EXPLORING VISUAL FACTORS INFLUENCING WOMEN'S PERCEIVED INSECURITY IN METRO STATIONS AND ADJACENT BUILT ENVIRONMENTS

A case study of Milan, Italy

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Abstract. Prior research has established a direct correlation between women's perceived insecurity in public spaces and the design of the surrounding built environment. However, limited attention has been given to investigating how the built environment influences women's security perceptions within metro systems. This study introduces a novel methodology to analyze the impact of visual factors on the entire walking experience within commuter cores, covering both the station and surrounding areas in Milan Metro Line 1. Both Street View Imagery (SVI) and manual photography are employed for semantic segmentation analysis, followed by expert auditing and machine learning for evaluation. Finally, the study constructs regression models to analyze the relationship between the area ratio of visual factors and women's perceptions. The results demonstrate that certain factors, such as wider platforms and sidewalks, can positively influence women's safety perceptions in the surrounding and interior spaces, respectively. The models could be used to dissect Milan's other metro stations and their surroundings, offering insights applicable to other metro lines. Moreover, the methodology presents serves as a framework for investigating analogous concerns in diverse cities and delving into the experiences of other marginal groups.

Keywords. Metro Station, Perceived Insecurity, Women Perception, Google Street View, Built Environment, Deep Learning, Inclusive City.

1. Introduction

Building inclusive cities is a global aspiration and a core tenet of the United Nations Sustainable Development Goals. One of the key concepts of inclusive cities is to create

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environments where different social groups feel welcome, respected, and included, that help fulfill the emotional needs of its residents. As highlighted by Barabás (2018), women, who are in a 'vulnerable' position from a biological perspective, are more likely to experience feelings of insecurity. Whilst women may negatively perceive the security of metro stations, they are often the primary means of public transportation in cities. It is therefore imperative to address women's security when using the metro.

Milan, a city that has garnered international attention as the 'Italian Gotham City' due to high levels of crime (Pozzi, 2023), frequently reported by women on social media platforms due to concerns about insecurity, is selected for this study. The research focuses on an entire metro line, incorporating buffer zones around each station. Segmentation of selected key factors are extracted from SVI datasets to provide exterior images, while interior images are captured through manual photography. Post segmentation, ratio areas of all visual factors can be obtained.

Through analysis of the weights of all visual factors, done using a combination of expert auditing and machine learning, we construct regression models for essential factors in the built environment that influence women's perception of security. The framework could be applied in the analysis of other metro lines in Milan to formulate targeted redevelopment plans. Furthermore, the framework could be adapted to investigate other marginal groups, contributing to the creation of inclusive cities.

2. Literature Review

Previous research has demonstrated that various cues in the built environment can trigger fear. BoTryggt2030, a Swedish contemporary initiative, highlights nine key factors critical to safety issues, encompassing elements such as lighting, urban design, and residents (Jansson, 2019). In studies focusing on the female perspective, Paydar et al. (2017) confirm that the most significant factors can be categorized as vitality, the arrangement of furniture, passive surveillance, disorder, and types of vegetation. As for the prior metro station research, factors in built environment affecting crowd perception of safety are mainly related to visual accessibility, surveillance, and disorder. For example, security is linked to visual accessibility, poor lighting is the main concern among passengers (Cozens et al., 2003). Natural or formal surveillance are both effective methods (Ceccato et al., 2013). Litter and vandalism make the area look like a potential crime target (Ceccato et al., 2013).

For the method of evaluating urban perceptions, the traditional method has relied on cumbersome interviews and questionnaires (Yao et al., 2019). The rapid growth of geospatial big data, particularly the emergence of massive datasets of geo-tagged imagery such as street-view , has significantly influenced the field (Zhou et al., 2014). Yao et al. (2019) employ SVI to establish a human-machine adversarial auditing framework for rapid assessment of human perceptions. From a gender perspective, Gong et al. (2023) evaluate human perceptions, utilizing the TrueSkill rating system to audit SVI, integrating GIS, computer vision, clustering analysis, and machine learning. Research on public transport safety perceptions is also departing from traditional methods. Ceccato et al. (2013) use crime and public disorder data, employing GIS, spatial data analysis, and regression models to assess the security conditions at stations.

