Mapping Mobility Justice: A Deep Learning and GIS-Based Framework for Micro-Scale Sustainable Mobility Policy Assessment

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Abstract. The development of inclusive and sustainable transport policies demands accurate, spatially detailed data on the built environment and mobility infrastructure—particularly at the neighborhood level, where daily mobility patterns and access disparities are most visible. This study proposes MiSHar (Micro-Scale Sustainable Mobility Index), an integrated analytical framework that leverages deep learning-based object detection and Geographic Information Systems (GIS) to systematically evaluate the sustainable mobility potential of urban micro-regions. High-resolution satellite and aerial imagery are processed using convolutional neural networks to automatically detect physical features such as buildings, green areas, paved surfaces, pedestrian and bicycle networks. These are subsequently combined with GIS-based public transport bus stop yielding a multi-dimensional index formulation. The index incorporates weighted parameters related to population density, infrastructure provision, and land use patterns. A pilot implementation in Adapazarı District (Sakarya, Türkiye) demonstrates the model's ability to reveal intra-urban mobility inequalities and provide spatial evidence for transport-oriented development strategies. MiSHar represents a policy-responsive, survey-independent, and scalable approach to mobility diagnostics. By integrating AI-powered spatial analytics with urban planning principles, it offers a valuable tool for local governments seeking to target infrastructure investments, design equity-focused interventions, and align with European and global sustainable mobility goals.

Keywords: Sustainable mobility index, Deep learning, GIS, Micro-scale analysis

1 First Section

Urban mobility systems are undergoing profound transformations as cities grapple with rapid population growth, rising vehicle ownership, and escalating demands for equitable access to opportunities. In Europe and globally, sustainable mobility has been positioned as a cornerstone of climate resilience and social inclusion, reflected in the European Green Deal, Urban Mobility Framework (EC, 2021), and the Sustainable Development Goals (SDG 11: Sustainable Cities and Communities). Yet, achieving these goals requires more than macro-scale transport planning; it necessitates granular, micro-scale analyses of how mobility infrastructures and services are distributed across neighborhoods.

Traditional transport planning models—such as the four-step travel demand framework—have proven valuable for forecasting aggregate travel behavior. However, their effectiveness is highly dependent on the definition of spatial units. In many developing countries, including Türkiye, traffic analysis zones (TAZs) are defined at relatively large scales, often encompassing entire neighborhoods or even broader areas (Altan & Ayözen, 2018; McNally, 2007). While this coarse zoning structure reduces the burden of data collection and survey design, it also masks fine-grained variations in mobility patterns. As a result, although intra-urban disparities remain less visible, the use of large-scale TAZs in Türkiye contributes to strengthening the spatial coverage and applicability of the traditional model. Consequently, the equity and sustainability dimensions of daily mobility—particularly walkability, cycling potential, and access to public transport—remain underexplored at the neighborhood level.

Emerging advances in GIS and artificial intelligence (AI) provide opportunities to overcome these limitations. Deep learning techniques applied to high-resolution satellite imagery enable automated extraction of built environment features, while open datasets such as OpenStreetMap (OSM) and municipal transit records allow integration of infrastructure and service attributes. Together, these tools make it possible to construct fine-grained indices of sustainable mobility potential without the prohibitive costs of large-scale surveys (Liu et al., 2020; Esch, 2011).

This paper introduces MiSHar a framework designed to quantify sustainable mobility capacity at the sub-neighborhood scale. By combining deep learning–based building and land-use detection with GIS-based transit and active transport infrastructure data, MiSHar provides a composite measure of mobility justice. A pilot study is conducted in Karaman/Yenikent region of Sakarya (Türkiye), where rapid urbanization, mixed land-use patterns, and increasing travel demand create both opportunities and challenges for sustainable mobility.

The contributions of this study are threefold:

1. Methodological innovation – integrating AI-powered remote sensing with GIS to produce a scalable, survey-independent mobility index.
2. Policy relevance – generating actionable spatial evidence to support transport-
3. Empirical application – demonstrating the feasibility of MiSHar through a pilot implementation in a rapidly growing Turkish urban district.

