Australasian Transport Research Forum 2024 Proceedings
27-29 November, Melbourne, Australia
Publication website: https://australasiantransportresearchforum.org.au/

Exploring cyclists' perceptions of safety and comfort: A machine learning approach to enhancing urban cycling environments

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1 Introduction

Cycling presents an efficient solution for developing sustainable transportation systems (Ito and Biljecki, 2021). A key factor influencing the decision to cycle is the subjective perception of the built environment (BE), as it directly affects individuals' choice to travel by bike (Ullmann et al., 2022). The safety and comfort of the built environment (BE) are particularly important in shaping these perceptions and influencing cyclists' experiences (Winters and Tucker, 2004). When people feel safe and comfortable, they are more inclined to choose cycling as their primary mode of transport (Aziz et al., 2018). Therefore, understanding how BE features affect these perceptions is crucial for fostering a cycling-friendly environment that encourages more people to adopt cycling.

While on-site surveys have traditionally been used to assess the bike-friendliness of built environments, they are limited in spatial resolution and data granularity (Qiu et al., 2022). In contrast, the integration of Street View Imagery (SVI), Computer Vision (CV), and Machine Learning (ML) offers a promising alternative for subjective evaluations across large regions, with enhanced spatial resolution and the ability to account for spatial heterogeneity (Koo et al., 2022). SVI facilitates data collection at fine geographic intervals (e.g., 50m along road networks), enabling detailed mapping of urban environments (Ito and Biljecki, 2021). With the aid of CV, it is possible to systematically extract features of the BE as independent variables across extensive spatial areas (SONG et al., 2022). Leveraging ML's predictive accuracy, data gathered from a subset of sites can be extrapolated to predict results across an entire geographic area (Verma et al., 2020).

Despite these advancements, the research gaps remain in the subjective evaluation of cyclists' perceptions. To our knowledge, only two studies have combined SVI, CV, and ML to assess cyclists' perceptions over broad areas, and the accuracy and reliability of these predictive methods have not been fully validated (Ito and Biljecki, 2021, Costa et al., 2023). Moreover, the complex relationships between BE features and cyclists' perceptions, particularly in accounting for spatial heterogeneity, have not been thoroughly investigated. This is crucial, as empirical knowledge about the relationship between the built environment and bike usage is not universally applicable, even in cities with similar geographic and cultural contexts (Wu et al., 2021).

To bridge the identified research gaps, this study introduced a comprehensive framework that integrates multi-source data, CV technology, and ML models for the subjective evaluation of the cycling environment across large spatial regions. This study sets out to address two key **research questions**: **1)** How can cyclists' perceived safety and comfort be evaluated with high-resolution data granularity across a broad area? **2)** To what extent do BE features influence cyclists' subjective perceptions of safety and comfort, and does this vary across different spatial contexts?

2 Methodology

This study focuses on Gusu District in Suzhou City, China (83.4 square kilometers). Using SVIs as input data, eight street-level BE features were extracted through deep learning models, including image classification (https://github.com/microsoft/Swin-Transformer) and semantic segmentation (https://github.com/CSAILVision/semantic-segmentation-pytorch), serving as independent variables. To measure the dependent variables—perceived safety and comfort—an online pairwise voting survey was conducted with 150 volunteers (http://47.242.149.177), using the TrueSkill algorithm and Random Forest model to process and analyze responses. After validation, Ordinary Least Squares (OLS) and Multiscale Geographically Weighted Regression (MGWR) models were applied to explore the spatially heterogeneous relationships between BE features and perceptions of safety and comfort.

3 Main findings

First, the MGWR results (Table 1) reveal discrepancies in how BE features influence perceived comfort and safety, respectively. Key factors affecting perceived safety include the presence of segregated cycle lanes, road width, and spatial chaos, while perceived comfort is primarily influenced by spatial chaos and greenery, followed by road width. Second, the spatial heterogeneity is evident in the MGWR visualizations (Figure 1), showing that the impact of BE features on perceptions of safety and comfort varies significantly across different areas. Notably, the sky ratio has inconsistent effects in the northern part of the Old Town, where it negatively affects the sense of safety, contradicting the common belief that greater openness enhances safety (Harvey et al., 2015).

Table 1: MGWR model

Variables	OLS coefficients		MGWR coefficients			
	Mean		Mean		Min, Max	
	Comfort	Safety	Comfort	Safety	Comfort	Safety
Intercept	0.626**	0.680**	0.040	0.045	(-0.170, 0.203)	(-0.5790, 0.4898)
Cycle lanes	0.292**	0.082**	0.039	0.127*	(-0.165, 0.147)	(-0.0926, 0.3780)
Relative road width	-0.001	0.033**	0.073*	0.130*	(-0.276, 0.172)	(-0.3808, 0.2982)
No. vehicles	-0.010	-0.297**	-0.016	-0.140	(-0.193, 0.063)	(-1.4662, 0.0762)
Physical disorder	-0.446**	-0.484**	-0.593***	-0.658***	(-0.728, -0.420)	(-0.8450, 0.1436)
Sky ratio	0.005	0.025*	0.071	-0.023	(-0.168, 0.294)	(-0.3224, 0.4691)
Greenery	0.572**	0.116**	0.472***	0.088	(0.302, 0.667)	(-0.0722, 0.3744)
Enclosure	-0.095**	-0.026	0.012	-0.018	(-0.254, 0.229)	(-0.2016, 0.2856)
Waterfront	0.023**	0.026**	0.011	0.012	(-0.011, 0.041)	(-0.0125, 0.0356)
Adjusted R^2 / AICC						
Comfort	0.872 / 9094.132		0.8925 / 3337.3276			
Safety	0.759 / 12179.489		0.8313 / 5905.8463			

