Reconstructing Mobility in 1740's Venice: Transportation Modeling of a Multimodal Canal-City Network

EPFL CIVIL-477 Transportation Network Modeling and Analysis

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1 Introduction

The city of Venice in 1740 presented a distinctive urban landscape, characterized by a dense network of narrow pedestrian streets and an extensive system of canals. The Grand Canal, the city's principal waterway, acted as both a thoroughfare and a barrier, making cross-canal mobility a central challenge for Venetians. At that time, only a limited number of bridges, such as the iconic Rialto Bridge, spanned the Grand Canal, and for most residents, the primary means of crossing was the *traghetto*—a public rowing ferry operated by guilds.

Understanding historical patterns of movement in such a multimodal network is not only of historical interest but also provides valuable insights into the evolution of urban transportation systems, the accessibility of neighborhoods, and the socio-economic dynamics of pre-modern cities. However, the lack of direct mobility data from this era requires the use of modeling techniques that combine historical sources, urban geography, and modern network analysis.

In this study, I reconstruct the daily traffic flows in 18th-century Venice by integrating spatial data from historical property records (the *catastici*) with a multimodal network model consisting of both walking and traghetto links. By applying traffic assignment methodologies—specifically, the User Equilibrium (UE) and System Optimum (SO) formulations—I analyze patterns of congestion, modal split, and the role of traghetti and bridges in shaping urban mobility. This research demonstrates how quantitative modeling and computational tools can shed light on the functioning of historical transport systems and the impact of infrastructure on daily life.

2 Research Objectives

The main objectives of this research are:

1. **To reconstruct and estimate daily origin-destination (OD) demand flows in 18th-century Venice.**
   - Using historical property registration records (*catastici*) to infer likely home and work locations for residents.
   - Applying appropriate modeling techniques to estimate OD flows in the absence of direct mobility data.
2. **To model and analyze multimodal traffic assignment on Venice's historical street and traghetto network.**
   - Constructing a network with both pedestrian (walking) and traghetto (ferry) links.
   - Solving for User Equilibrium (UE) and System Optimum (SO) traffic flow distributions using contemporary network assignment algorithms.
3. **To quantify and discuss the effects of traghetti and limited bridges on cross-canal mobility and overall congestion.**
   - Evaluating modal split, congestion patterns, and accessibility impacts under different network and demand scenarios.
   - Investigating how changes in ferry fare, value of time, or capacity constraints affect system performance.

3 OD-Data and Demand Estimation

The *catastici* dataset contains 33,297 land registration records for 18th-century Venice, including information on tenants, rent, geographic coordinates, and parcel functions. We systematically classified properties by extracting keywords from the parcel function field, enabling us to distinguish homes, workplaces, and traghetti stations, and to reconstruct land-use patterns across the city.

For demand modeling, we defined each "agent" as a person renting more than one property. Properties classified as "Residential" were designated as home locations, while other categories were assigned as workplaces. For agents with multiple homes or workplaces, all possible home–work location pairs were considered as OD pairs.

In total, this process yielded 3,473 agent-based OD pairs, which serve as the foundation for simulating daily travel demand in the Venice network.

Table 1: Classification of OD Categories and Associated Keywords

OD	Category	Keywords
Home	Residential	casa, appartamento, casetta
Workplace	Commercial / Retail	bottega, magazen
	Mixed Use	casa e bottega
	Religious / Institutional	chiesa
	Traghetto / Squero	traghetto, liberta, squero, gondola
	Unknown / Other	—