By situating mobility analysis at the micro-scale, this research aligns with TRA 2026's theme of "Advancing Sustainable and Inclusive Mobility", providing a replicable framework for European and global cities seeking to bridge the gap between smart data analytics and socially just transport policies.

2 Literature Review

Sustainable urban mobility has long been recognized as a multi-dimensional challenge encompassing environmental, economic, and social objectives (Litman & Burwell, 2006). The European level emphasize integrated, people-centered planning approaches. Internationally, frameworks such as the UN Sustainable Development Goals and the Paris Agreement further highlight mobility's role in reducing carbon emissions and promoting equitable access.

Despite this policy momentum, the translation of strategic goals into localized interventions remains difficult. Scholars stress that accessibility, rather than mobility alone, should be the central metric for transport justice (Boschmann & Kwan, 2008). Accessibility encompasses not only the physical presence of infrastructure but also its affordability, safety, and usability across diverse social groups.

While metropolitan-scale transport models dominate practice, micro-scale assessments provide crucial insights into neighborhood-level disparities. Studies on walkability indices (Chatziioannou et al., 2023), school-area accessibility metrics (Prado, 2016), and sustainable mobility scales (Saiu et al., 2022) highlight how localized indicators can reveal inequities hidden in aggregated data. However, many of these tools rely on manual surveys or limited datasets, constraining their applicability across diverse urban contexts.

In Türkiye, reliance on traditional TAZ structures has further limited precision. Household surveys underpinning Istanbul's master plans in 1997 and 2012 grew from 12,000 to 160,000 responses, yet still struggled to capture heterogeneity at the sub-neighborhood scale (Altan & Ayözen, 2018). For mid-sized cities such as Sakarya, comprehensive survey efforts are often absent, creating a critical data gap in planning.

GIS has become an indispensable tool for transport and urban planning, enabling integration of land use, demographic, and infrastructure data. Remote sensing adds a powerful dimension by providing consistent, high-resolution imagery for built environment monitoring. Applications range from building density estimation (Kajimoto & Susaki, 2013; Xu et al., 2022) to green space mapping (Liu et al., 2020). Such data sources can support fine-grained accessibility analyses, particularly when traditional survey data are lacking. Attempts to operationalize sustainability at the micro-scale have produced various composite indices. For example, ElDessouki (2022) proposed a time-based equity index, while the IMPES model (Prado, 2016) evaluated pedestrian accessibility around schools. Yet most indices remain limited in scope, focusing on single modes or specific contexts.

The MiSHar framework builds on these precedents by combining multiple dimensions—built environment density, transport infrastructure, population distribution, and green space availability—into a unified index. Unlike survey-heavy approaches, MiSHar relies on open-source datasets (OSM), municipal transit records, and AI-based image analysis. This not only reduces costs but also enhances scalability, making it suitable for mid-sized cities where resources are limited. Existing literature demonstrates the potential of GIS and deep learning for mobility assessment but stops short of integrating these methods into comprehensive policy-oriented tools. Moreover, few studies have applied such approaches in the Turkish context, where urban growth pressures are intense and planning data are sparse.

This study addresses these gaps by:

- Developing a survey-independent mobility index tailored to micro-scale analysis,
- Demonstrating its application in Karaman/Yenikent, Sakarya, and
- Positioning the results within broader European sustainable mobility policy debates.

3 Methodology

This study develops the Micro-Scale Sustainable Mobility Index (MiSHar) for the Karaman/Yenikent district of Sakarya by combining Geographic Information Systems (GIS), deep learning–based feature extraction, and statistical weighting approaches. The index is designed to provide a standardized and reproducible measure of sustainable mobility capacity at the micro-zone level, avoiding the limitations of survey-dependent transport planning methods

These spatial features were subsequently integrated with open data from OpenStreetMap (OSM) and municipal datasets, which provided information on pedestrian and cycling networks, public transport stops, and service coverage. The combined dataset allowed for the computation of six key indicators (Table 1):

- Green area (GA) – total green space in each zone,
- Building density (BD) – ratio of built-up area to total area,
- Pedestrian network length (PL),
- Cycling network length (CL),
- Public transport stops (PTS),
- Population density (PD).

