Digital Twin and Social Implications

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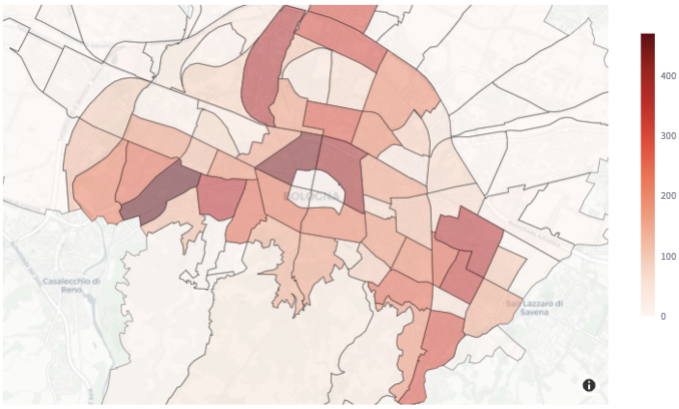

Abstract

Urban traffic simulations are critical tools for informing transportation planning and policy, yet traditional models often overlook the social and demographic disparities that shape mobility experiences and environmental exposure. This report presents the design and implementation of an ethical cost function that integrates demographic and socioeconomic vulnerabilities—specifically gender composition and a fragility index—into traffic flow and emissions modeling. By incorporating logistic smoothing and temporal sensitivity, the function applies nuanced, non-linear adjustments that reflect the fluctuating nature of social responsibilities and population fragility throughout the day. Applied to the city of Bologna, Italy, the model demonstrates how ethical considerations can be embedded within traffic simulations to promote equitable treatment of vulnerable communities. The approach advances justice-aware urban planning by enabling more inclusive and context-sensitive decision-making, thereby supporting the fair allocation of traffic, emissions, and mobility infrastructure. This work contributes a practical framework for embedding fairness and environmental justice into urban mobility models, encouraging responsible and ethical development of sustainable cities.

1 Introduction

Urban traffic modeling plays a pivotal role in shaping the design and management of transportation systems, directly impacting accessibility, environmental quality, and overall urban livability. However, traditional traffic models typically adopt a uniform treatment of all urban areas, overlooking the complex social and demographic realities that influence how different populations experience mobility and environmental risk. This uniformity risks perpetuating systemic inequities, particularly for vulnerable groups who may face disproportionate exposure to traffic congestion, pollution, and limited mobility options.

In response to these challenges, this project introduces an *ethical cost function* that systematically integrates demographic and socioeconomic vulnerabilities into traffic simulation outputs—specifically targeting flow costs and emissions. The function incorporates two critical dimensions of vulnerability:

- **Gender** [3], operationalized as the percentage of female residents, reflecting caregiving roles and social factors linked to mobility constraints;
- **Fragility Index** [2], a composite measure capturing socioeconomic and health-related vulnerabilities.

By embedding these factors, our approach moves beyond traditional optimization frameworks that treat all spatial units identically. Instead, it advances an *equity-oriented* paradigm that recognizes and compensates for disparities in mobility needs and environmental burdens.

To demonstrate the practical application and impact of this framework, we integrate the ethical cost function with traffic simulation data for the city of Bologna, Italy. The adjusted simulation outputs offer actionable insights for planners seeking to promote just and inclusive urban development, ensuring that policies are informed by a nuanced understanding of demographic diversity and vulnerability.

This work contributes to a growing body of research that advocates for socially-aware urban modeling, emphasizing fairness and justice as foundational criteria in the design of sustainable and resilient cities.

2 Objective

The primary objective of this ethical cost function is to enhance urban traffic simulations by integrating social equity considerations directly into the modeling process. Specifically, the function aims to:

- **Adjust cost values based on gender demographics**, with targeted reductions in areas exhibiting high concentrations of women, particularly during time periods associated with caregiving and school-related activities. This reflects the heightened mobility challenges and social responsibilities often experienced by women.
- **Incorporate socioeconomic vulnerability** by lowering cost values in zones characterized by elevated fragility indices. These areas are more susceptible to environmental hazards, traffic congestion, and limited access to reliable transportation, warranting prioritized ethical consideration.
- **Embed temporal sensitivity** to account for the dynamic nature of social responsibilities and vulnerabilities throughout the day. This ensures that the ethical adjustments are contextually relevant, adapting to fluctuating demands such as peak caregiving hours.