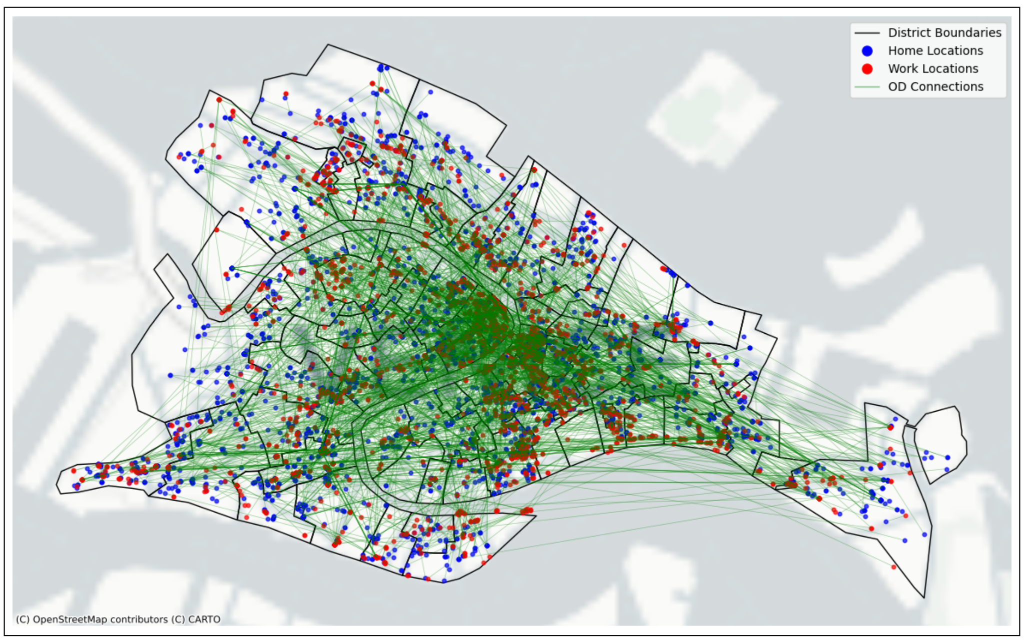

Figure 1: Agent-based OD Network based on Home and Work location

To make the analysis compatible with the multimodal network model, I aggregated all agent-based OD pairs to the district level. Each origin and destination was mapped to its corresponding historical district (based on the 18th-century administrative boundaries of Venice). The resulting OD matrix thus represents the total travel demand between each pair of districts and serves as the basis for simulating daily flows in the Venice network.

For modeling purposes, I represent each district by its geometric centroid and assume that all trips originate and terminate at these centroids.

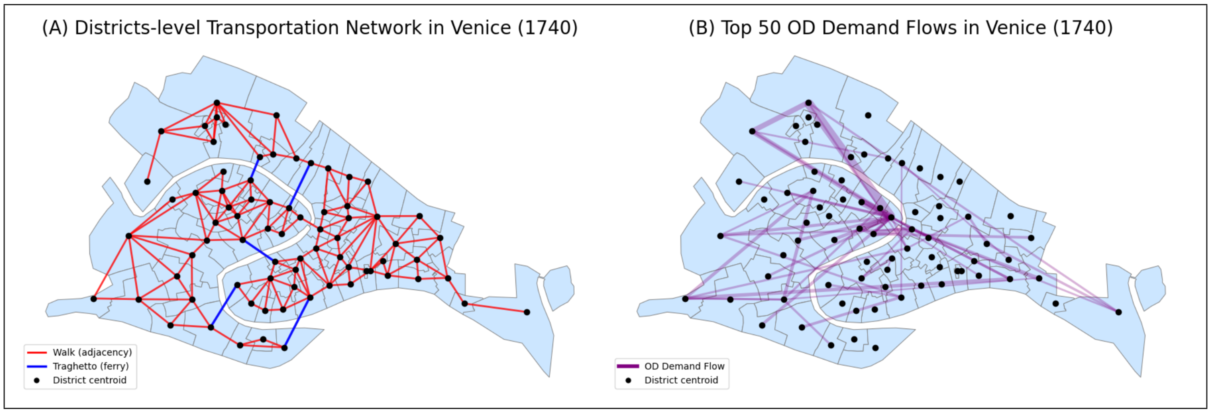

Figure 2: **(A)** District-level multimodal network **(B)** Top 50 OD Demand Flows

4 Model Formulation and Assumptions

4.1 Key Assumptions

Though some assumptions were mentioned in earlier sections, to satisfy the format of the report, here I address the following assumptions underpin the analysis:

