Designing Autonomous Aerial Cable Car Networks for Sustainable Urban Logistics

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Abstract

This paper investigates the emerging autonomous aerial cableway technology to reduce the negative impacts of urban freight transportation. We focus on the infrastructure design problem to minimize the road-transportation externalities, taking pricing, investment costs, and the physical footprint into account. The network design problem is formulated as a mixed-integer linear programming (MILP) model that explicitly incorporates user participation constraints, ensuring that the resulting infrastructure configurations are consistent with the adoption behavior of freight service users. The proposed framework is evaluated through a case study conducted in the Historic Peninsula of Istanbul, one of the world's most prominent historic and touristic urban regions. To realistically capture user adoption behavior, we conduct a stated-preference experiment with more than 200 store owners operating in the study area and estimate a utility-based adoption model that reflects their sensitivity to service attributes and pricing. Our results demonstrate that the proposed aerial cableway system can substantially reduce the environmental and operational costs associated with conventional road-based freight transportation while maintaining economically viable operations. In particular, the findings show that the network design and its environmental performance are highly robust to pricing, remaining stable across a tenfold range of service fees (1–10 TRY/kg), and that public subsidies yield negligible additional benefit once a cost-reflective price is in place. Emission reductions of up to 80% can be achieved without external subsidies, requiring only modest service fees from participating businesses. Full decarbonisation of ground freight transfers remains feasible within the same moderate price range, though it becomes infeasible when prices exceed a critical threshold, highlighting the importance of careful tariff design. The study highlights the potential of autonomous aerial freight systems as a financially self-sustaining and environmentally effective logistics alternative for dense urban environments facing congestion and infrastructure limitations.

Keywords: Aerial cableway systems, Sustainable last-mile delivery, Fixed-charge network design, Hub networks, Discrete choice experiment

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1. Introduction

The continued concentration of economic activity in congested metropolitan regions has rendered urban freight operations among the most complex and resource-intensive elements of supply chains. The pressure becomes particularly pronounced in dense city centers, where scarce infrastructure must simultaneously serve passenger movements, commercial functions, and goods distribution.

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These challenges are particularly acute in historic downtown areas, which are typically characterized by narrow streets with limited vehicle accessibility, insufficient loading and unloading areas, and pedestrian-priority zones (Navarro et al., 2016). At the same time, such districts host highly active economic environments, including restaurants, cafés, boutique hotels, souvenir shops, artisan retailers, and local cuisine establishments that depend on the frequent and reliable movement of goods. Many of these businesses operate with limited storage capacity (due to scarce and expensive space) and require regular replenishment, while some additionally engage in e-commerce, generating both inbound and outbound freight flows. In these complex environments with the coexistence of intense commercial activity and severe spatial limitations, freight operations must take place within infrastructure originally designed for pedestrian-scale circulation. As a result, conventional ground-based delivery vehicles face significant operational difficulties while also causing substantial disruptions to pedestrian flows and visitor activity due to constrained street space, often under tight time windows and regulatory restrictions. In such districts, which also serve as major tourist destinations, the concentration of freight movements amplifies congestion, noise, visual intrusion, and emissions. These impacts not only affect local residents but also directly compromise the visitor experience and the cultural and aesthetic value of historically sensitive environments.

Addressing the growing tension between essential freight demand and limited ground-level capacity may require more than restrictive regulatory adjustments. The development of new public infrastructure has been identified as a critical measure to mitigate the negative impacts associated with urban freight transport (Wolpert and Reuter, 2012). In this context, we propose the adoption of an emerging aerial cableway transport technology as an alternative freight mode for historic and touristic urban areas that are currently dependent almost exclusively on road-based distribution for store replenishment and order fulfillment.

Aerial cableway systems offer several intrinsic advantages, including environmental sustainability, minimal land occupation, and high adaptability within dense urban fabrics (Lagerev and Lagerev, 2023). Unlike ground-based systems, aerial transport operates in a spatial layer that remains largely underutilized in cities. By partially decoupling freight movements from congested street networks, such systems can reduce dependence on road transport and contribute to pedestrianization and traffic calming in sensitive areas.

While aerial cableways are traditionally associated with tourism, winter sports, or mountainous geographies, they are increasingly being considered as viable public transit options in urban settings (Cardona-Urrea et al., 2023). Notable examples include the integration of cable cars into the public transport networks, where they serve as daily commuting infrastructure (Heinrichs and Bernet, 2014; Matsuyuki et al., 2020). More recently, aerial systems have been explored for combined passenger and freight applications in alpine tourist regions (Pernkopf and Gronalt, 2021).

Conventional cableway systems, however, rely on continuously moving cables to which cabins are permanently attached. This configuration restricts operations to fixed linear routes between predefined terminals, offering limited routing flexibility and service coverage. In contrast, our study considers a technological innovation in which cables remain stationary while cabins are equipped with electric motors that enable autonomous movement along a cable grid. This design allows vehicles to operate independently and flexibly across interconnected routes. The concept, introduced under systems such as Halfgrid and further developed by companies like Whoosh (Rees et al., 2022; Booth, 2024), has been featured by the World Economic Forum as a potentially game-changing technology, signaling its transformative potential for the future of urban logistics (World Economic Forum, 2024).

Distinct from existing studies that primarily focus on passenger mobility, we investigate the application of autonomous aerial cable systems specifically for urban freight transport. In many historic districts, mobility within the core is already largely pedestrianized, and policy objectives aim to preserve and enhance this human-centered environment. The challenge, therefore, is not to introduce additional passenger capacity, but to enable essential goods movements without disrupting pedestrian flows. Moreover, compared to passenger-oriented aerial systems, which require larger cabins, stricter safety redundancies, and more substantial structural components, freight-dedicated cabins can be designed to transport small loads (e.g., parcels and replenishment goods up to 20–30 kg) and operate with significantly lighter infrastructure. This reduces construction complexity, physical footprint, visual intrusion, and cost, thereby increasing the attractiveness of the system.

1.1. Design problem

Designing an aerial freight network for dense urban areas involves several intertwined challenges. First, the system must be economically viable and, ideally, capable of sustaining its operational and capital costs without continuous public subsidies. Second, adoption by local businesses cannot be taken for granted. Retailers and service providers will compare the proposed system with existing delivery modes based on cost, reliability, flexibility, and contribution to the attractiveness of their districts for visitors. For the system to be appealing, it must offer competitive operational performance, not increase transportation costs (ideally reduce them), and contribute to improved urban quality, including lower emissions, reduced traffic, and less noise, which are particularly valued in touristic districts. Third, the physical presence of the infrastructure must remain proportionate to its benefits. Even though aerial systems operate above ground level, towers, stations, and cable alignments introduce visual and spatial elements into protected urban landscapes. The network design must therefore minimize physical footprint and visual intrusion, avoiding them altogether in certain locations, while ensuring operational efficiency and coverage.

To operationalize this concept, we envision a network composed of the following elements:

- *Access points:* Located within the service region, these nodes enable local businesses to send and receive freight through the aerial network. They are positioned sufficiently close to the businesses they serve, allowing goods to be transferred using lightweight equipment for the final segment, such as hand carts, pallet jacks, or small electric trolleys, thereby avoiding the need for conventional, motorized delivery vehicles.

- *Main entry and exit terminals:* Positioned at the boundaries of the service region, these terminals act as transfer hubs where inbound and outbound freight is exchanged between the aerial system and external logistics operations, such as conventional delivery trucks or consolidation centers.

- *Junction points:* These are intermediate support structures required to sustain and route the cable infrastructure between nodes. Their placement determines the feasible layout of the network and directly affects construction cost and visual impact, making them a critical design component, especially in sensitive urban environments.

- *Cable grid:* Access points, boundary terminals, and junction points together define the nodes of the network. The aerial infrastructure connecting these nodes forms a cable grid that enables the movement of autonomous freight cabins across the system. In addition to the physical infrastructure, the cables themselves and the movement of cabins along them constitute a visible footprint that must be carefully accounted for in the design.

Based on this structure, the design problem we consider is defined as follows. The locations of the boundary terminals are given, along with the service region and the set of businesses to be covered, their transfer demand and preferences, and the level of subsidies, including the possibility of no subsidy. The objective is to determine the locations of access points and junction points, as well as the configuration of the cable grid connecting all nodes, such that the system is financially sustainable under the given subsidy scheme and eliminates the need for ground based freight transfers for the covered businesses, while minimizing the physical infrastructure and visual footprint of the system.

1.2. Contributions of our study

In this study, we propose a novel approach that leverages an emerging transportation technology: autonomous cable cars to support sustainable freight distribution in dense urban environments. To determine the system design, we first conduct a discrete choice experiment with more than 200 local businesses to capture their adoption behavior and estimate their preferences for the proposed aerial freight system. The experiment quantifies the contributions of different attributes to form adoption decisions, including the service price, the distance businesses must travel to access the nearest access point, and the perceived environmental benefits associated with reductions in freight-related emissions and congestion in the district.