In our study, the lack of internal imagery poses a significant challenge in utilizing image datasets for built environment analysis, despite empirical evidence supporting a strong link between the built environment and human perception. Moreover, the built environment within a metro station, encompassing various unique factors, differs significantly from the outside. However, previous studies on public transportation perceptions rarely distinguish between indoor and outdoor spaces. To address these gaps, we conduct systematic image capture photography of the interior spaces of metro stations, allowing development of a novel methodology for analyzing the entire walking experience, both in the station and the surrounding area. By extracting different influencing factors, we study these two types of spaces separately.

3. Method and Data

3.1. RESEARCH FRAMEWORK

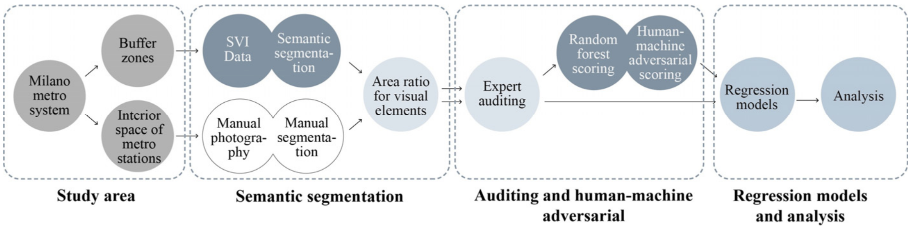

Figure 1. Research framework for the analysis of two spaces

Figure 1 illustrates the framework established to evaluate the visual factors in the built environment that contribute to women's insecurity when using the metro system in Milan. We employ various methods for analyzing indoor and outdoor spaces. For buffer zones, we extract Google Street View (GSV) images and use the ADE20K dataset for semantic segmentation, determining the area ratio for each visual element within the images. Subsequently, a virtual audit is applied to obtain women's perceptual scores, employing a combination of expert auditing, random forest scoring, and human-machine adversarial scoring. This approach streamlines the survey process, enabling efficient collection of substantial questionnaires and discerning differences between various elements correlated with women's safety perception. Finally, the study constructs regression models to analyze the linkage between different visual elements and women's sense of safety in the built environment.

For the interior metro space, we use manual photography to capture images. Unlike the process of studying buffer areas, the unique characteristics of the internal environment pose challenges, resulting in reduced accuracy in semantic segmentation when using general datasets like ADE20K. Moreover, the limited number of images presents obstacles for machine learning. Consequently, in the interior areas, our study manually segments each element and calculates the area ratio within the images, relying exclusively on expert auditing for the assessment of all images. Finally, regression models are also constructed for further analysis.

3.2. STUDY AREAS AND DATA RESOURCES

3.2.1. The Study Areas

The study focuses on an entire metro line in Milan——Line 1, with buffer zones characterized as walkable areas of 400 metres centred on each metro station. Line 1 spans a length of 27 kilometers and serves 38 stations. It has been selected for study due to its high research value and potential for improvement. Firstly, due to the early construction in 1957, the condition of the interior of metro stations is more concerning than the condition of stations on other lines, and secondly, Line 1 connects to the core area with high passenger flow, with a daily passenger volume of over half a million.

3.2.2. Data Source of Buffer Areas

We construct GSV sampling points for the images at 50m spacing along the road network, using OpenStreetMap. For each sampling point, we retrieve three street view images, with directions of 0, 120, and 240 degrees, respectively, to collect panoramic street views. In total, we obtain 1497 sampling points and 4296 images. After conducting data cleaning and selection, we retain 4041 valid images.

Building on the findings of prior studies and taking into account the recognizability of SVI, we choose identifiable visual elements to serve as representative factors in the images for segmentation and subsequently classify them into distinct groups (Table 1).

Table 1. Principal component analysis of built environment in the buffer area

Visual Accessibility		Vitality		Surveillance		Spatial Dimension	
Factors	Segmentation	Factors	Segmentation	Factors	Segmentation	Factors	Segmentation
Light	Streetlight	Vegetation	Plant	Person	Person	Road Width	Road
Enclosure	Building		Tree		Car	Sidewalk Width	Sidewalk
	Wall	Living	Person	Monitor	Surveillance Camera	Unpaved Area	Earth
	Fence		Animal	Window	Window	Height Variation	Steps
		Infrastructure	Traffic Light	Commerce	Shop Sign		
			Traffic Signboard				
		Commerce	Shop Sign				

In the subsequent phases, using a fully connected network trained by the ADE-20K dataset to semantically segment elements in each image and obtain the areal ratio of each semantic object. The method has been shown to be useful in identifying factors that influence people's perception (Yao et al., 2019). Three pre-trained neural network models based on the 150-category ADE20K dataset, are compared, including ResNet50, SETR, and Mask2Former. Figure 2 reveals ResNet50's weaknesses in recognizing sidewalks, and SETR's lower accuracy in identifying signboards. Therefore, Mask2Former is selected due to its superior accuracy.