- **Network structure:** Each node represents a historical district; links represent either walkable connections (bridges/adjacent islands) or cross-canal traghetto routes. Only major traghetti operating in 1740 are included.
- **OD demand:** Origin-destination demand is derived from aggregated agent-based home–work pairs, mapped to districts and assumed to represent average daily flows.
- **Trip assignment:** All trips are assumed to start and end at district centroids.
- **Travel time:** Walking links use a BPR-type delay function with parameters (α_{walk}, β_{walk}). Traghetto links use a separate BPR delay (α_{boat}, β_{boat}), reflecting both queueing and rowing time.
- **Capacity:** Link capacities for walking and traghetto links are assigned based on historical plausibility and sensitivity analysis, given the lack of empirical 18th-century flow data.

- **Value of time (VoT) and fare:** Generalized travel cost on traghetti combines rowing time and fare divided by an assumed value of time.

- **Steady state:** The system is assumed to reach daily equilibrium, and temporal variation within the day is not explicitly modeled.

The resulting model is a node-link network with a demand matrix (q_{od}), link travel time functions $t_{ij}(x_{ij})$, and capacity constraints, enabling multimodal traffic assignment using Frank–Wolfe algorithm.

4.2 Mathematical Formulation

Network definition. Let $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ be an oriented graph whose nodes $n \in \mathcal{N}$ represent 18^{th}-century Venetian districts and whose links $a = (i, j) \in \mathcal{A}$ represent either *walking connections* ($\mathcal{A}_{\text{walk}}$) or *traghetto links* ($\mathcal{A}_{\text{boat}}$). For each link a we define

$$t_a(x_a) = t_a^0\Big(1 + \alpha_a\big(\tfrac{x_a}{c_a}\big)^{\beta_a}\Big) \qquad \text{(BPR delay)}$$

with

$$t_a^0 = \begin{cases} \text{network-derived free-flow walking time} & a \in \mathcal{A}_{\text{walk}} \\ T_{\text{row}} + \dfrac{\text{Fare}}{\text{VoT}} & a \in \mathcal{A}_{\text{boat}} \end{cases}$$

and capacity c_a, shape parameters (α_a, β_a) taken from Tab. 2.

Optional queue delay (disabled in the calibrated base case):

$$t_a^{\text{queue}}(x_a) = \begin{cases} 0 & x_a \le c_a \\ \gamma_a\, t_a^0\big(x_a/c_a - 1\big) & x_a > c_a \end{cases}$$

so that the effective link cost is $t_a^*(x_a) = t_a(x_a) + t_a^{\text{queue}}(x_a)$.

Origin–destination demand. Denote by q_{rs} the daily trips between origin r and destination s (aggregated to district level and assumed to depart/arrive at each centroid). Peak-hour demand is approximated by $0.1q_{rs}$.

User Equilibrium (Wardrop). Find link flows $\{x_a^{\text{UE}}\}$ such that

$$\sum_{k \in \mathcal{K}_{rs}} x_{k,rs}\, t_a^*(x_a^{\text{UE}}) = \text{minimum for each } r, s, \quad a \in k,$$

or equivalently solve the Beckmann problem

$$\min_{\{x_a\}} \sum_{a\in\mathcal{A}} \int_0^{x_a} t_a^*(w)\,dw \quad \text{s.t.} \quad \sum_{k\in\mathcal{K}_{rs}} x_{k,rs} = q_{rs},\ x_{k,rs} \geq 0.$$

System Optimum. Minimise total system travel time:

$$\min_{\{x_a\}} \sum_{a\in\mathcal{A}} x_a\, t_a^*(x_a) \quad \text{s.t. the same flow-conservation constraints.}$$

The SO first-order conditions are obtained by replacing
$t_a^*(\cdot)$ with its *marginal cost* $m_a(x_a) = t_a^*(x_a) + x_a\,\frac{dt_a^*}{dx_a}$.