Second, we embed the estimated utility functions obtained from the discrete choice experiment into a MILP model that determines the optimal system design. The model operates on a time-expanded network and jointly determines infrastructure deployment and freight routes on the system. The objective is to identify designs that minimize the physical and visual footprint of the aerial infrastructure while ensuring that a targeted share of businesses is served, under different subsidy regimes, including the case of zero public subsidy.

Finally, we conduct extensive numerical experiments based on a case study of the Historic Peninsula of Istanbul, a densely built and highly touristic urban district facing significant urban freight challenges. The computational study evaluates the potential benefits of the proposed system and analyzes the trade-offs between reductions in ground-level freight traffic, the spatial extent of the aerial network, and the level of public support required for implementation. Our results indicate that economic viability is not the primary barrier to deployment: under realistic demand conditions, the system can offer competitive service costs to businesses without requiring government subsidies. Instead, the main design constraint arises from the need to limit visual intrusion in the historic urban landscape. Nevertheless, the results show that carefully optimized network configurations can substantially reduce ground freight traffic while maintaining a minimal aerial infrastructure footprint.

The remainder of this paper is organized as follows. Section 2 provides a literature review focusing on research streams on sustainable last-mile delivery and network design problems. Section 3 introduces the formal definition of the design problem we address and the associated nomenclature, Section 4 describes the discrete choice experiment and our case study, and Section 5 presents the MILP formulation of the design problem. In Section 6, we report the computational experiments and the analysis of the results. And Section 7 summarizes the study and its main findings, presents managerial insights, and outlines future research directions.

2. Literature Review

The problem addressed in this study contributes to the literature on last-mile logistics innovations from a practical perspective, while being methodologically positioned within the class of network design problems.

This section reviews both research streams to clarify the position of our work and to highlight its contributions to the existing literature.

2.1. Last-mile innovations

As last-mile delivery has become a critical component of customer-oriented supply chains, the need for sustainable solutions in last-mile delivery operations has received growing attention, and a substantial body of literature has emerged in this area. According to Bonilla et al. (2024), consolidation centers, shared micro-depots and freight transport, the use of electric vehicles such as bicycles and tricycles, and the deployment of collection and delivery points should be incorporated in last-mile distribution networks to account for economic, social, and environmental sustainability. The literature presents a variety of approaches for achieving these goals. Deployment of electric vehicles plays a crucial role in preventing the air pollution caused by fossil-fuel emissions (Schneider et al., 2014; Agarwal et al., 2025; Boroujeni et al., 2025). We also consider electrification of freight transport, but exploring a novel technology that has not been explored before: electric-powered cable cars that can move independently on a cable grid. Motivating new research, aerial transport systems offer notable benefits in reducing traffic congestion, minimizing land use, and lowering noise pollution. While existing research in this area primarily focuses on drone applications (Figliozzi, 2017; Stolaroff et al., 2018; Li et al., 2020), and although drones provide superior routing flexibility, the cableway system introduced in this study demonstrates distinct advantages across several operational dimensions. Primarily, the system ensures continuous functionality by eliminating the downtime due to battery charging inevitable for drones, while simultaneously offering significantly higher capacities. Furthermore, the cableway serves as a self-sustaining infrastructure that achieves greater cost-efficiency per transportation unit. Finally, the system is more durable due to its relative insensitivity to adverse weather conditions. Various self-collection strategies are studied, which helps with the pedestrianization of urban areas and eases traffic congestion (Morganti et al., 2014; Lin et al., 2020; Bruno et al., 2025). In this respect, our study introduces a public infrastructure involving hubs to serve local stores as access points for their collection and drop-off operations within walking distance. Complementing these efforts, Pahwa and Jaller (2025) assesses the economic, environmental, and social sustainability of various last-mile distribution strategies for managing customer-focused deliveries. The authors showcase the urgent need for green delivery alternatives by highlighting that the conventional approaches cause significant amount of distribution-related emissions. In line with these findings, our study benefits from the reduction in carbon emissions by the utilization of electric vehicles and further reduces road traffic by facilitating deliveries through an aerial freight network. However, this infrastructural approach also has some drawbacks, as the user acceptance of autonomous delivery vehicles is not guaranteed. Recent studies suggest that factors such as price sensitivity, performance expectancy, or environmental concerns have been shown as significant determinants regarding adoption (Kapser and Abdelrahman, 2020; Cicek et al., 2025). To account for the acceptance of proposed system in our paper, we conduct a SP experiment and extracted a utility function for stores involving unit service price, proximity to hubs, and reduction in carbon emissions.

2.2. Network Design Problems

Network design problem (NDP) involves the decision of determining the subset of arcs in a graph to satisfy flow requirements, which typically correspond to demand amounts associated with origin–destination pairs, while minimizing the total transportation cost. We refer the interested reader to the following reviews of specialized application areas: financial considerations (Jahani et al., 2024), sustainability (Eskandarpour et al., 2015), urban transportation (Farahani et al., 2013). Although the majority of the existing literature focuses exclusively on financial objectives (Conde and Leal, 2021; Oliveira et al., 2022); there is a growing body of research to which our work contributes, exploring diverse environmental and social objectives. These objectives include mitigating greenhouse gas emissions (Shi et al., 2017; Truden and Hewitt, 2024), minimizing travel times (Zhang et al., 2025) or evacuation times (Xu et al., 2024), maximizing accessibility based equity measures (Antunes et al., 2003; Aboolian et al., 2016; Zhang and Khani, 2020) or reducing risks (Fontaine et al., 2020). Our study extends this stream of literature by prioritizing urban aesthetic preservation from a public authority standpoint. The continuous movement of aerial vehicles along cable grids in touristic regions poses a risk of visual pollution. To the best of our knowledge, this is the first paper to develop an infrastructural design that minimizes the visual impact on the environment, formulated as a fixed-charge network design problem (FCNDP). FCNDP is differentiated from the standard NDP in the sense that there is a fixed cost to be paid for using the capacity of an arc independent of the amount of flow sent through it (Crainic et al., 2020). FCNDP has been extensively studied due to its practical relevance in areas such as transportation and telecommunication networks (Gendron and Larose, 2014; Gendron et al., 2018; Zetina et al., 2019). Notably, we offer a novel problem formulation that differs from the classical FCNDP by involving a facility location requirement: the arcs can be opened only if a hub or tower is located in both adjacent nodes. This creates a dependency between infrastructure and flow that reflects the physical constraints of aerial cableway systems. Despite a variety of perspectives, standard FCNDP models are often formulated by assuming fixed demand volumes without considering the effect of user adoption decisions. It is not guaranteed whether potential users will actually utilize the proposed infrastructure. Our study contributes to the literature by integrating the utility of potential users as a central element of the design process. Furthermore, we adopt a public value perspective in which infrastructure decisions are guided not only by efficiency considerations but also by broader societal objectives.

3. Problem Definition and Assumptions

We formulate the design problem from the perspective of a public agency (hereafter, the designer) responsible for managing urban mobility and logistics systems. The objective is to establish an Autonomous Cable Car Network (ACNET) to serve the freight transportation needs of a given set of businesses K in a dense urban area (e.g., a historic downtown), with the aim of eliminating associated motorized logistics traffic while ensuring economic viability and minimizing the visual footprint of the required infrastructure.

The proposed service accounts for both inbound and outbound freight flows. The inbound flow is associated with the procurement activities of the stores, whereas the outbound flow, generated by online orders and similar activities, operates in the reverse direction. The total freight volume associated with a store $k \in K$ is given by $a_k = a_k^{\text{in}} + a_k^{\text{out}}$. As a typical condition in dense urban areas such as those considered in this study, where access to the region is predominantly realized through a set of main entry corridors, it is assumed that, in the status quo, the commodities of a store $k \in K$ enter and leave the study area through entry/exit points o_k located at the periphery, and are transported directly to and from the store location d_k via conventional motor vehicles.