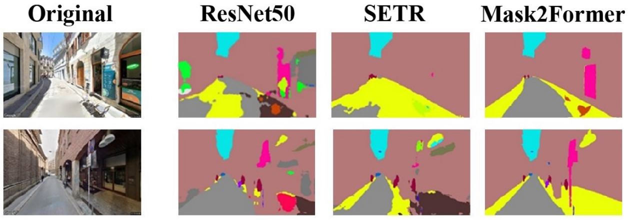

Figure 2. Comparison of neural network recognition of street view images showing the Mask2Former to result in the highest level of accuracy

3.2.3. Data Source of Interior Areas

We employ equipment to manually capture the interior spaces of metro stations. Specifically, we use the DJI Pocket 2 camera to capture 180-degree photographs of various key areas, including exit access points, ticket gates, platforms, and interchange passages—all of which are critical locations in commuter cores. After removing invalid images, we obtain a total of 227 images for further processing.

We recognize that the built environment within a metro station differs from buffer areas, so the influence factors should be identified reconsidered. Based on previous studies, combined with the current state of the internal environment of the Milan metro stations, we identify the key factors and classify them into distinct groups (Table 2).

Table 2. Principal component analysis of built environment in metro station

Visual Accessibility		Surveillance		Disorder	
Factors	Segmentation	Factors	Segmentation	Factors	Segmentation
Light	Artificial Light	Passengers	People	Broken	Broken Infrastructure / Pavement
	Natural Light	Storefronts	Store / Vending Machine	Litter	Scattered Litter
Platform Width	Platform	Monitor	Surveillance Camera		
Access Width	Access	Security	Security Booth		
Window	Visual Window	Window	Visual Window		

Due to the unique characteristics of the environment, we conjecture that using a general dataset for semantic segmentation could result in lower accuracy. To validate this, we manually segment each element in the images using Adobe Photoshop software and compare it with semantic segmentation using ADE20K datasets (Figure 3). The result shows limitations in accuracy of semantic segmentation for certain elements such as windows, platforms, stores, and vending machines. Acknowledging the limitations and considering the limited number of photos, we decide to manually segment each element. Then we compute the area ratio for each element within images.

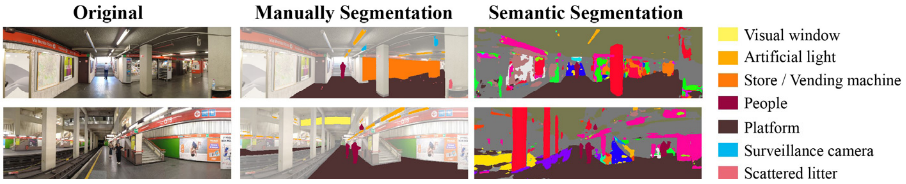

Figure 3. Comparison the segmentation results

3.3. DATA ANALYSIS

3.3.1. Obtaining Data of Buffer Areas

After image segmentation, 10 female volunteers, aged 22-28 years old, comprising university students and practitioners with majors in architecture or urban planning, who frequently use the metro and have safety concerns about Milan's metro system, are engaged in auditing 1000 street view images (from 0-100 points). As illustrated in Figure 4, we develop a Graphical User Interface (GUI) for the auditing process. Firstly, volunteers provide scores to evaluate safety perception in the walking environment. Subsequently, building upon prior research indicating that visual accessibility, vitality, surveillance, and spatial dimension are crucial aspects influencing people's sense of security, we independently collect scores to assess volunteers' perceptions of these dimensions. To ensure consistency in the evaluation criteria, all volunteers are provided with an operational manual. This manual includes auditing criteria and explanations for intervals: under 40 for very unsafe/uncomfortable, 40-60 for unsafe/uncomfortable, 60-80 for safe/comfortable, and over 80 for very safe/comfortable.