Table 2: Model parameters and justification

Symbol / Value	**Description**	**Historical / Technical Rationale**
$POP = 140{,}000$	Estimated 1740 population	Histrorical statistics [1]
$T_{\text{row}} = 5\,\text{min}$	Pure rowing time across Grand Canal	Average crossing duration in guild tariffs.
Fare = 0.3 lire	Princely traghetto fare	Based on average monthly rent (30 lire) in the dataset
VoT = 0.1 lire/min	Value of Time	
$c_{\text{walk}} = 5\,000$ pax/h	District-to-district walking capacity	5 parallel lanes of 1.5 m width at 0.67 p/s/m.
$c_{\text{boat}} = 500$ pax/h	Traghetto hourly capacity	5 boats × 20 pax × 5 trips/h per station.
$\alpha_{\text{walk}} = 0.20,\ \beta_{\text{walk}} = 1$	BPR parameters for streets	Low sensitivity: narrow alleys but high permeability.
$\alpha_{\text{boat}} = 0.40,\ \beta_{\text{boat}} = 1$	BPR parameters for traghetti	Higher delay sensitivity due to queuing and rowing effort.
$\gamma_{\text{walk}} = 0,\ \gamma_{\text{boat}} = 2.5$	Queue-penalty factors	Only applied when $x_a > c_a$; derived from observed waiting times at modern traghetti.
$\varepsilon = 10^{-2}$	Frank–Wolfe convergence threshold	Standard practice in network assignment
$k_{\max} = 50$	Maximum iterations	Sufficient for convergence in this sparse network.

Solution algorithms. The multimodal traffic assignment problem is solved using the classical Frank–Wolfe (FW) algorithm, which is well established for convex network equilibrium problems. Both UE and SO formulations are addressed within this unified framework. The process of FW algorithm can be found in Appendix 2.

5 Numerical results and analyses

We compare two different senario: Table 3 summarizes the traffic assignment outcomes for both the "with traghetti" and "no traghetti" scenarios. The introduction of traghetti increases cross-canal connectivity, which is reflected in the decrease of modal share and overall travel times.

Table 3: Traffic Assignment Results: With and Without Traghetti (Ferry)

Scenario	**Traghetti Share(UE)**	**Traghetti Share(SO)**	**Avg Trip Time(UE)**	**Avg Trip Time(SO)**	**Price of Anarchy**
No traghetti	0.0%	0.0%	23.53 min	23.49 min	1.002
With traghetti	13.7%	11.8%	21.53 min	21.40 min	1.006