In ACNET, commodities destined for or sourced from a store $k \in K$ enter and leave the system through a *feeder terminal* o_k, which is assumed to be located at the same entry/exit point used in the status quo. From the feeder terminal, inbound freight is transported over the cable grid via autonomous cable cars and delivered to an *access hub* located within walking distance of the store. Store personnel can then collect their commodities from the assigned hub without relying on road-based vehicles. For outbound operations, store

Table 1: Summary of Notations

Sets	
K	Set of all customers
N	Set of all nodes
$N_1 \in N$	Set of candidate hub nodes
$N_2 \in N$	Set of candidate junction nodes
$A \subseteq N \times N$	Set of all feasible arcs in $N \times N$
$W_k \subseteq N_1$	Set of feasible access points to store k
T	Set of time periods spanning the planning horizon
N'	Set of all time-expanded nodes
N_1'	Set of time-expanded candidate hub nodes
N_2'	Set of time-expanded candidate junction nodes
$W_k' \subseteq N_1'$	Set of time-expanded feasible access points to store k
$H' \subseteq N_1' \times N_1'$	Set of holding arcs
$A' \subseteq N' \times N'$	Set of movement arcs
Parameters	
a_k^{in}	Inbound freight volume associated with store k
a_k^{out}	Outbound freight volume associated with store k
a_k	Total freight volume associated with store k
e	Unit emission saving rate per kilogram of freight per kilometer diverted from road transport
β	Unit service price for transporting one kg of product through ACNET
α_k	Walking distance from store k to its access point
θ_k	Expected savings in CO_2 emission via ACNET instead of road transport
f_1	Fixed cost of building a hub
f_2	Fixed cost of building a tower
f_3	Fixed cost of installing cables between two nodes
p_{ij}	Level of visual pollution for installing cables from node i to node j
p_1	Unit cost of electricity consumption associated with loading activities
p_2	Unit cost of electricity consumption associated with unloading activities
p_3	Unit cost of electricity consumption associated with horizontal movement of cable cars
$o_k \in N_1$	Entry/exit terminal node associated with store k
$d_k \in N_1$	Location of store k
v_n	Storage capacity of the hub at node n
u_{ij}	Flow capacity on arc (i, j)
s	Subsidizing budget for cable car operations
l	Predetermined level of target emission savings (%)
c	Carrying capacity of a cable car
r	Ratio of the weight of the cable car to its carrying capacity
Decision Variables	
h_n	1 if a hub is opened at node n, 0 otherwise
y_n	1 if a junction point is built at node n, 0 otherwise
q_{ij}	1 if cables are installed from i to j, 0 otherwise
w_{ntk}^{in}	1 if hub n is allocated to store k for the collection of commodities at time t
w_{ntk}^{out}	1 if hub n is allocated to store k for dropping off the commodities at time t
x_{ijkt}^{in}	Amount of flow routed from (i, t) to $(j, t+1)$, related to inbound freight movement of store k
x_{ijkt}^{out}	Amount of flow routed from (i, t) to $(j, t+1)$, related to outbound freight movement of store k
m_{ijt}^{in}	Number of cable cars routed from (i, t) to $(j, t+1)$, related to inbound freight movement (integer)
m_{ijt}^{out}	Number of cable cars routed from (i, t) to $(j, t+1)$, related to outbound freight movement (integer)
z_k	1 if store k is served by ACNET, 0 otherwise

personnel bring their outgoing commodities to the same access hub. After drop-off, the freight is routed via the cable system to the store's designated feeder terminal, where it is retrieved by the store's logistics partner. To ensure operational consistency and simplicity, each store is assigned to a single access hub, which it uses for both the collection of incoming commodities and the drop-off of outgoing shipments.

The adoption of the proposed system by the businesses is not guaranteed, as some store owners may prefer convenience over environmental sustainability and be willing to maintain the status quo. To capture this behavior, in the design problem, we explicitly consider the utility that each store associates with the available alternatives to model their participation decisions based on our preliminary consultation with the store owners in the Historic Peninsula of Istanbul, and the results of the discrete choice experiment we conducted with them (details in Section 4).

The aerial freight network under consideration is represented as a directed graph $G(N, A)$. N is the set of all nodes consisting of possible hub locations $N_1 \subseteq N$, and possible locations of towers $N_2 \subset N$ that function as junction points for routing. The two subsets are not disjoint; in fact, we assume that all potential hub locations are also valid candidates for junction points, hence $N_1 \subseteq N_2$. $A \subseteq N \times N$ is the set of all feasible arcs representing the links between nodes where cables can be wired.

When a store is served through ACNET, the resulting emission savings are assumed to be proportional to the distance traveled (from store to the feeder terminal or vice versa), and the freight volume carried. Accordingly, the emission saving associated with a store $k \in K$ is defined as $\theta_k = e \cdot (\Delta_D(o_k, d_k) \cdot a_k^{\text{in}} + \Delta_D(d_k, o_k) \cdot a_k^{\text{out}})$, where e denotes the unit emission saving per kilogram per unit distance; and $\Delta_D(n_1, n_2)$ is defined as the shortest path driving distance from n_1 to n_2.

Given p_{ij} as the level of visual pollution for using the cable installed from node i to node j, we define an optimization problem as follows.

Definition 1. *Given a set of stores K, their associated logistics demand a_k, and adoption utilities U_k, and the graph $G = (N, A)$, Autonomous Cable Car Network Design Problem (AC-NDP) is to determine the optimal locations of hubs, junctions, and cables while meeting an emission savings target of l with the objective of minimizing the total visual impact $\sum_{(t,t+1) \in T} \sum_{(i,j) \in A} p_{ij} (m_{ijt}^{in} + m_{ijt}^{out})$, where m_{ijt}^{in} and m_{ijt}^{out} are the number of cable cars routed along arc (i, j) at time t, associated with the inbound and outbound freight flows over a planning horizon T.*

For quick reference, we present the notation of all sets, parameters, and decision variables used in the mathematical formulation $\mathcal{P}$ of the AC-NDP in Table 1.

4. Discrete Choice Experiment

We employ a discrete choice experiment to evaluate the potential adoption of ACNET by the target businesses. Our goal is to quantify how store owners trade off different service attributes when deciding between traditional road transport and the proposed aerial distribution system.

Based on a focus group study with business owners in the Historic Peninsula of Istanbul, we identify the primary determinants of user utility as accessibility, service cost, and perceived environmental benefits. Accordingly, we define three attributes: (i) walking distance to the access hub (α_k), (ii) the unit service price for transporting one kg of product through ACNET (β), and (iii) the expected emission savings (θ_k), measured as the amount of CO_2 (in grams) that would have been emitted if the goods were delivered via road transport instead of the proposed system. The levels for each attribute used in the choice scenarios are detailed in Table 2.

Table 2: Attributes and Levels for Scenarios

Attribute	**Levels**	**Unit**
distance	$0, 50, 100, 200$	meters
price	$5, 10, 20, 30$	TRY/kg
emission saving	$0, 20, 40$	grams

The discrete choice scenarios were generated using Ngene, an experimental design software (ChoiceMetrics, 2012). We utilized a D-efficient choice design based on a Multinomial Logit (MNL) error structure. The design consists of 18 discrete choice tasks distributed over three blocks, and the Modified Fedorov algorithm is used for searching the solution space. Attribute combinations were regulated to avoid dominant or unrealistic alternatives. For instance, a scenario with a higher service price was required to offer a compensating benefit, such as shorter walking distance or higher emission savings, to provide a meaningful trade-off for the respondent.

The adoption decisions of the stores are modeled using a random utility framework. Random utility theory is founded on the assumption of utility-maximizing behavior, which implies that the individual chooses the alternative that maximizes their utility when faced with a set of discrete and mutually exclusive alternatives (McFadden, 1972). The utility U_k (1) represents the utility obtained from alternative i by store k:

$$U_{ik} = V_{ik} + \epsilon_{ik} \tag{1}$$

where V_{ik} is the systematic part of the utility and ϵ_{ik} is a random error term which captures unobserved factors not represented in the systematic component of the utility function and is assumed to be normally distributed with mean zero. We define the utility of the current road transport (the opt-out option) as a reference point of zero. Consequently, a store owner is assumed to be willing to receive/send their goods via ACNET only if it offers higher utility than the status quo (U_k>0). The systematic part of the utility for the ACNET alternatives is formulated as a linear function of the normalized attributes:

$$V_{ik} = \mathrm{ASC}_i + b_{\mathrm{price}}\bar{\beta}_{ik} + b_{\mathrm{distance}}\bar{\alpha}_{ik} + b_{\mathrm{emission}}\bar{\theta}_{ik} + b_{\mathrm{interaction}}\bar{\beta}_{ik}\bar{\alpha}_{ik} \tag{2}$$

$\bar{\beta}_{ik}, \bar{\alpha}_{ik}, \bar{\theta}_{ik}$ represent the normalized values for price, distance, and emission savings, respectively, using standard scaling. The last term included is the interaction term that is hypothesized to capture non-linear relationships between price and distance. $b_{\mathrm{price}}, b_{\mathrm{distance}}, b_{\mathrm{emission}}, b_{\mathrm{interaction}}$ are the coefficients to be estimated, and ASC_i is the alternative specific constant of alternative i.

4.1. Data Collection and Model Estimation

We conducted our survey on the Historic Peninsula of Istanbul. This region is characterized by high-density urban infrastructure, with narrow and congested streets where residential, tourist, and commercial activities overlap. The area is heterogeneous in terms of the spatial distribution of stores and product groups, and we focus on three main categories—food, textiles, and electronics- which together account for over 80% of the commercial activity in the region, according to the municipality records. These product categories have volumes and weights compatible with transport via cable car cabins of acceptable size. Criteria for inclusion are defined as volunteers who operate businesses within the Historic Peninsula. The sample size is determined based on the preliminary consultations held with Fatih Municipality. As a result, we target the maximum number of businesses in each category to ensure a representative data set without disrupting local commercial activities.