Note: for OLS, **at the 1% level, and * at the 5% level

for MGWR, */**/*** mean the significance (features percentage) >30%/ >60% / >90%, respectively

4 Discussion

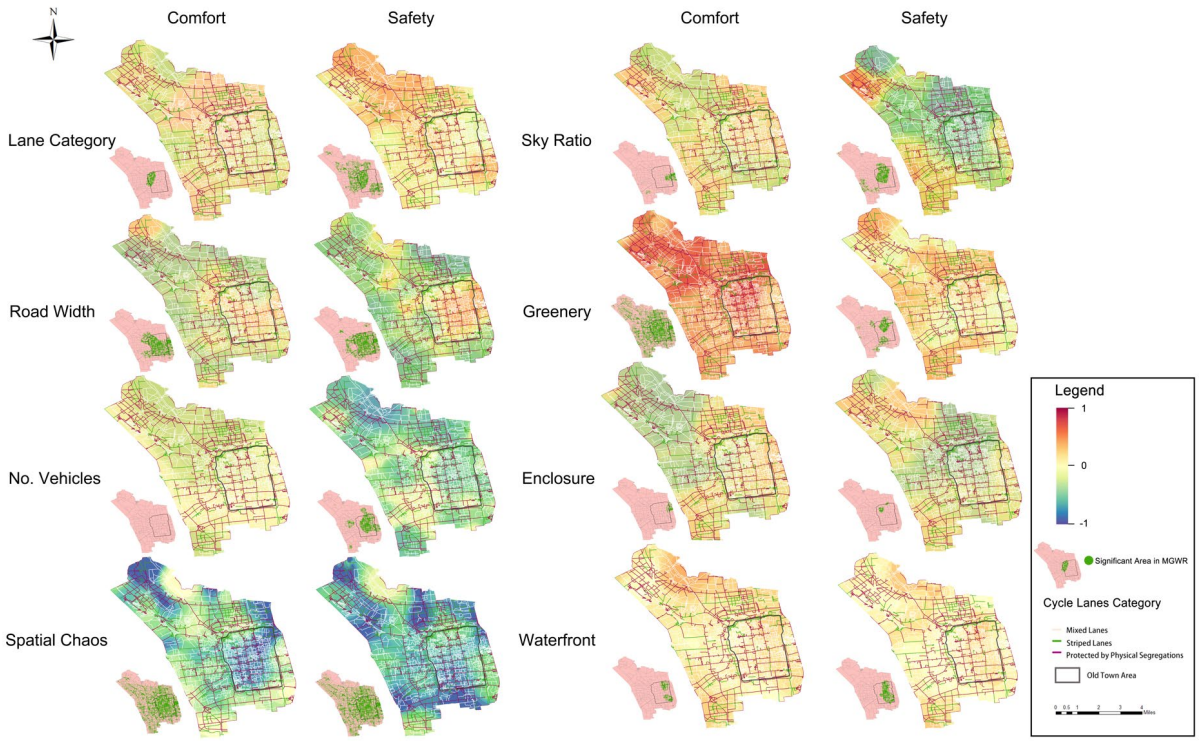
This research integrated Street View Imagery (SVI), Computer Vision (CV), and Machine Learning (ML) techniques to facilitate subjective assessments of the cycling environment over a broad geographical area. The findings of this study underscore the necessity for localized, context-sensitive development strategies that prioritize regions where BE features have a substantial local impact on perceived comfort and safety, and where such interventions may yield higher policy sensitivity.

The following policy implications highlight key interventions based on the study's findings. Although the prioritization of interventions such as widening roads, reducing vehicle traffic,

and implementing cycling facilities is critical for enhancing perceived safety (Cahyanti et al., 2022, Arellana et al., 2020). However, these measures require careful consideration of the availability of road resources, which are often constrained by conservation mandates and limited space (Nuñez et al., 2020). Alternatively, for **old town region**, the decreasing of spatial chaos, the introduction of green spaces can be considered as an efficient strategy to enhance perceived comfort. Specifically, the central and northern parts of the region should be mainly focused on because the increasing of greenery alongside measures to reduce openness revealed significant effects on improving perceived safety, too. For **new town area**, the focus should shift towards managing spatial chaos, particularly in the southern parts and around the transportation hubs. In addition, the deployment of cycling facilities within residential areas and near transportation hubs, along with the expansion of greenery in the northern parts of new urban regions, is recommended. These interventions are expected to significantly elevate both perceived safety and comfort, showcasing the importance of tailored urban planning approaches.

This study acknowledges several limitations. First, the participants were relatively homogeneous in terms of cycling experience, which suggests that evaluator tendencies, particularly among different groups of cyclists, require further investigation in future research. Additionally, the reliance on Street View Imagery (SVI) may limit the ability to capture the dynamic nature of cyclists' perceptions in real-world environments. To address this, future studies could incorporate advanced technologies like Virtual Reality to simulate urban scenarios. This would allow for comparisons between static and dynamic settings, potentially leading to more refined strategies for creating cyclist-friendly environments.

Figure 1: Coefficient of BE features for Comfort and Safety score in MGWR model



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