors in highly constrained airspace environments. The results demonstrate that fixed UAV freight corridors can be feasibly designed within the constraints of Dutch airspace while effectively balancing ground risk and energy efficiency. Experimental validation across urban, suburban, and rural contexts confirms the practical viability of the proposed approach, with balance points around $\alpha = 0.10$-0.20 achieving risk reductions of approximately 70-80% at the cost of only 15-20% efficiency loss.

The framework provides a robust foundation for risk-integrated UAV planning. Its modular design supports iterative refinement as empirical evidence accumulates, facilitating the transition from theoretical assessments to evidence-based corridor design. Future work is necessary for validation of the framework using incident databases or operational data to replace assumptions with observed likelihoods.



(a) $\alpha = 0.00$



(b) $\alpha = 0.10$

Figure 4: Corridor segment usage by edge type in Breda for $\alpha = 0.00 - 0.10$

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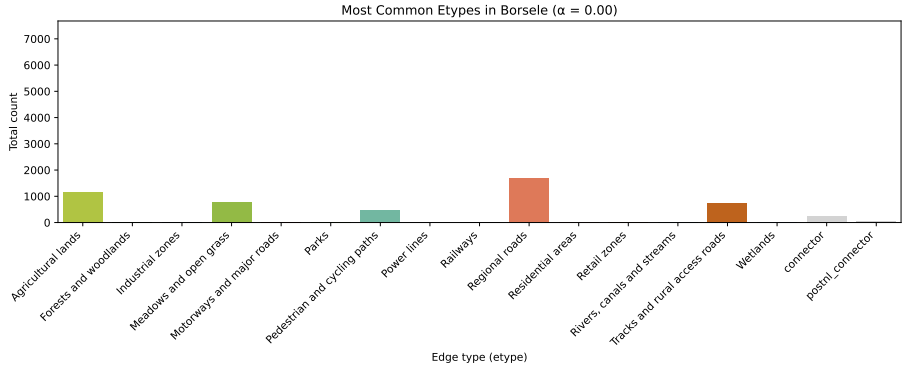
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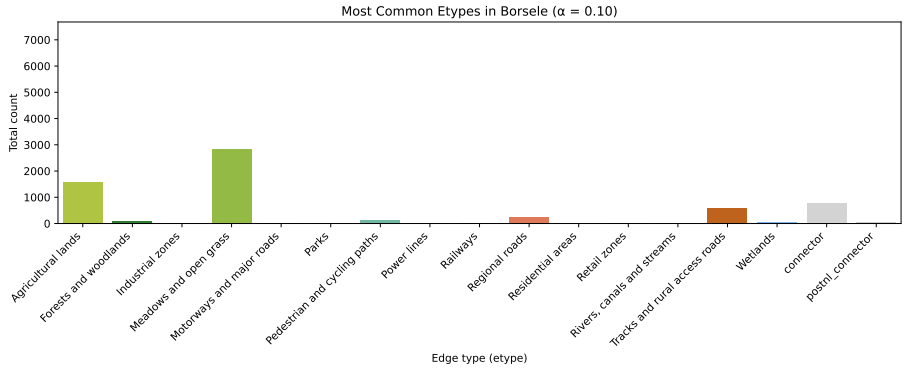
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(a) $\alpha = 0.00$



(b) $\alpha = 0.10$

Figure 5: Corridor segment usage by edge type in Borsele for $\alpha = 0.00 - 0.10$

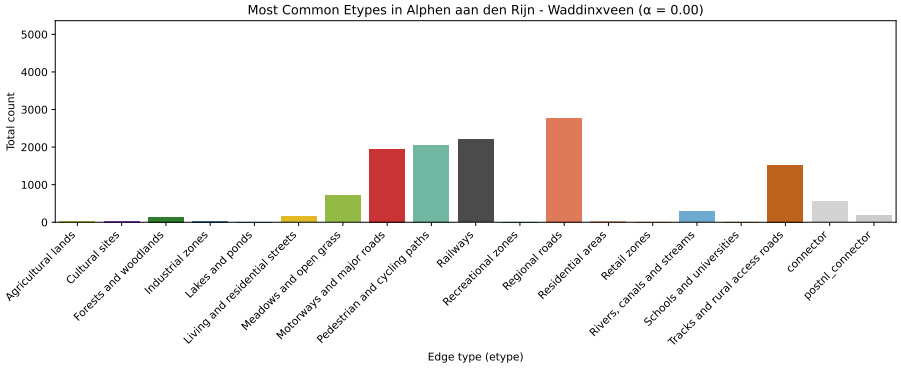
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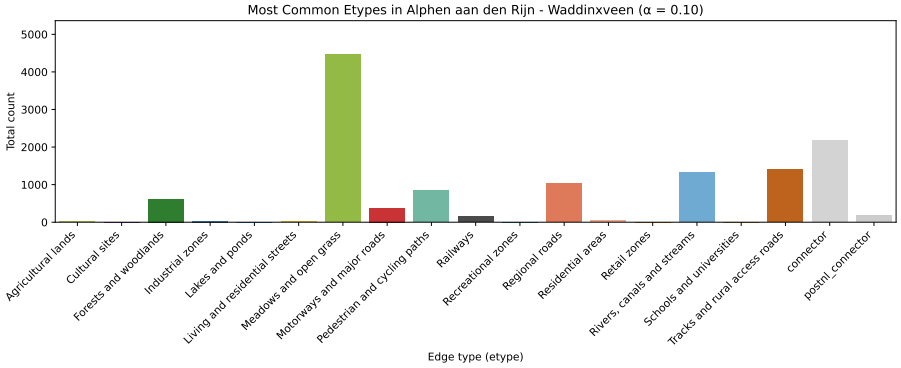
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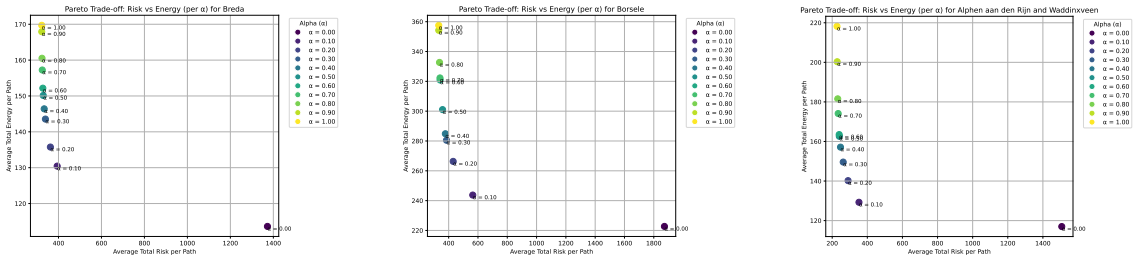


(a) $\alpha = 0.00$



(b) $\alpha = 0.10$

Figure 6: Corridor segment usage by edge type in Alphen aan den Rijn and Waddinxveen for $\alpha = 0.00 - 0.10$



(a) Breda (b) Borsele (c) Alphen-Waddinxveen

Figure 7: Pareto fronts showing trade-offs between energy consumption and risk across the three study areas