Data was collected through a face-to-face survey conducted in November 2024. Before starting the survey, the participants are verbally informed about the objectives, procedures, potential benefits, and the data privacy protocol of the study. We proceeded with the questionnaire after obtaining the verbal informed consent from each participant.

The survey consists of two sections. In the first section, respondents were asked a series of questions regarding their business operations. They provided data on the procurement/shipment frequency, daily freight volume, average package weight, locations regarding the logistics patterns of both inbound and outbound freight movements, and the type of products sold. The second section of the survey constitutes the SP experiment. The respondents were informed through a written description of the proposed electric aerial distribution system. Subsequently, they were presented with six discrete choice scenarios. In each of these scenarios, the respondents are asked to choose between two unlabeled aerial service configurations, varying in distance, price and emission saving, and an opt-out alternative, which is maintaining road-based transport. A sample of these discrete choice scenarios presented to the respondents is provided in Appendix A.

In total, 237 store owners (41 from electronics, 118 from food, and 78 from textiles) participated in the survey. Only one respondent in the food category provided an incomplete response; all other data points were included in the analysis, resulting in 1421 choice observations.

Using the collected data, the model estimation is performed using the Biogeme software package in Python, assuming the multinomial logit (MNL) structure. Biogeme package is specifically developed for predicting the parameters in discrete choice models by applying maximum likelihood estimation (Bierlaire and Fetiarison, 2009). Resulting parameter estimations are shown in Table 3.

Table 3: MNL Model Estimation Results

Name	**Value**	**Err**	**p-val**
Parameter Estimates			
ASC	0.130	0.058	0.026
b_{price}	-0.129	0.041	0.002
b_{distance}	0.047	0.059	0.426
b_{emission}	0.208	0.035	<0.001
$b_{\text{interaction}}$	-0.166	0.050	<0.001
Model Summary			
Sample Size	1421		
Num. of Param.	5		
Init. LL	-1561.19		
Final LL	-1536.58		
AIC	3083.16		
BIC	3109.46		

Note: Err: Robust standard error; p-val: Robust p-value; LL: Log-likelihood; AIC: Akaike Information Criterion; BIC: Bayesian Information Criterion.

We observe that the coefficents b_{price} and b_{emission} have the expected signs, and both are statistically significant attributes according to p-values. This means the gained utility of a store increases as lower prices are charged and higher emission saving is achieved. The interaction term $b_{\text{interaction}}$ having a negative sign suggests that at greater distances, price sensitivity increases. However, the distance attribute alone is not statistically insignificant ($p = 0.426$). Consequently, a reduced model was estimated by omitting the distance term. The results are presented in Table 4.

Table 4: MNL Reduced Model Estimation Results

Name	**Value**	**Err**	**p-val**
Parameter Estimates			
ASC	0.130	0.058	0.026
b_{price}	-0.133	0.041	0.001
b_{emission}	0.210	0.035	<0.001
$b_{\text{interaction}}$	-0.161	0.049	0.001
Model Summary			
Sample Size	1421		
Num. of Param.	4		
Init. LL	-1561.19		
Final LL	-1536.90		
AIC	3081.81		
BIC	3102.84		

Note: Err: Robust standard error; p-val: Robust p-value; LL: Log-likelihood; AIC: Akaike Information Criterion; BIC: Bayesian Information Criterion.

The coefficient signs in this version are consistent with the theoretical assumptions of our study, and we see that all estimations are statistically significant. We also note that this model achieves a superior fit, it has a slightly higher final log-likelihood compared to the original model while involving one less parameter. Considering these reasons, we prefer to proceed with this model for determining the ACNET adoption of the stores in the subsequent network design phase.

The aforementioned models were estimated without incorporating the product group information present in the data set. To identify potential heterogeneities across different sectors, an additional sensitivity analysis is conducted by estimating separate models for each product group.

Table 5: MNL Reduced Model Estimation Results for Distinct Product Groups

	Electronics			**Food**			**Textiles**		
Parameter	**Value**	**Err.**	**p-val**	**Value**	**Err.**	**p-val**	**Value**	**Err.**	**p-val**
Estimation Results									
ASC	0.299	0.144	0.038	0.062	0.082	0.451	0.147	0.103	0.152
b_{price}	-0.124	0.097	0.198	-0.110	0.059	0.063	-0.169	0.069	0.014
b_{emission}	0.117	0.081	0.147	0.206	0.051	<0.001	0.266	0.063	<0.001
$b_{\text{interaction}}$	-0.064	0.117	0.583	-0.199	0.070	0.005	-0.155	0.085	0.068
Model Summary									
Sample Size		246			707			468	
Init. Log-Likelihood		-270.26			-776.72			-514.15	
Final Log-Likelihood		-266.32			-765.95			-502.07	
AIC		540.64			1539.90			1012.13	
BIC		554.66			1558.15			1028.73	

Note: Err: Robust standard error; p-val: Robust p-value; LL: Log-likelihood; AIC: Akaike Information Criterion; BIC: Bayesian Information Criterion.

As shown in Table 5, all parameter estimations have the expected signs and the behaviors associated with different sectors do not significantly divert from the results observed by the pooled model. However, disaggregating the data by sector substantially reduces the sample size for individual models and degrades the statistical power. As the pooled model remains the most statistically reliable representation that leads to logical conclusions, we maintain the aggregated data set for fitting a single utility function shared by all sectors.

5. Mathematical model for the design problem

The design problem (AC-NDP) is formulated on a time-expanded network as an MILP model. Let $T = \{0, 1, \dots, \tau\}$ denote the discrete set of time periods spanning the planning horizon. The time-expanded node sets are defined as follows; $N_1' = \{(n,t) | n \in N_1, t \in T\}$, $N_2' = \{(n,t) | n \in N_2, t \in T\}$ and $N' = N_1' \cup N_2'$.

Two types of arcs are defined in the time-expanded network. Holding arcs represent the situation of remaining in the same node between consecutive time periods and are defined as $H' = \{((i,t),(i,t+1)) | i \in N_1, t \in T\}$. Movement arcs represent the transitions between distinct nodes as time progresses and are defined as $A' = \{((i,t),(j,t+1)) | i \neq j, i \in N, j \in N, t \in T\}$. Let $\bar{K}$ denote the set of stores served through ACNET. The target emission savings level (l) is defined as the percentage of eliminated carbon emissions associated with the road transport, accounting for both amount and distance:

$$l = \frac{\sum_{k \in \bar{K}} (a_k^{in} \cdot \Delta_D(o_k, d_k) + a_k^{out} \cdot \Delta_D(d_k, o_k))}{\sum_{k \in K} (D_k^{in} \cdot \Delta_D(o_k, d_k) + a_k^{out} \cdot \Delta_D(d_k, o_k))},$$

A store cannot be served through any arbitrary hub, the feasibility of allocation depends on the gained utilitiy of the store for using the particular hub as its access point. For each store k, the set of hubs that are feasible for allocation is determined by describing the utility as a function of the potential access point. According to the model estimation results presented in the previous section, we define the set of hubs that are feasible for allocation to store k as $W_k := \{n \in N_1 | b_0 + b_1\bar{\beta} + b_3\bar{\theta}_k + b_4\bar{\beta}\bar{\alpha}_{nk} \geq 0\} \backslash \{o_k\}$ where $\bar{\alpha}_{nk}$ corresponds to the scaled shortest path walking distance between hub n and the location of store k. If $W_k = \emptyset$ for any store k, ACNET is unable to serve that store, and its logistics operations remain dependent on road transport vehicles. The time-expanded feasible hub set associated with store k is given by $W_k' = \{(n,t) | n \in W_k, t \in T\}$.