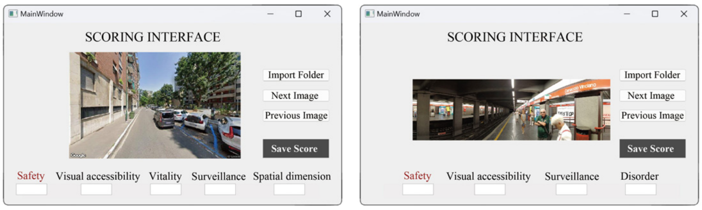

Figure 4. Volunteer auditing interfaces for buffer areas and internal areas

Following image segmentation, a random forest model is utilized for automated rating. This module is designed to establish a fitting relationship between visual scenic features and user scores. The visual scenic feature is represented as a 151-dimensional vector, capturing the areal proportion of each object category in segmentation. The model is trained by fitting the scores of the initial 1000 images, taking into account the proportion of different types of objects in each image. Subsequently, the trained random forest model is utilized to predict perceptual scores for other images.

To enhance model accuracy, we implement a human-machine adversarial auditing approach. Firstly, the trained random forest model automatically computes safety scores and scores for the four dimensions based on the proportion of different object types in the images. Then the calibration process concludes when the recommended scores from the model and those provided by the volunteers achieve a high level of agreement, with a root mean square error of less than 10 for the preceding 100 images.

Subsequently, we conduct a validation of the calibrated model to assess its accuracy and reliability. One hundred images are randomly selected, and all scores are given by both the model and volunteers. The scores generated by the model exhibit a high correlation with those provided by the volunteers ($r=0.76$, $p<0.05$). Finally, perceptions of safety and the other four dimensions for all street view images in buffer areas are automatically assessed using this model based on machine learning.

3.3.2. Obtaining Data of Interior Areas

Due to the limited number of images (227 images), employing machine learning to collect scores poses challenges. Therefore, volunteer auditing is used to collect scores for all images. Using a GUI, ten female volunteers—comprising university students and professionals with backgrounds in architecture or urban planning—are assigned to score all images. They access the perception of safety and three dimensions: visual accessibility, surveillance, and disorder, following the operational manual.

4. Results

4.1. THE RESULT OF BUFFER AREAS

4.1.1. Analysis of Safety Perception

To explore the factors influencing women's safety perception in buffer zones, we utilize Correlation and Regression Analysis to examine the link between safety scores and the area ratio of various visual elements. This allows us to investigate the impact of independent variables Q_1- Q_{18} on the dependent variable P (Safety scores), using the SPSS software. Subsequently, the model fitting situation undergoes analysis based on the R squared value, and the Variance Inflation Factor (VIF) is examined to assess the presence of collinearity issues. As illustrated in Table 3, the model formula is:

$$P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_{18} Q_{18}$$

where β_0 is the constant; $\beta_0 - \beta_i$ is the coefficients.

Table 3 indicates that the presence of walls and unpaved areas are negatively linked with women's safety perception (coef. = -0.202, coef. = -0.133). Conversely, the presence of trees, cars, streetlights, and windows contribute positively (coef. = 0.483, coef. = 0.472, coef. = 0.289, coef. = 0.231). Additionally, greater sidewalk and road width significantly enhance women's safety perception (coef. = 0.535, coef. = 0.458).

Table 3. Model summary and parameter estimates of safety perception

Model Summary

R	R²	Adj.R²	D-W	P
0.873	0.761	0.757	1.638	0.001

Parameter Estimate

Idx	Factors	Coefficients		VIF
	Constant	14.866		
Q_1	Streetlight	1909.002	0.289	1.099
Q_2	Building	13.601	0.174	2.458
Q_3	Wall	-83.251	-0.202	1.277
Q_4	Fence	17.812	0.045	1.417
Q_5	Plant	96.531	0.199	1.181
Q_6	Tree	67.063	0.483	1.629
Q_7	Person	197.821	0.042	1.036
Q_8	Animal	-122.470	-0.033	1.639
Q_9	Traffic Light	539.542	0.058	1.018
Q_{10}	Traffic Signboard	343.804	0.148	1.051
Q_{11}	Shop Sign	387.424	0.177	1.022
Q_{12}	Car	96.852	0.472	2.245
Q_{13}	Surveillance Camera	6856.104	0.159	1.639
Q_{14}	Window	81.256	0.231	1.333
Q_{15}	Road	58.732	0.458	3.777
Q_{16}	Sidewalk	119.781	0.535	2.283
Q_{17}	Earth	-36.982	-0.133	1.833
Q_{18}	Steps	-29.373	-0.038	1.059

4.1.2. Analysis of the Perceptions of Four Dimensions

After investigating the factors influencing women’s safety perception, we utilize the same method to examine the relationship between selected elements and various perceptions (visual accessibility, vitality, surveillance, spatial dimension). Utilizing SPSS software and incorporating scores from machine learning, we develop four regression models to assess the connection between women’s perceptions in different dimensions and the area ratio of elements in the built environment separately (Table 4):
Table 4 elucidates the positive and negative factors influencing women's perception across different dimensions. For instance, the visual accessibility model indicates that the existence of buildings and walls has a negative impact on women's perception of visual accessibility (coef. = -0.841, coef. = -0.410).
Conversely, the presence of streetlights marginally improves women's sense of visual accessibility (coef. = 0.068).