Table 1. Pilot Study Area Data extracted from OSM database

Zone	Green Area (m^2)	Number of Building	Building Density	Pedestrian Road Distance (m)	Cycling Path Distance (m)	Number of Public Transport Stop	Population Density ($person/m^2$)
1	300,96	61	0,0999	5660,44	0	7	0,012887734
2	300,96	75	0,1107	7697,67	0	14	0,014066377
3	723,41	76	0,0696	13533,36	1361,4	18	0,006486118
4	20396,25	53	0,0808	3464,22	0	8	0,008541925
5	0	83	0,12	8138,56	0	11	0,01070640

			18				4
6	129 60,14	49	0,14 10	6747,47	0	7	0,00815508 9
7	170 98,75	94	0,14 45	8185,84	345,67	12	0,01126761 5
8	951 4,07	47	0,09 07	6031,89	1015,73	9	0,00829556 7
9	499 9,24	43	0,11 50	4395,69	0	3	0,01212293 8

These variables were normalized by dividing by their observed maxima across the study area, used here as proxies for theoretical maxima. The general formulation of MiSHar is:

$$MiSHar = (\alpha \cdot (GA/GAmax) + \beta \cdot (BD/BDmax) + \gamma 1 \cdot (PL/PLmax) + \gamma 2 \cdot (CL/CLmax) + \gamma 3 \cdot (PTS/PTSmax) + \delta \cdot (PD/PDmax)) \quad (1)$$

Three different approaches were applied to determine these weights:

- Equal weights: each component assigned the same importance (1/6). This baseline approach assumes equal contribution of all factors to sustainable mobility.
- Policy weights: higher priority was assigned to active and public transport components (PL, BD, PTS each weighted 0.20), moderate weight to green space and building density (0.15 each), and lower weight to population density (0.10). This reflects policy priorities in European sustainable mobility strategies, where accessibility and low-carbon modes are central.
- PCA-derived weights: to avoid subjective assumptions, a Principal Component Analysis (PCA) was conducted on the normalized variables. The loadings from the first principal component (explaining ~50% of total variance) were converted into positive, normalized weights summing to one. This unsupervised method objectively identified the relative importance of each component in explaining variation in mobility-related attributes.

The MiSHar index was then computed for each micro-zone under all three weighting schemes, producing values on a 0–1 scale. While equal and policy-weighted indices provide useful benchmarks, the PCA-based index was preferred as the primary analytical tool in this study because it reflects the inherent structure of the data without requiring expert judgment or external calibration.

4 Results

The MiSHar index was calculated for nine micro-zones in the Karaman/Yenikent district (Figure 1), applying the three weighting schemes defined in the methodology: equal weighting, policy weighting, and PCA-derived weighting. Across all approaches, MiSHar values were normalized on a 0–1 scale, with higher scores reflecting greater sustainable mobility potential.

Fig. 1. Study Area (Karaman/Yenikent, Sakarya)

The equal-weighted MiSHar produced a relatively compressed distribution (mean = 0.390, SD = 0.055), ranging from 0.303 to 0.488. This smoothing effect arises because all factors contribute equally, so weaknesses in one dimension are balanced by strengths in another. In contrast, the policy-weighted MiSHar introduced greater differentiation (mean = 0.351, SD = 0.067; range = 0.260–0.460), with higher emphasis placed on zones with robust transit and active mobility infrastructure (Figure 2)

The PCA-based MiSHar generated the most pronounced contrasts, with scores spanning from 0.240 to 0.510. Because PCA empirically derives weights from the dataset, it amplified disparities that were less visible under equal and policy weighting. Zones combining dense pedestrian and cycling networks with multiple public transport stops consistently achieved the highest scores, while peripheral areas lacking such infrastructure were downgraded.

The PCA index results reveal a distinct intra-district hierarchy. Centralized zones with greater connectivity and multimodal service provision scored highest, underscoring the decisive role of functional accessibility infrastructure. Conversely, areas dominated by green space or moderate building density but lacking public transport and active mode networks exhibited weaker sustainable mobility performance. This highlights that infrastructure enabling access—rather than simply land-use form—constitutes the critical determinant of mobility justice at the neighborhood scale.