We present the following MILP formulation $\mathcal{P}$ for AC-NDP spanning one working day.

$$Z = \min \sum_{((i,t),(j,t+1)) \in A'} p_{ij}(m_{ijt}^{\text{in}} + m_{ijt}^{\text{out}}) \tag{3}$$

$$\text{s.t. } q_{ij} \leq h_i + y_i, \qquad \forall i \in N_1, \forall (i,j) \in A \tag{4}$$

$$q_{ij} \leq y_i, \qquad \forall i \in N_2, \forall (i,j) \in A \tag{5}$$

$$q_{ij} \leq h_j + y_j, \qquad \forall j \in N_1, \forall (i,j) \in A \tag{6}$$

$$q_{ij} \leq y_j, \qquad \forall j \in N_2, \forall (i,j) \in A \tag{7}$$

$$\begin{aligned}(1+r) \sum_{k \in K} \left(z_k a_k (p_1 + p_2) + \sum_{((i,t),(j,t+1)) \in A'} p_3 \|i - j\|_2 (x_{ijkt}^{\text{in}} + x_{ijkt}^{\text{out}}) \right) \\ - \sum_{k \in K} \beta z_k a_k + \sum_{i \in N_1} f_1 h_i + \sum_{i \in N} f_2 y_i + \sum_{(i,j) \in A} f_3 q_{ij} - s \leq 0\end{aligned} \tag{8}$$

$$\sum_{k\in K}(x^{\text{in}}_{ijkt}+x^{\text{out}}_{ijkt})\leq q_{ij}u_{ij}, \qquad \forall((i,t),(j,t+1))\in A' \tag{9}$$

$$\sum_{k\in K}(x^{\text{in}}_{iikt}+x^{\text{out}}_{iikt})\leq h_i v_i, \qquad \forall((i,t),(i,t+1))\in H' \tag{10}$$

$$z_k\leq h_{o_k}, \qquad \forall k\in K \tag{11}$$

$$w^{\text{in}}_{ntk}\leq h_n, \qquad \forall(n,t)\in W'_k,\forall k\in K \tag{12}$$

$$w^{\text{out}}_{ntk}\leq h_n, \qquad \forall(n,t)\in W'_k,\forall k\in K \tag{13}$$

$$\sum_{(n,t)\in W'_k}w^{\text{in}}_{ntk}-\sum_{(n,t)\in W'_k}w^{\text{out}}_{ntk}=0, \qquad \forall n\in W_k,\forall k\in K \tag{14}$$

$$\sum_{(n,t)\in W'_k}w^{\text{in}}_{ntk}=1, \qquad \forall k\in K \tag{15}$$

$$\sum_{(n,t)\in W'_k}w^{\text{out}}_{ntk}=1, \qquad \forall k\in K \tag{16}$$

$$\sum_{A'\cup H'}x^{\text{in}}_{ijk,t-1}-\sum_{A'\cup H'}x^{\text{in}}_{jikt}=\begin{cases}-z_k a^{\text{in}}_k, & (j,t)=(o_k,1)\\ w^{\text{in}}_{jtk}a^{\text{in}}_k, & (j,t)\in W'_k\\ 0, & \text{otherwise}\end{cases} \qquad \forall(j,t)\in N'_1,\forall k\in K \tag{17}$$

$$\sum_{A'\cup H'}x^{\text{out}}_{ijk,t-1}-\sum_{A'\cup H'}x^{\text{out}}_{jikt}=\begin{cases}z_k a^{\text{out}}_k, & (j,t)=(o_k,\tau-1)\\ -w^{\text{out}}_{jtk}a^{\text{out}}_k, & (j,t)\in W'_k\\ 0, & \text{otherwise}\end{cases} \qquad \forall(j,t)\in N'_1,\forall k\in K \tag{18}$$

$$\sum_{((i,t-1),(j,t))\in A'}x^{\text{in}}_{ijk,t-1}-\sum_{((j,t),(i,t+1))\in A'}x^{\text{in}}_{jikt}=0, \qquad \forall(j,t)\in N'_2,\forall k\in K \tag{19}$$

$$\sum_{((i,t-1),(j,t))\in A'}x^{\text{out}}_{ijk,t-1}-\sum_{((j,t),(i,t+1))\in A'}x^{\text{out}}_{jikt}=0, \qquad \forall(j,t)\in N'_2,\forall k\in K \tag{20}$$

$$\sum_{k\in K}x^{\text{in}}_{ijkt}\leq c\cdot m^{\text{in}}_{ijt}, \qquad \forall((i,t),(j,t+1))\in A' \tag{21}$$

$$\sum_{k\in K}x^{\text{out}}_{ijkt}\leq c\cdot m^{\text{out}}_{ijt}, \qquad \forall((i,t),(j,t+1))\in A' \tag{22}$$

$$\begin{aligned}&\sum_{k\in K}z_k(a^{in}_k\Delta_D(o_k,d_k)+a^{out}_k\Delta_D(d_k,o_k))\geq\\ &\quad l\sum_{k\in K}(a^{in}_k\Delta_D(o_k,d_k)+a^{out}_k\Delta_D(d_k,o_k)), \qquad \forall A',\forall k\in K\end{aligned} \tag{23}$$

$$h_n \in \{0,1\}, \qquad \forall n \in N_1 \tag{24}$$

$$y_i \in \{0,1\}, \qquad \forall i \in N \tag{25}$$

$$q_{ij} \in \{0,1\}, \qquad \forall (i,j) \in A \tag{26}$$

$$w^{\text{in}}_{ntk} \in \{0,1\}, \qquad \forall (n,t) \in W'_k, \forall k \in K \tag{27}$$

$$w^{\text{out}}_{ntk} \in \{0,1\}, \qquad \forall (n,t) \in W'_k, \forall k \in K \tag{28}$$

$$x^{\text{in}}_{ijkt} \geq 0, \qquad \forall A' \cup H', \forall k \in K \tag{29}$$

$$x^{\text{out}}_{ijkt} \geq 0, \qquad \forall A' \cup H', \forall k \in K \tag{30}$$

$$m^{\text{in}}_{ijt} \geq 0, \text{ integer}, \qquad \forall ((i,t),(j,t+1)) \in A' \tag{31}$$

$$m^{\text{out}}_{ijt} \geq 0, \text{ integer}, \qquad \forall ((i,t),(j,t+1)) \in A' \tag{32}$$

$$z_k \in \{0,1\}, \qquad \forall k \in K \tag{33}$$

The objective function (3) minimizes the total visual pollution caused to environment by the cable car movement on ACNET. Constraints (4) and (5) ensure that a cable may only be installed on an arc incident to node i only if a hub or a junction is opened at node i. Similarly, constraints (6) and (7) ensure that a cable installment can be done on an arc incident to node j only if a hub or a junction is opened at node j. Constraint (8) is to force financial feasibility, ensuring that the sum of the subsidy budget and the revenues collected from the stores is sufficient to cover the construction costs and operating costs caused by the electricity consumption associated with loading, unloading and routing activities. Constraints (9) ensures that the total inbound and outbound freight flows of all stores $k \in K$ on arc (i,j) at time t do not exceed the installed cable capacity u_{ij}. These also ensure that no flow is routed along arc (i,j) if it is not opened. Constraints (10) imposes a limit on the total inventory stored at hub nodes n, ensuring it does not exceed the hub's storage capacity v_n. These also ensures that no inventory is stored at hub n if it is not opened. Constraints (11) ensure that for being able to serve a store k through ACNET, a hub should be constructed at node o_k. Constraints (12) and (13) ensure that a hub is constructed at node n if it serves as an access point for store k. Constraints (14) ensures that to serve store k through ACNET, exactly one access point n should be allocated to store k, forcing the collection and drop-off operations to be performed via the same hub. Constraints (15) and (16) ensure that, for each served store, the collection of inbound freight and the drop-off of outbound freight are completed within the same time period. This requirement is imposed for the operational convenience of stores and rules out split deliveries and pickups. Constraints (17) and (18) ensure the flow conservation on the potential hub nodes for inbound and outbound freight flow, respectively. Constraints (19) and (20) ensure the flow conservation on the potential junction nodes for inbound and outbound freight flow, respectively. Constraints (21) and (22) calculate the number of cable cars needed to carry the corresponding flow. (23) ensures attaining a predetermined l. (24)-(33) state the domain restrictions.

6. Computational Study

In this section, we evaluate the environmental and structural implications of the proposed ACNET through a computational study based on the solution of $\mathcal{P}$ under a range of operating conditions. The analysis is guided by two research questions:

- **RQ1:** What trade-offs arise between the targeted emission savings and the visual impact of the resulting network?
- **RQ2:** How do financial factors, such as subsidy support and service pricing, influence the feasibility and structure of the network?

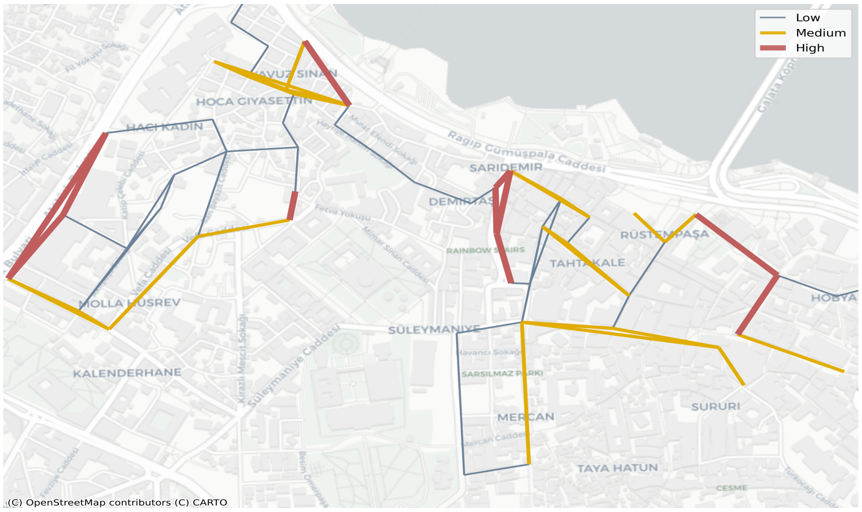
To address these questions, we generate problem instances with varying target emission savings levels, subsidy amounts, and service prices. The study is based on a case study of Istanbul's Historic Peninsula and combines empirical demand data collected through a survey with open-source spatial data.