Table 4. Model summary and parameter estimates of four dimensions

Model Summary (Visual Accessibility)

R	R²	Adj.R²	D-W	P
0.904	0.817	0.817	1.546	0.001

Parameter Estimate (Visual Accessibility)

Idx	Factors	Coefficients		VIF
	Constant	74.860		
Q_1	Streetlight	242.268	0.068	1.024
Q_2	Building	-37.630	-0.841	1.065
Q_3	Wall	-88.936	-0.410	1.008
Q_4	Fence	-38.450	-0.125	1.035

Regression model: $P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_4 Q_4$

Model Summary (Vitality)

R	R²	Adj.R²	D-W	P
0.918	0.842	0.842	1.686	0.001

Parameter Estimate (Vitality)

Idx	Factors	Coefficients		VIF
	Constant	48.008		
Q_1	Plant	26.576	0.119	1.018
Q_2	Tree	43.349	0.714	1.028
Q_3	Person	25.756	0.035	1.017
Q_4	Animal	374.276	0.226	1.006
Q_5	Traffic Light	136.657	0.032	1.003
Q_6	Traffic Signboard	541.943	0.404	1.269
Q_7	Shop Sign	180.245	0.174	1.27

Regression model: $P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_7 Q_7$

Model Summary (Surveillance)

R	R²	Adj.R²	D-W	P
0.796	0.634	0.634	1.590	0.001

Parameter Estimate (Surveillance)

Idx	Factors	Coefficients		VIF
	Constant	41.680		
Q_1	Person	286.352	0.489	1.017
Q_2	Car	50.695	0.634	1.067
Q_3	Surveillance Camera	-541.451	-0.070	1.185
Q_4	Window	18.513	0.186	1.057
Q_5	Shop Sign	253.450	0.308	1.191

Regression model: $P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_5 Q_5$

Model Summary (Spatial Dimension)

R	R²	Adj.R²	D-W	P
0.838	0.779	0.779	1.600	0.001

Parameter Estimate (Spatial Dimension)

Idx	Factors	Coefficients		VIF
	Constant	41.027		
Q_1	Road	40.508	0.759	1.257
Q_2	Sidewalk	51.734	0.493	1.131
Q_3	Earth	-31.845	-0.317	1.157
Q_4	Steps	11.832	0.035	1.007

Regression model: $P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_4 Q_4$

4.2. THE RESULT OF INTERIOR AREAS

4.2.1. Analysis of Safety Perception

Like the study of buffer zones, Correlation and Regression Analysis is used to assess the linkage between independent variables $Q_1 - Q_{11}$ and the dependent variable P (safety scores) in the interior areas of metro stations (Table 5):

$$P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_{11} Q_{11}$$

Table 5 indicates that the presence of poorly maintained infrastructure including pavement, and scattered litter is negatively correlated with women's safety perception (coef. = -0.265, coef. = -0.315). Conversely, the presence of other people, greater platform width, and the existence of a security booth having the positive impact (coef. = 0.526, coef. = 0.427, coef. = 0.231).

Table 5. Model summary and parameter estimates of safety perception

Model Summary

R	R²	Adj.R²	D-W	P
0.839	0.703	0.688	1.572	0.001

Parameter Estimate

Idx	Factors	Coefficients		VIF
	Constant	63.179		
Q_1	Artificial Light	84.5	0.116	1.376
Q_2	Natural Light	139.564	0.164	1.111
Q_3	Platform	49.082	0.427	3.107
Q_4	Access	8.366	0.134	3.919
Q_5	People	127.239	0.526	1.057
Q_6	Store/Vending Machine	10.729	0.065	1.099
Q_7	Surveillance Camera	318.019	0.088	1.149
Q_8	Security Booth	102.408	0.231	1.212
Q_9	Visual Window	240.792	0.193	1.057
Q_{10}	Broken Infrastructure / Pavement	-304.951	-0.265	1.019
Q_{11}	Scattered Litter	-5145.838	-0.315	1.028

4.2.2. Analysis of the Perception of Three Dimensions

We establish three independent models to interpret the linkage between women's perceptions about visual accessibility, surveillance, disorder and the area ratios of various visual elements in the metro stations (Table 6).