By aligning simulation outputs with these principles, the function supports more equitable urban planning and policy-making. It enables fairer distribution of traffic flows, emissions, and mobility infrastructure investments—thereby advancing ethical and inclusive urban design.

3 Calculation of New Values for Area Statistiche

This section describes the process of calculating values for zones of **statistical areas(Aree Statistiche)** based on values of zones in **green areas(Area Verde)**. The statistical areas receive a derived value based on the overlap with surrounding green area zones.

3.1 Source Data

We use two main GeoDataFrames:

- `gdf_zones`: Contains geometry and value data for zones in green ares.
- `aree_statistiche_gdf` [1]: Contains geometry of statistical areas.

The Coordinate Reference Systems (CRS) of both datasets are aligned to EPSG:4326.

3.2 Methodology

The methodology is illustrated in Figure 1, which visualizes the relationship between one statistical area (zone D) and three overlapping green areas (A, B, and C). The value assigned to D is calculated as a weighted sum of the values from zones A, B, and C based on their geometric overlap with D.

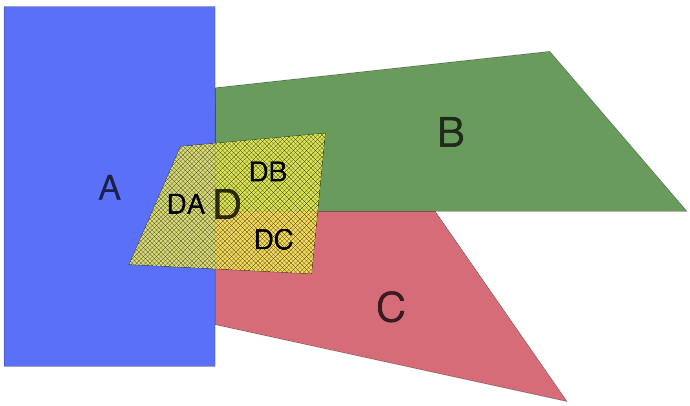

Figure 1: Illustration of zone overlap and coefficient computation.

Steps:

For each statistical area D:

1. Identify all zones X in `gdf_zones` such that $X \cap D \neq \emptyset$.
2. For each intersecting zone X:
   - Calculate the intersection area $D_X = \text{Area}(X \cap D)$.
   - Compute the total area $A_X = \text{Area}(X)$.
   - Derive coefficient $\text{Coeff}_{X,D} = \frac{D_X}{A_X}$.
3. The value for D is then given by:

$$\text{Value}_D = \sum_X \text{Value}_X \cdot \text{Coeff}_{X,D}$$

3.3 Implementation Details

The implementation occurs in the function `new_plot_statistical_area_map`, where:

- Temporal filtering is optionally applied to the raw values (e.g., per time interval).
- Zone values are mapped from `evals` using the supplied `index` dictionary.
- Spatial intersection is used to distribute values from zones to statistical areas.
- Ethical adjustments are applied based on gender and fragility indicators (see below).

Ethical Adjustment

Two additional metrics are introduced for equity-aware planning:

- **Female percentage** (from census): increases priority during school-related hours.
- **Fragility index** (from municipal data): decreases burden on fragile populations.

The raw values are adjusted using the `ethical_cost_function` which accounts for time-of-day and demographic characteristics.

4 Function Overview

4.1 ethical_cost_function

The function receives a raw simulation output (e.g., traffic flow, emission level) and returns an **ethically adjusted version** based on local demographic data and the time of day.

```
def ethical_cost_function(
    raw_value: float,
    female_percentage: float,
    fragility_index: float,
    time_of_day: Optional[float] = None,
    params: Optional[Dict] = None
) -> float:
```

Input Descriptions:

- `raw_value`: The original, unadjusted metric from the simulator.
- `female_percentage`: The proportion of the zone's population that identifies as female.
- `fragility_index`: A socioeconomic vulnerability score for the zone.
- `time_of_day`: Hour of the day (0 to 24), used to trigger time-sensitive adjustments.
- `params`: An optional dictionary of tunable parameters.

The returned value reflects **adjustments based on ethical considerations**, such as who is affected by the traffic, and when.