In the following, we explain how the problem parameters are determined, describe the experimental design, and finally discuss the resulting insights.

6.1. Parameter Values

We use the following parameter values in our experiments.

- **visual pollution:** In consultation with local public authorities, road segments along which cables may be installed in the Historic Peninsula are assigned visual pollution scores based on factors such as tourist density, the historical and cultural significance of the surrounding area, and visibility from the coastline. Three levels with associated visual impact scores are considered: low (1 unit), medium (4 units), and high (9 units). The resulting classification is illustrated in Figure 1.



(C) OpenStreetMap contributors (C) CARTO

Figure 1: Visual Pollution Levels of Potential Cable Installations

- **cabin-weight-to-payload ratio:** Each cabin is assumed to be equipped with a 1.5 kW three-phase electric motor to enable autonomous operation. Considering the motor mass (approximately 17 kg), the cabin structure weight, and the target payload capacity of 30 kg, the cabin-weight-to-payload ratio r is assumed to be 1.0, implying that the unloaded cabin weight is equal to its payload capacity.

- **energy cost:** Operating costs are estimated using the industrial electricity tariff in Türkiye, 4.78 TRY/kWh EPDK (2025), together with the power ratings and efficiencies of the motors used in the system.
  - Vertical movements are assumed to be powered by a 0.18 kW motor with an efficiency of 85.3%, resulting in operating costs of $p_1 = 0.00017$ TRY and $p_2 = 0.00014$ TRY for upward and downward movements, respectively.
  - Horizontal movements are assumed to be powered by a 1.5 kW motor with an efficiency of 59.7%, yielding an operating cost of $p_3 = 0.00002$ TRY.
- **fixed costs:** Daily amortized fixed costs of building network components are calculated considering a total lifetime of 10 years for the system:
  - f_1: 2336.11 TRY - This includes the monthly rent of a storage unit in the study area (25000 TRY), personnel cost including taxes (45000 TRY) and a 0.18 kW electric motor to perform loading and unloading activities (10000 TRY).
  - f_2: 1.39 TRY - This accounts for the material cost associated with the structural iron required for constructing the towers (5000 TRY).
  - f_3: 3.47 TRY - This covers the material cost for the cables (500 TRY) and four 1.5 kW electric motors (4 × 3000 TRY), as one cable can support up to four cable cars simultaneously.
- **storage and flow capacity:** Storage capacities at hubs are set to 160 tons, while flow capacities on arcs are derived by considering that a cable car moves at 15 km/h and a cable can support up to four cable cars simultaneously.
- **road transport emissions:** For the road transport alternative, we adopt the average CO_2 emissions of a Light Goods Vehicle (LGV) operating in a very dense urban area, which is reported as 254.61 g/km by Coulombel et al. (2018). Assuming a 1000 kg carrying capacity, this translates into an emission parameter of $e = 0.25461$ g per $kg \cdot km$. The shortest driving distances $\Delta_D(\cdot)$ and walking distances $\Delta_W(\cdot)$ are calculated using the Dijkstra algorithm implementation in the networkx library. These calculations are performed on graphs derived from OpenStreetMap (OSM) via the osmnx library.
- **transport demand:** The study area is heterogeneous in terms of the spatial distribution of stores and product categories. We divide the study area into 123 sub-areas geographically, and each sub-area acts as a centralized demand node (incorporating the stores located in the area), sharing a common entry/exit terminal. The distribution of the centralized demand nodes across the study area is demonstrated in Figure 2. The shape sizes are proportional to the demand volumes that are generated based on data provided by store owners participated in the discrete choice survey.

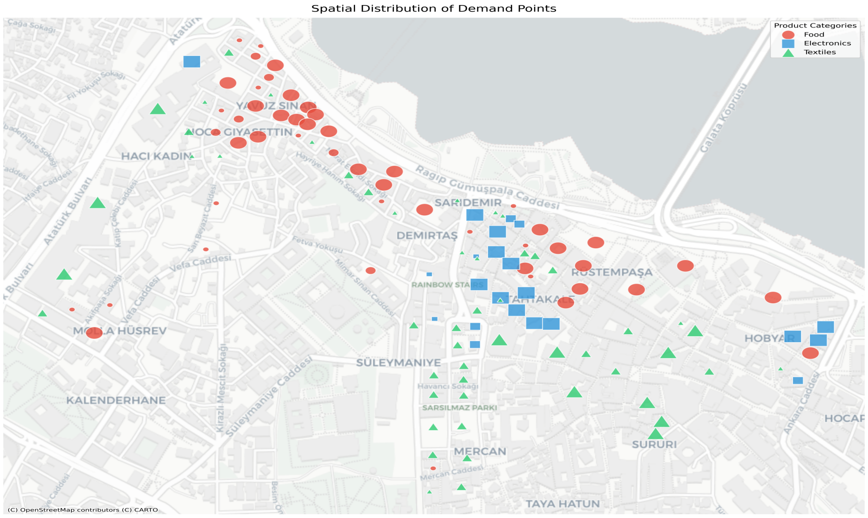


Figure 2: Spatial Distribution of the Demand Nodes

6.2. *Experiment Design and Implementation Details*

A representative daily demand scenario is generated using the details such as average package weight and procurement frequency reported in the discrete choice survey by the participated store owners. We projected all fixed costs to a daily scale, and constructed the time-extended network with 30-minute time resolution.

Each problem instance is characterized by the daily subsidy $s \in \{0, 25000, 50000, 75000\}$ in TRY, unit service price $\beta \in \{0, 1, 5, 10, 20, 30\}$ in TRY/kg, and the level of target emissions saving level $l \in \{40\%, 60\%, 80\%, 100\%\}$. Note that 75000 TRY is the amount sufficient to cover the fixed costs of opening all potential network components. Employing a full-factorial experimental design, we solved the design problem $(\mathcal{P})$ on 96 distinct configurations.

The design problem $(\mathcal{P})$ is solved using IBM ILOG CPLEX Optimization Studio v22.1.1 with Java 14. All computational experiments are conducted on a 64-bit Linux workstation equipped with dual Intel Xeon Gold 5418Y processors running at 2.0 GHz and 512 GB of RAM.

6.3. *Analysis*

The complete set of computational results is reported in Appendix B. In the remainder of this subsection, we focus on the insights derived from these results with respect to our research questions.

6.3.1. *Emission Savings and Visual Impact Trade-off*

The adoption of ACNET introduces a fundamental trade-off, offsetting the environmental benefits of displacing road transport by introducing visual pollution from cable car movements. To analyze this trade-off, we evaluate how the visual impact scales as higher emission saving targets are pursued, illustrated in Figure 3. For every emission savings target level, the plot depicts the parameter configuration yielding the minimum objective function value.

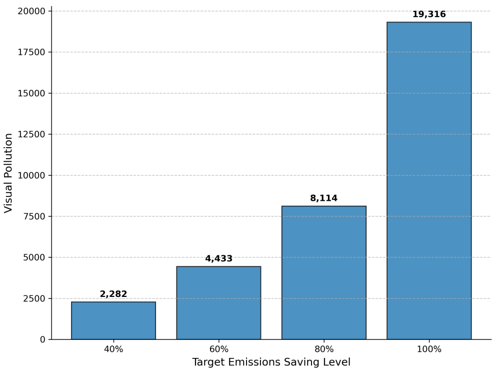


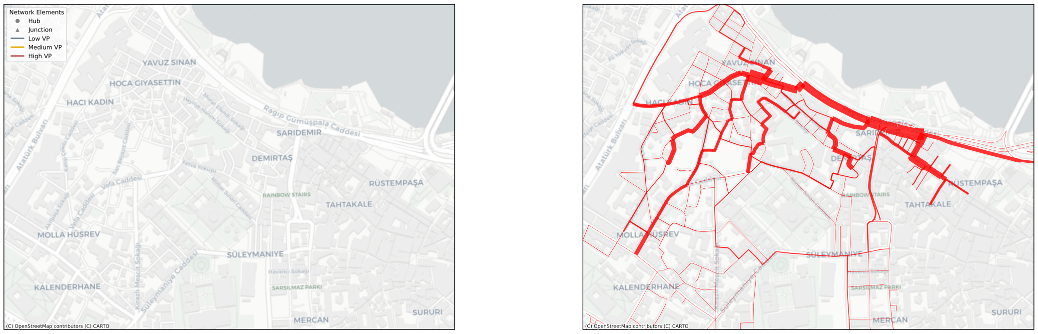
Figure 3: Target Emission Saving Level vs. Introduced Visual Pollution

The results indicate that, up to an emission reduction target of 80%, the increase in the network's visual impact is approximately linear with the percentage of emissions eliminated. Beyond this threshold, however, further emission reductions become increasingly costly in terms of visual pollution, as ACNET must accommodate a larger share of transfer demand. Most notably, the relationship becomes strongly non-linear when moving from an 80% reduction target to full decarbonization. Eliminating the remaining 20% of logistics emissions requires more than a doubling of the resulting visual pollution, revealing a pronounced trade-off between environmental benefits and urban landscape preservation at high levels of decarbonization.