Table 6 illustrates the positive and negative factors influencing women's perception in different dimensions. For example, greater access and platform width significantly enhance women's perception of visual accessibility (coef. = 1.120, coef. = 0.953).

Table 6. Model summary and parameter estimates of three dimensions

Model Summary (Visual Accessibility)

R	R^2	Adj.R^2	D-W	P
0.787	0.619	0.610	1.855	0.001

Parameter Estimate (Visual Accessibility)

Idx	Factors	Coefficients		VIF
	Constant	55.163		
Q_1	Artificial Light	156.371	0.179	1.350
Q_2	Natural Light	136.446	0.134	1.097
Q_3	Platform	131.311	0.953	2.990
Q_4	Access	83.983	1.120	3.707
Q_5	Visual Window	214.026	0.143	1.054

Regression model: $P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_5 Q_5$

Model Summary (Surveillance)

R	R^2	Adj.R^2	D-W	P
0.864	0.747	0.741	1.917	0.001

Parameter Estimate (Surveillance)

Idx	Factors	Coefficients		VIF
	Constant	53.506		
Q_1	People	322.099	0.800	1.021
Q_2	Store/Vending Machine	64.942	0.237	1.020
Q_3	Surveillance Camera	567.729	0.095	1.055
Q_4	Security Booth	203.300	0.275	1.039
Q_5	Visual Window	277.298	0.133	1.019

Regression model: $P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_5 Q_5$

Model Summary (Disorder)

R	R^2	Adj.R^2	D-W	P
0.778	0.605	0.602	1.848	0.001

Parameter Estimate (Disorder)

Idx	Factors	Coefficients		VIF
	Constant	81.552		
Q_1	Broken Infrastructure /Pavement	-889.605	-0.585	1.005
Q_2	Scattered Litter	-11015.182	-0.511	1.000

Regression model: $P = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2$

4.3. MULTIDIMENSIONAL EVALUATION FOR SAFETY PERCEPTION

Based on the regression models, it is possible to multidimensionally evaluate the safety perception of any metro stations and buffer areas in Milan. Figure 5 provides exemplary results, illustrating the evaluation of the built environment with a low score. This evaluation could assist us in formulating a strategy to optimize the safety perception of any built environment with a targeted approach.

Figure 5. Multidimensional evaluation of low built environment

5. Conclusion and Future Work

With a specific focus on women's perceived safety, the study explores the influential factors in the built environment within commuter cores, covering both the station and the surrounding area in Milan. The findings indicate that in buffer areas, the presence of walls and unpaved areas negatively affects women's safety perception, while trees, cars, streetlights, windows, and wider sidewalks have a positive impact. Therefore, in prospective renovations, augmenting the abundance of trees and streetlights, widening walkways, and minimizing unpaved areas are highly likely to amplify women's sense of safety while walking. Regarding the interior space of metro stations, the study posits that broken infrastructure or pavements, and scattered litter is correlated with a negative impact, while the presence of other people, security booths, and a wider platform could have a positive influence. As such, effective strategies encompass the repair of damaged equipment, rectification of broken pavement, and the maintenance of a clean environment. We could envision with optimism that in newly proposed subway station constructions, increasing platform width and the number of security booths are highly likely to enhance women's safety perception.

The study establishes a multidimensional evaluation system and addresses a gap in SVI data related to internal metro stations in Milan. However, the study grapples with limitations. Firstly, it relies on a visual-based measurement approach, lacking the capacity to evaluate more subjective experiences contributing to women's sense of security. Secondly, our method can be further refined through digital advancements, involving the creation of a new dataset with an extensive collection of images captured in metro stations. This dataset will be enriched with pixel-level annotations, aiming to produce densely annotated images where each pixel is assigned a semantic label. It would be valuable for research focused on the interior aspects of metro stations and beyond. Thirdly, this study exclusively focused on Milan's subway system, and the findings may not generalize to other contexts due to Milan's specific characteristics. Nevertheless, the methodologies employed offer valuable insights for assisting other cities. Furthermore, the research framework can be adapted to investigate related issues in the future, such as evaluating the perceptions of the older adults, children, or other marginal groups, thereby contributing to the creation of inclusive cities.

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