4.2 Logistic Smoothing Function

To ensure that the adjustments made by the model change gradually rather than abruptly, we apply a smoothed logistic transformation to normalized inputs. This is particularly useful when modulating effects such as gender distribution or fragility index, allowing for a more interpretable and ethically sensitive scaling of values.

The logistic smoothing function is defined as:

$$L(x;k) = \frac{\sigma(x;k) - \sigma(0;k)}{\sigma(1;k) - \sigma(0;k)}, \quad \text{where} \quad \sigma(x;k) = \frac{1}{1 + e^{-k(x-0.5)}}$$

Here:

- $x \in [0,1]$ is the normalized input value (e.g., female percentage or fragility ratio),
- k is the steepness parameter (we use $k = 6$ in practice),
- $\sigma(x;k)$ is a standard logistic function centered at $x = 0.5$.

This transformation maps the input x to the $[0,1]$ interval using a smooth "S"-shaped curve. The output increases slowly when x is near 0, grows rapidly around $x = 0.5$, and then levels off near 1 as x approaches 1. The use of $k = 6$ provides a good balance between smoothness and responsiveness.

The normalization step (subtracting $\sigma(0)$ and dividing by the range $\sigma(1) - \sigma(0)$) ensures that the final result is strictly bounded between 0 and 1, regardless of the steepness k.

4.3 Gender-Based Adjustment

Rationale

Women disproportionately carry the burden of *unpaid care work*, such as school drop-offs and household errands. They are also more likely to rely on public or slower transport modes. Traffic policies that ignore gender differences risk reinforcing inequality.

Implementation

1. **Base Adjustment** (applies at all times):

$$\text{female\_factor} = 1 - (\text{female\_reduction\_base} \times L(female\_pct; k))$$

   Where L is the Logistic Smoothing function.

2. **Time-Sensitive Adjustment** (applies during caregiving hours):

   - Morning: 07:00–09:00
   - Midday: 13:00–15:00
   - Late Pickup: 16:00–18:00

   Additional reduction:

$$\text{fragility\_factor} = 1 - (\text{fragility\_reduction\_base} \times L(fragility\_ratio; k) \times \text{time\_modifier})$$

   Where L is the Logistic Smoothing function.

4.4 Fragility-Based Adjustment

Rationale

The **fragility index** captures a zone's socioeconomic vulnerability, incorporating indicators such as income level, housing stability, and access to public services. Areas with high fragility are typically more susceptible to environmental stressors, less equipped to handle disruptions, and more likely to experience long-term negative impacts. As such, the model assigns preferential treatment to these zones by reducing the simulated value (e.g., emissions, inflow) accordingly. This ensures that the burden of traffic-related harm is not unfairly concentrated in the most vulnerable communities.

Implementation

1. **Smooth Scaling via Logistic Transformation**
   The normalized fragility score is passed through a logistic smoothing function to produce a continuous effect that increases with fragility but avoids sharp jumps. This makes the model's behavior more ethical, interpretable, and resilient to noise in the data.

2. **Time-Sensitive Scaling**
   Fragility effects are further modulated based on the time of day to reflect the daily rhythm of human activity and exposure risk:

   - **Off-peak hours** (10:00–15:00): amplification factor $\times 1.2$
   - **Early morning or late evening** (before 07:00 or after 20:00): dampening factor $\times 0.7$
   - **Other times**: standard reduction factor

   This temporal sensitivity reflects patterns of social vulnerability throughout the day.

3. **Final Scaling Formula**
   The final fragility reduction factor applied to the raw value is computed as:

   $$\text{fragility\_factor} = 1 - (\text{fragility\_reduction\_base} \times L(\text{fragility\_ratio}; k) \times \text{time\_modifier})$$

   where $L(\cdot)$ is the logistic smoothing function and time_modifier $\in \{0.7, 1.0, 1.2\}$ depending on the time window.

This adjustment allows the simulator to reflect not only structural vulnerability but also daily cycles of exposure, ultimately aligning the model with principles of equity and justice in urban decision-making.

4.5 Fragility Mobility Penalty

In our model, we introduce the concept of a *fragility mobility penalty*, represented by the parameter `fragility_mobility_penalty`, which ranges from 0 to 1. This penalty accounts for the observed tendency in economically fragile zones to have lower vehicle ownership and usage, often due to reduced financial means to purchase or maintain cars.