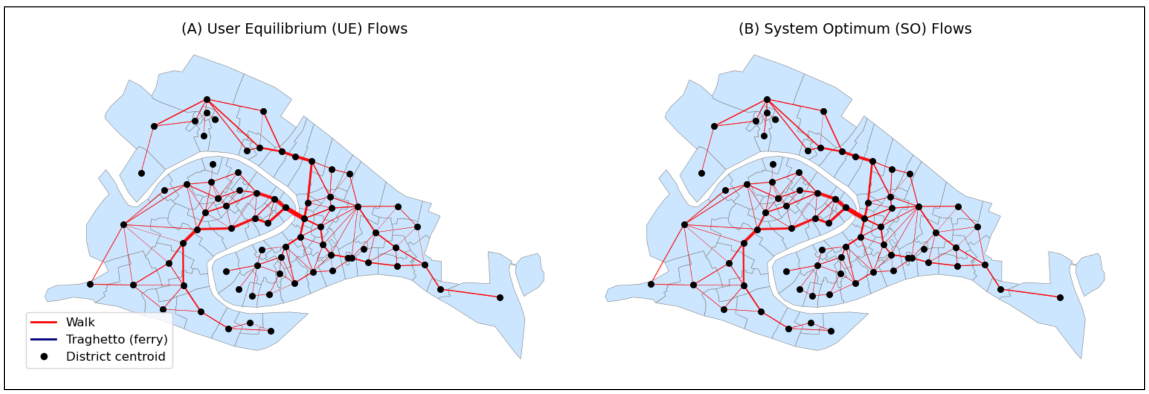

Figure 3: **(A)** UE and **(B)** SO without Traghetti network

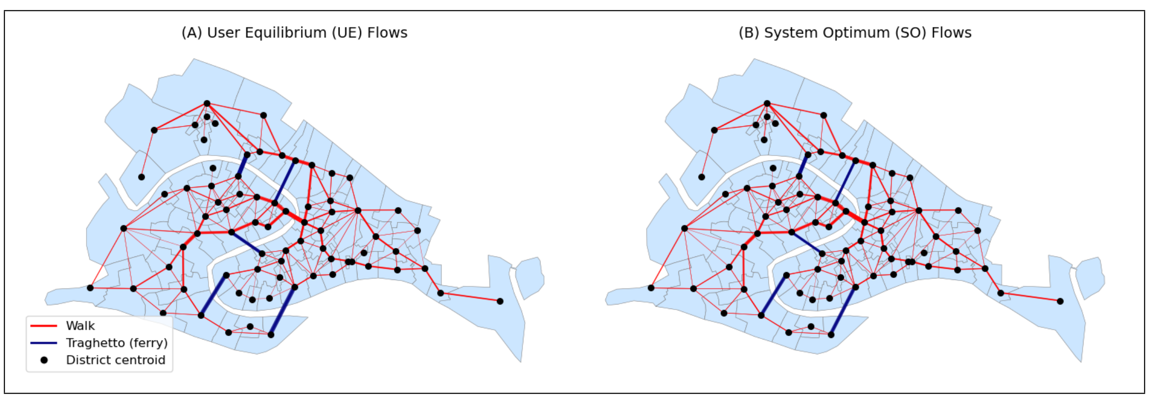

Figure 4: **(A)** UE and **(B)** SO with Traghetti network

With traghetti available, approximately 13.7% of trips under User Equilibrium (UE) and 11.8% under System Optimum (SO) utilize ferry services, indicating a significant modal split enabled by enhanced cross-canal connectivity. When traghetti are removed, all trips are reassigned to the walking network, resulting in a notable increase in average travel time (from 21.53 to 23.53 minutes for UE, and from 21.40 to 23.49 minutes for SO). This demonstrates the important role of ferries in facilitating efficient movement across the Grand Canal.

The difference between UE and SO outcomes in both modal share and average trip time is relatively small. This is primarily because the delay function's beta parameter was set to 1, yielding a nearly linear cost-flow relationship and thus minimizing the discrepancy between selfish and system-optimal routing behaviors. Additionally, not all users are compelled to use traghetti for their cross-canal trips: as illustrated in **Figure 2.B.**, the core of Venice is concentrated around the Rialto Bridge, which provides a key walking connection across the Grand Canal. As a result, a substantial portion of OD pairs are naturally served by existing bridges, further limiting the system-wide impact of traghetti availability.

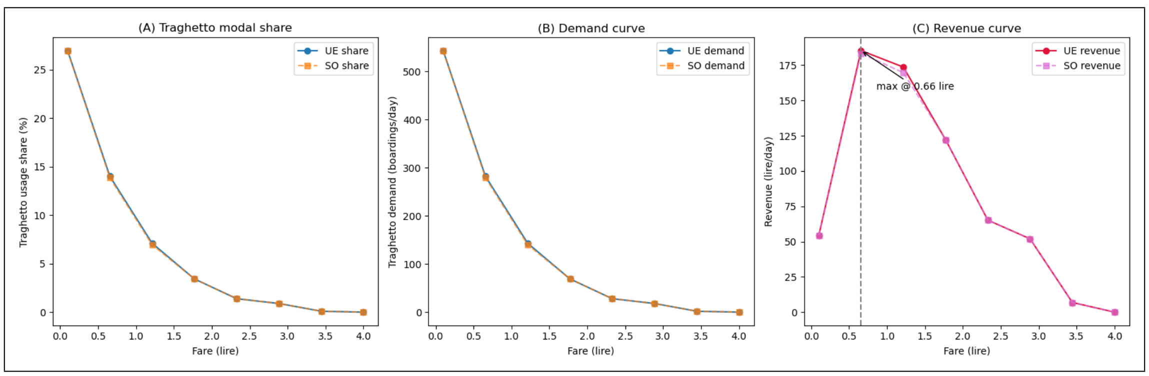

Figure 5: **(A)** Traghetti usage share **(B)** Demand curve **(C)** Revenue curve