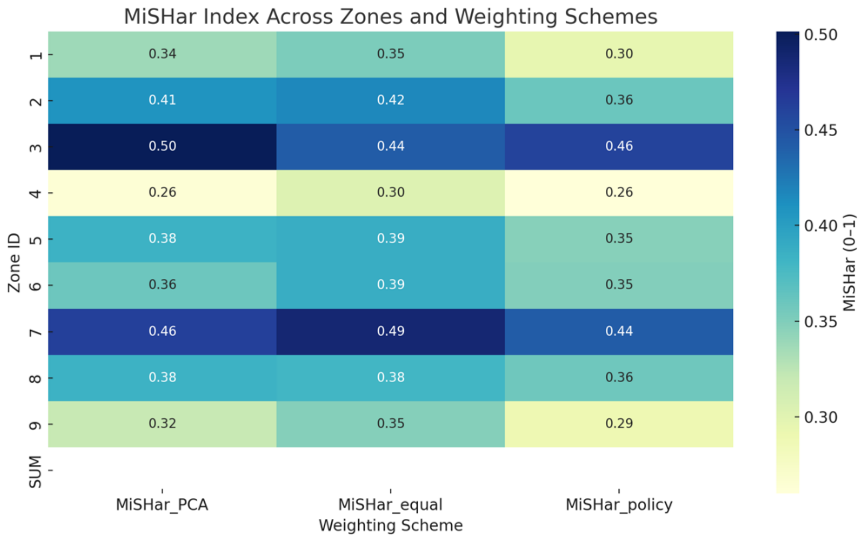

Fig 2. MiSHar Index Across Zones

The PCA model explained approximately 50% of the total variance in the six input dimensions. Factor loadings indicated that public transport stops (PTS), pedestrian network length (PL), and cycling network length (CL) carried the greatest weights, jointly accounting for nearly two-thirds of the PCA variance. Green area (GA) and population density (PD) received lower weights, reflecting their weaker contribution to differentiating micro-zones. These findings are consistent with international evidence that accessibility and multimodality are stronger predictors of mobility sustainability than morphological indicators alone (Boschmann & Kwan, 2008; Saiu et al., 2022).

5 Discussion and Conclusion

The results of this study demonstrate that the design of weighting schemes has a decisive influence on how sustainable mobility capacity is measured and interpreted at the micro-scale. The equal-weight formulation provided a neutral benchmark, producing balanced yet relatively homogenous scores. While useful as a diagnostic baseline, this approach risks obscuring the differentiated role of transport infrastructure in shaping accessibility. The policy-weighted index, by contrast, aligned directly with European mobility agendas such as the Urban Mobility Framework and the European Green Deal, rewarding zones with stronger provision of active and public transport facilities. Yet this method presupposes normative priorities, which may not fully reflect the complex realities of diverse urban contexts.

The PCA-derived MiSHar index proved most robust by empirically estimating weights from the dataset itself. This data-driven approach minimized subjectivity and revealed that public transport stops, pedestrian pathways, and cycling networks are the dominant contributors to intra-district variations in sustainable mobility. By contrast, morphological attributes such as green space and building density—though valuable for broader urban quality of life—played a secondary role in determining accessibility and mobility equity. The finding that PCA explained approximately half of the total variance across all dimensions underscores the methodological strength of allowing the data, rather than expert judgment, to determine factor importance.

From a policy perspective, the implications are clear: investments in functional accessibility infrastructure yield disproportionately greater improvements in sustainable mobility capacity than marginal increases in green area or adjustments to building density. For municipalities such as Sakarya, this provides a powerful, evidence-based rationale for prioritizing the expansion of pedestrian and cycling networks and the densification of public transport stops. By shifting emphasis from form to function, MiSHar supports the evolution of planning paradigms from mobility to accessibility, ensuring that investments directly enhance equity, usability, and climate resilience.

In conclusion, MiSHar offers a scalable, transferable, and survey-independent framework for diagnosing and addressing intra-urban mobility disparities. By integrating AI-powered feature detection, GIS-based analysis, and statistically derived weighting, it bridges methodological innovation with policy relevance. Applied to Karaman/Yenikent, the framework not only illuminated local inequalities but also provided actionable guidance that aligns with European climate and mobility objectives. In doing so, MiSHar exemplifies the advancing sustainable and inclusive mobility through approaches that are rigorous, data-driven, and policy-responsive.

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