Mathematically, this penalty reduces the effective traffic, inflow, and emission values proportionally to the fragility of the zone. The penalty is applied smoothly using a sigmoid-like function (hyperbolic tangent) to model the gradual increase in mobility reduction with rising fragility. The formula used is:

$$\text{mobility\_scaling} = 1 - \texttt{fragility\_mobility\_penalty} \times \tanh(2 \times \text{fragility\_ratio})$$

where:

- **fragility_ratio** is the normalized fragility index of the zone (from 0 to 1).
- **fragility_mobility_penalty** controls the maximum reduction fraction.

This means that:

- Zones with low fragility experience little to no reduction in mobility-related metrics.
- Zones with high fragility can see their traffic, inflow, and emissions reduced by up to the maximum penalty fraction.

For example, a penalty value of 0.4 implies up to a 40% reduction in these metrics for the most fragile zones, reflecting a realistic scenario where fewer residents use private vehicles and potentially rely more on bicycles or public transport.

This approach allows the model to capture ethical and socioeconomic factors more accurately, adjusting the environmental impact estimations accordingly.

5 Emissions Weighting Based on Fragility

In addition to adjusting traffic costs, the model assigns emission weights to each zone based on fragility using the function:

```
def classify_fragility_emission_weight(fragility_score):
```

Multipliers by Fragility

Fragility Score	Category	Multiplier
81–89	Low	1.00
89–97	Medium-Low	1.10
97–105	Medium	1.20
105–113	Medium-High	1.30
113–120	High	1.40

This discourages high-emission traffic from routing through vulnerable areas and aligns the model with principles of **environmental justice**.

6 Ethical Justification

The design of the ethical cost function is rooted in key ethical principles to ensure that the adjustments it makes promote fairness, sensitivity, and justice in urban planning decisions:

- **Equity over Uniformity**
  Traditional cost models apply the same treatment across all areas, ignoring existing social and environmental inequalities. This function deliberately incorporates demographic data—such as gender distribution—and fragility indices to identify and protect vulnerable populations. By doing so, it ensures that resources and risks are distributed more fairly, addressing systemic disparities rather than perpetuating them.

- **Temporal Sensitivity**
  Vulnerabilities and ethical considerations are not static; they fluctuate throughout the day. For example, certain hours correspond to increased caregiving responsibilities or higher exposure for vulnerable groups (like school commute times). The model dynamically adjusts ethical weights based on the time of day, allowing for context-aware sensitivity that reflects real-world patterns.

- **Environmental Justice**
  Disadvantaged communities often bear a disproportionate share of environmental harms, such as pollution from traffic emissions. To counteract this, the function applies heavier penalties to emissions in fragile areas. This targeted weighting discourages harmful activities in vulnerable zones, promoting healthier, more just environmental outcomes for all populations.

7 Integration and Visualization

Once the ethical adjustments have been calculated for each statistical area, these updated values are merged back into the original GeoDataFrame containing the spatial boundaries and demographic data of each area. This integration ensures that the adjusted metrics—such as traffic flow or emissions modified by ethical factors—are linked directly to their corresponding geographic regions.

To make these results accessible and insightful for urban planners and decision-makers, we create interactive choropleth maps using Plotly. These maps visually represent the adjusted values across different areas, with color gradients indicating the magnitude of traffic or emissions after ethical corrections.

Additionally, demographic information—like the proportion of vulnerable populations or fragility scores—is overlaid or accessible through interactive tooltips. This layering enables planners to easily explore how ethical adjustments correlate with demographic vulnerabilities in different locations, facilitating more informed, equity-focused planning decisions.

8 Conclusion

This ethically-informed cost function represents a significant step forward in justice-aware urban simulation. By explicitly integrating demographic and socioeconomic factors into traffic and emissions modeling, the function ensures that vulnerable populations receive fairer and more considerate treatment.

When applied to the city of Bologna, the model:

- Protects areas with a high presence of women and elevated fragility indices from disproportionate traffic and environmental burdens.
- Promotes traffic management that is sensitive to caregiving hours, reducing negative impacts during critical times.
- Encourages more equitable routing of emissions, minimizing environmental harm in vulnerable communities.

By moving beyond traditional, neutral optimization approaches and embedding principles of fairness directly into the simulation logic, this function provides a practical foundation for more inclusive and ethically responsible urban development and planning.

References

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