Nevertheless, Figure 4 suggests that even the highest decarbonization targets may remain attractive from an urban planning perspective. The figure jointly illustrates the evolution of the ACNET infrastructure and the corresponding reduction in road-based freight activity. The left column depicts the constructed cableway network, including hubs, junctions, and opened cable links, where line thickness is proportional to the intensity of cable car movements. The right column shows the commodity flows that continue to be served by road vehicles, with thicker lines indicating corridors carrying larger freight volumes. Together, the two columns provide a visual representation of the trade-off between visual pollution and the displacement of road freight traffic.

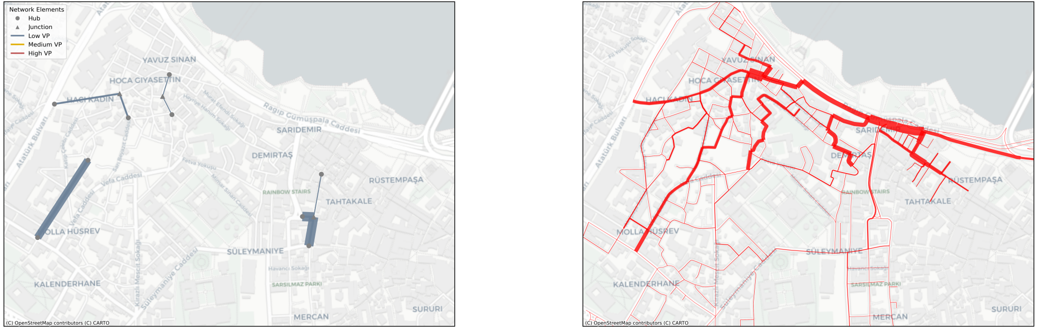
As the emission reduction target increases from 40% to 80%, the network expands gradually by reinforcing existing corridors and extending service onto arcs with medium visual sensitivity. The increasing thickness of several cable links indicates that these corridors carry a growing share of freight demand. At the same time, the remaining road freight network becomes progressively thinner, particularly along the heavily utilized coastal corridor. Thus, moderate increases in visual impact are accompanied by substantial reductions in road-based freight activity.

The transition from 80% to 100% constitutes a more fundamental change. To eliminate the remaining freight vehicle activity, ACNET must extend into a limited number of medium- and high-sensitivity corridors and operate these links intensively. This requirement explains the pronounced increase in visual impact observed in Figure 3. However, the resulting network remains far from pervasive. Even under full decarbonization, the additional infrastructure is concentrated on a relatively small number of strategically selected links rather than being distributed throughout the study area. From an urban planning perspective, this suggests that the additional visual burden associated with full decarbonization may still constitute a reasonable trade-off, particularly in dense urban environments where reducing freight traffic, congestion, noise, and other urban externalities is a primary policy objective.



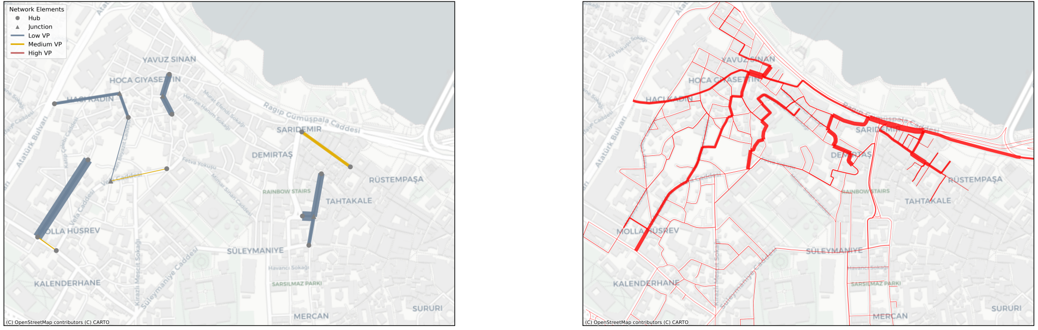
(a) Constructed Aerial Cableway Network with Target Emission Saving of 0%

(b) Remaining Road Flows with Target Emission Saving of 0%



(a) Constructed Aerial Cableway Network with Target Emission Saving of 40%

(b) Remaining Road Flows with Target Emission Saving of 40%



(a) Constructed Aerial Cableway Network with Target Emission Saving of 60%

(b) Remaining Road Flows with Target Emission Saving of 60%

(a) Constructed Aerial Cableway Network with Target Emission Saving of 80%

(b) Remaining Road Flows with Target Emission Saving of 80%

(a) Constructed Aerial Cableway Network with Target Emission Saving of 100%

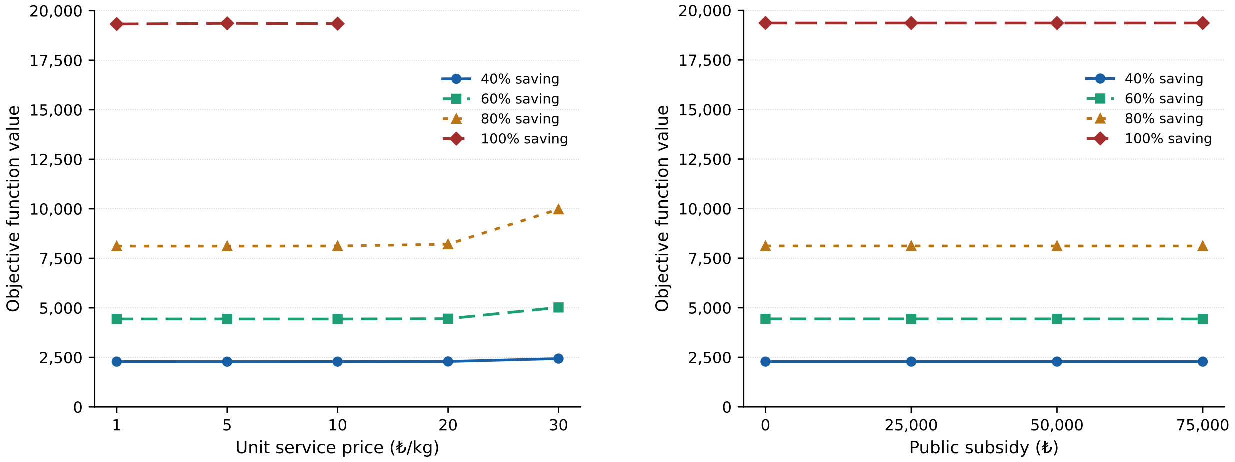
(b) Remaining Road Flows with Target Emission Saving of 100%

Figure 4: Network Configuration and Uncovered Flow of Commodities for Varying Emission Saving Targets

6.3.2. Impact of Financial Factors on Network Structure and Performance

A key concern for any novel urban logistics infrastructure is whether it can sustain itself under realistic financial conditions or whether its environmental benefits come only at the cost of economic viability. This subsection examines how two central financial levers, the unit service price charged to freight operators per kilogram of freight, and the level of public subsidy provided by municipal or regional agencies, jointly affect the optimal network design and its environmental performance as measured by the objective function (minimum visual footprint score).

Figure 5 presents two complementary sensitivity views from our experiment results presented in detail in Table B.6. Figure 5a depicts the effect of the unit service price at zero subsidy, and Figure 5b shows the effect of public subsidy at a representative mid-range price of 5 TRY/kg.



(a) Unit service price sensitivity (subsidy = 0).

(b) Subsidy sensitivity (unit price = 5 TRY/kg).

Figure 5: Impact of financial factors on network performance

The most striking finding in Figure 5a is the near-flatness of all four curves across unit service prices from 1 to 10 TRY/kg. For the 40% saving target, the objective function value ranges from 2,283 to 2,285 across these three price levels. A comparable pattern holds at higher ambition levels: at 60%, values lie between 4,436 and 4,439; at 80%, between 8,117 and 8,122. This insensitivity is not trivial. It implies that the operator of the aerial network enjoys substantial pricing latitude (spanning at least a tenfold range) without any deterioration in the visual footprint outcome. The result arises because, in this price regime, freight operators still find it cost-effective to route sufficient volume through the aerial network and the optimiser can achieve equivalent visual-footprint scores regardless of which financially viable route configurations are selected.