Figure 5 summarizes the economic effects of fare setting on traghetto usage.The modal share of ferry usage declines rapidly as the fare increases, with the majority of users switching to walking when fares exceed approximately 2 lire. Panel (B) confirms this pattern in terms of total demand: daily boardings fall sharply in response to higher prices. Panel (C) plots total revenue as a function of fare. Notably, the revenue curve is unimodal, peaking at an intermediate fare. This demonstrates the trade-off between price and ridership: while higher fares increase per-trip revenue, they also reduce demand to the point where total income declines. The existence of a revenue-maximizing fare (the apex of the curve) is consistent with basic microeconomic theory.

These results indicate the high price sensitivity (elasticity) of traghetto demand. In terms of supply, it was fixed under the historical contex. Only those with libertà (lisence)were allowed to operate a traghetto service. Indeed, in the ownership of the traghetti business in catastici dataset, the owner of the traghetti usually came from big family.

6 Conclusions and Key Takeaways

- **Traghetto services significantly improved cross-canal accessibility and efficiency.** The introduction of traghetti resulted in about 12–14% of trips using the ferry, reducing overall average travel times by approximately two minutes. This demonstrates the substantial impact of multimodal networks on urban mobility, even in historical contexts.

- **Traghetto demand is highly price-elastic.** As fares increase, both the usage share and total demand for traghetto services decline sharply. The revenue curve is unimodal, peaking at an intermediate fare—reflecting the classic trade-off between price and ridership, and confirming basic microeconomic principles.

- **User Equilibrium (UE) and System Optimum (SO) outcomes are very similar.** Because the cost-flow delay function was set to be nearly linear ($\beta = 1$), the gap between selfish routing and system-optimal assignments is minimal, resulting in a low price of anarchy.

- **Most origin–destination pairs do not strictly require traghetto use.** The majority of OD pairs, especially those near the Rialto Bridge, are naturally served by existing walking connections. Traghetto services mainly benefit those OD pairs where bridges are absent.

Policy and Research Implications:

- Integrating multimodal infrastructure can greatly enhance urban accessibility, even when physical space or resources are limited.

- Understanding the rigidity of historical transport supply provides valuable context for comparing past and present urban mobility policies.

- The modeling and analysis approach developed here can be extended to other historical cities to explore the long-term interactions between infrastructure and urban spatial economics.

7 Code Availability

The codes of the research are in the following github repository:
https://github.com/trip1ech/Venice1740-Transportation

References

[1] Statista. Population of venice, italy from 1300 to 2022. `https://www.statista.com/statistics/1281705/venice-population-historical/`, 2022. Accessed: 2025-06-08.

8 Appendix

Frank-Wolfe Algorithm implementation:

1. **Initialization:** An all-or-nothing (AON) assignment is performed based on free-flow link costs to generate an initial feasible flow.

2. **Direction finding:** At each iteration, link costs are updated using the current flows and the generalized BPR cost function (including optional queue penalties). A new AON assignment is computed—using current link costs for UE, and marginal costs for SO.

3. **Line search:** The optimal move size $\lambda^\star$ is computed by minimizing the total system travel time along the direction from the current flow to the auxiliary flow.

4. **Flow update:** Link flows are updated as a convex combination of the current and auxiliary flows.

5. **Convergence check:** The algorithm repeats until the relative flow gap falls below $\varepsilon = 10^{-2}$ or the maximum number of iterations is reached ($k_{\max} = 50$).

For the System Optimum, marginal link costs are used:

$$m_a(x_a) = t_a^*(x_a) + x_a \frac{dt_a^*}{dx_a}$$

where $t_a^*(x_a)$ denotes the effective link cost (including any queueing penalty).

All-or-nothing assignments are solved via shortest-path calculations using Dijkstra's algorithm. Computations were implemented in Python.