The pattern changes markedly when the price is raised to 20 or 30 TRY/kg. At 20 TRY/kg the objective function begins to rise, reaching 2,293 for the 40% target (+0.4%) and 8,211 for the 80% target (+1.1%). At 30 TRY/kg the deterioration accelerates sharply: the 40% scenario reaches 2,438 (+6.8% relative to the price of 1), the 60% scenario 5,020 (+13.2%), the 80% scenario 9,975 (+23.0%), and the 100% scenario becomes infeasible entirely. This threshold behaviour reflects a service pricing tipping point beyond which commercial participation in the network can no longer be sustained at the volumes required to meet the emission target, forcing the optimiser to select denser or more visually intrusive network configurations or put more subsidies.

Figure 5b reveals an equally important result from the public authorities perspective: once the unit service price is set at a commercially reasonable level, increasing the subsidy from zero to 75,000 TRY produces negligible additional improvement in network performance with no practical significance. For the 40% target, the objective function value moves from 2,283 at zero subsidy to 2,282 at 75,000 TRY. At 80%, the corresponding improvement is from 8,117 to 8,115. This finding has important policy implications. Public subsidies are often proposed as a prerequisite for the viability of sustainable urban logistics infrastructure, yet the results here suggest that this is not the case for the proposed system. The network is self-sustaining: commercially attractive pricing alone is sufficient to generate the participation incentives needed to achieve the emission target at minimal visual cost. Subsidies may nonetheless remain valuable for other policy objectives such as accelerating early-stage deployment or enabling the 100% decarbonisation scenario.

Taken together, these results paint a financially encouraging picture for ACNET as a innovative last-mile solution. The system achieves its environmental targets robustly across a wide price band (1–10 TRY/kg) and does so with or without meaningful public subsidy, up to the 80% emission-saving level. The one scenario that remains financially sensitive — full (100%) ground-to-aerial transfer — is inherently the most demanding, and even there, modest pricing (1–10 TRY/kg) yields feasible and consistent solutions. These properties substantially reduce the financial risk associated with deployment: neither operators nor public agencies face a narrow parameter window within which the system functions, making it resilient to the pricing uncertainties and revenue fluctuations inherent in any new logistics infrastructure.

7. Conclusion

This paper investigated the potential of autonomous aerial cableway systems as a sustainable urban freight transportation alternative for dense and touristic urban environments. We introduced a design problem (AC-NDP), which jointly determines the locations of access hubs, junction points, and cable infrastructure while explicitly accounting for user adoption behavior, financial feasibility, and environmental objectives. To realistically capture adoption decisions, we conducted a stated-preference experiment with more than 200 businesses operating in the Historic Peninsula of Istanbul and integrated the resulting utility model into a network design optimization framework.

The computational study demonstrates that autonomous aerial freight systems can substantially reduce the dependence on road-based freight transportation while requiring a relatively limited infrastructure footprint. The results reveal a clear trade-off between environmental performance and visual impact. Up to an 80% reduction in freight-related emissions, increases in the visual footprint are approximately proportional to the environmental benefits obtained. Beyond this threshold, however, further decarbonization requires infrastructure deployment in increasingly sensitive urban locations, resulting in a strongly non-linear increase in visual impact. Nevertheless, the resulting network remains geographically concentrated even under full decarbonization, suggesting that ambitious emission reduction targets may still be compatible with the preservation of urban landscapes.

A second key finding concerns the financial viability of the proposed system. The results indicate that ACNET can operate under commercially realistic pricing levels without requiring public subsidies. For a broad range of service prices, the optimal network configurations and associated environmental benefits remain virtually unchanged. This robustness suggests that autonomous aerial freight networks may represent a financially sustainable urban logistics solution rather than one that depends on continuous public support. While subsidies may accelerate deployment or reduce implementation risks, they are not a prerequisite for achieving substantial emission reductions.

Several directions for future research remain open. First, the present study focuses on strategic infrastructure planning and assumes deterministic demand and user preferences. Future work could investigate robust and stochastic formulations that account for demand uncertainty and behavioral variability. Second, the operational management of autonomous cable car fleets, including vehicle repositioning, congestion management, and dynamic routing decisions, presents a rich avenue for further study. Finally, extending the framework to multi-modal urban logistics systems that combine aerial freight transport with consolidation centers, cargo bicycles, or public transportation services could provide additional insights into the role of emerging technologies in sustainable city logistics.

Overall, the results suggest that autonomous aerial cableway systems constitute a promising and previously underexplored alternative for sustainable urban freight transportation. By exploiting underutilized aerial space, reducing dependence on road vehicles, and maintaining financial viability without substantial public support, such systems have the potential to become an important component of future urban logistics networks.

Acknowledgements

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Appendix A. Stated-Preferences Questionnaire

An alternative electric distribution system to road transport is planned to be established. The following questions are designed to evaluate different options for the design of this system.

1. To receive/send products, which of the following options would you prefer?

☐ Electric system with delivery from 0 m distance, service fee 5 TRY/kg, 0 g emission savings
☐ Electric system with delivery from 0 m distance, service fee 10 TRY/kg, 40 g emission savings
☐ By road transport

2. To receive/send products, which of the following options would you prefer?

☐ Electric system with delivery from 200 m distance, service fee 20 TRY/kg, 40 g emission savings
☐ Electric system with delivery from 200 m distance, service fee 10 TRY/kg, 20 g emission savings
☐ By road transport

3. To receive/send products, which of the following options would you prefer?

☐ Electric system with delivery from 200 m distance, service fee 30 TRY/kg, 40 g emission savings
☐ Electric system with delivery from 200 m distance, service fee 20 TRY/kg, 20 g emission savings
☐ By road transport

4. To receive/send products, which of the following options would you prefer?

☐ Electric system with delivery from 50 m distance, service fee 20 TRY/kg, 0 g emission savings

- ☐ Electric system with delivery from 50 m distance, service fee 30 TRY/kg, 20 g emission savings
- ☐ By road transport

5. To receive/send products, which of the following options would you prefer?

- ☐ Electric system with delivery from 0 m distance, service fee 20 TRY/kg, 0 g emission savings
- ☐ Electric system with delivery from 0 m distance, service fee 30 TRY/kg, 20 g emission savings
- ☐ By road transport

6. To receive/send products, which of the following options would you prefer?

- ☐ Electric system with delivery from 50 m distance, service fee 10 TRY/kg, 40 g emission savings
- ☐ Electric system with delivery from 50 m distance, service fee 5 TRY/kg, 0 g emission savings
- ☐ By road transport

Appendix B. Numerical Experiment Results

Table B.6: Experiment Results

Target Emissions Saving	**Subsidy**	**Unit Service Price**	**Objective Function Value**
40	0	1	2285
40	0	5	2283
40	0	10	2285
40	0	20	2293
40	0	30	2438
40	25000	0	2282
40	25000	1	2282
40	25000	5	2283
40	25000	10	2283
40	25000	20	2293
40	25000	30	2438
40	50000	0	2282
40	50000	1	2282
40	50000	5	2283
40	50000	10	2282
40	50000	20	2293
40	50000	30	2438
40	75000	0	2282
40	75000	1	2282
40	75000	5	2282
40	75000	10	2282
40	75000	20	2293
40	75000	30	2438
60	0	1	4438
60	0	5	4439
60	0	10	4436
60	0	20	4452
60	0	30	5020
60	25000	0	4524
60	25000	1	4436
60	25000	5	4437
60	25000	10	4436
60	25000	20	4452
60	25000	30	5020
60	50000	0	4436
60	50000	1	4436
60	50000	5	4437
60	50000	10	4436
60	50000	20	4452
60	50000	30	5020
60	75000	0	4434
60	75000	1	4436
60	75000	5	4433
60	75000	10	4436
60	75000	20	4452
60	75000	30	5020
80	0	1	8117
80	0	5	8117
80	0	10	8122
80	0	20	8211
80	0	30	9975
80	25000	0	9026

Table B.6: Experiment Results

Target Emissions Saving	**Subsidy**	**Unit Service Price**	**Objective Function Value**
80	25000	1	8117
80	25000	5	8116
80	25000	10	8114
80	25000	20	8211
80	25000	30	9966
80	50000	0	8115
80	50000	1	8117
80	50000	5	8115
80	50000	10	8114
80	50000	20	8211
80	50000	30	9966
80	75000	0	8115
80	75000	1	8117
80	75000	5	8115
80	75000	10	8114
80	75000	20	8211
80	75000	30	9966
100	0	1	19326
100	0	5	19363
100	0	10	19343
100	0	20	-
100	0	30	-
100	25000	0	23233
100	25000	1	19326
100	25000	5	19363
100	25000	10	19343
100	25000	20	-
100	25000	30	-
100	50000	0	19316
100	50000	1	19326
100	50000	5	19363
100	50000	10	19343
100	50000	20	-
100	50000	30	-
100	75000	0	19316
100	75000	1	19323
100	75000	5	19363
100	75000	10	19321
100	75000	20	-
100	75000	30	-