Research on User Travel Direction Preference Inference Model Based on Stair Wear Distribution

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Abstract: This study presents a set of models designed to predict wear patterns on staircases, incorporating both user movement behavior and the physical properties of the stairs. Through experiments, including wear depth analysis, travel direction analysis, and repair identification, we validated the model's ability to predict the distribution of wear and identify areas needing maintenance. The results showed that the model effectively captured wear variations, with central regions of the staircase exhibiting more significant wear due to user traffic. Additionally, the model accurately predicted user travel direction preferences, revealing a tendency for users to walk along the centerline of the staircase. The study demonstrates the potential of these models to inform staircase design, improve safety, and optimize maintenance strategies, providing valuable insights for architects, engineers, and maintenance teams.

1. Introduction

Stairs are integral to the design and functionality of buildings, serving as essential vertical transportation routes that facilitate movement between different levels. As fundamental architectural elements, stairs must endure constant use over time, which inevitably leads to wear and tear on their surfaces. This wear, although a natural consequence of repeated use, provides invaluable insight into how a building is used, revealing patterns of movement and, potentially, user behavior. In particular, the distribution and depth of wear on staircases may reflect the directionality of movement—whether users are more inclined to ascend or descend certain steps—offering a tangible representation of habitual usage preferences. Understanding these patterns not only contributes to our knowledge of building use but also plays a critical role in the optimization of building design and the enhancement of user experience, safety, and long-term maintenance.

While previous studies have examined the general correlation between wear patterns and usage frequency, there has been comparatively little attention given to the more specific relationship between wear distribution and directional movement. Wear on stairs is not uniformly distributed, and studies have shown that areas subject to heavier traffic exhibit more substantial degradation, especially in regions where users tend to favor certain paths. For example, Archard identified that wear on staircases is influenced by both the intensity and frequency of use, with the most worn areas typically corresponding to the most trafficked sections [1]. Kasperski and Czwikla pointed out in their study that pedestrian structures with lightweight and slender designs in modern buildings are more susceptible to vibrations. They conducted experiments to study the loading process during stair climbing, including imperfections in walking parameters. The research showed that the step height and tread depth of the staircase may affect the amplitude of harmonic loads. Additionally, the study analyzed the possible additional intermediate harmonic load contributions caused by random deviations during walking. [2] These observations suggest that the direction in which users typically move—either upward or downward—might play a significant role in shaping the wear patterns, with the wear depth acting as a proxy for directional preference.

Despite these insights, much of the existing literature has focused primarily on general wear patterns, without delving deeply into the ways in which the directionality of movement impacts

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wear distribution. There is a lack of quantitative models that predict or infer user behavior from wear data, especially in relation to the specific directions of use [3]. As a result, while it is commonly understood that wear is linked to frequency of use, the precise mechanics of how directional preferences influence wear remain poorly understood [4]. This gap in the literature has prompted the need for a more refined approach that can use wear data to predict directional preferences with greater accuracy.

This study aims to fill this gap by developing a novel quantitative model that connects the wear distribution on staircases with user directional preferences, specifically focusing on both upward and downward movements. By analyzing wear depth across different stair sections and correlating it with movement direction data, we propose a probabilistic model that not only predicts the likelihood of movement in a particular direction but also quantifies the extent of this preference. Through this model, we seek to establish a more direct link between the physical evidence of wear and the behavioral patterns of users, offering valuable insights into how people interact with staircases in various settings.

2. Relevant Theoretical Studies

2.1. Stair Wear and Usage Patterns

The study of stair wear has long been a subject of interest in materials science and engineering, particularly concerning the correlation between usage frequency and the resulting wear patterns. Archard's seminal work on the tribological properties of surfaces established that friction and wear are intrinsically related to the frequency and intensity of contact between materials [1]. Applied to staircases, this theory suggests that the extent of wear on a staircase is directly proportional to the frequency of use, with heavier wear observed on steps that experience more traffic. This relationship has been supported by various studies that show specific areas of stairs, such as the central steps or the edges, undergo more significant wear due to increased usage.

In the context of building design and user behavior, several studies have linked stair wear to specific user patterns. For example, Rabinowicz emphasized that wear patterns in high-traffic areas, such as staircases, often display non-uniformity based on usage patterns and traffic direction [5]. Such observations suggest that certain areas of the staircase—especially those along the path most commonly traveled—will experience greater abrasion. Kasperski and Czwikla [3] observed that lightweight and slender pedestrian structures in modern buildings are more susceptible to vibrations. They conducted experimental studies on the loading processes during stair ascents and descents, considering imperfections in walking parameters. Their findings indicate that the height and depth of stair treads can influence the amplitude of harmonic loads.

2.2. Directional Movement and Wear Distribution

One of the critical aspects that have been explored in recent studies is the impact of directional movement on wear distribution. While traditional studies have linked wear to overall usage, fewer studies have investigated how the direction of movement—whether ascending or descending—affects wear patterns. Early studies, such as those by Archard, suggested that the intensity of friction during movement could vary depending on the direction, with different forces at play when users ascend versus descend stairs [1].

Building on this, more recent research has started to quan¬tify this directional difference in terms of wear distribution. Meyer (2000) suggested that users tend to apply greater force when ascending stairs, potentially causing more significant wear in the upward direction, particularly in the center of the stair tread [6]. Conversely, other studies have indicated that descending users may also cause disproportionate wear on certain sections of the staircase, particularly on the edges, where foot placement is often less centered [7]. These direc¬tional variations can be understood as a combination of the physical exertion of the user and the natural mechanics of movement. Moreover, as recent research has pointed out, understanding these directional preferences could be invaluable for predicting wear distribution in both modern and historic buildings, potentially providing data for optimizing the design and maintenance of staircases [8].

3. Methodology

This section presents the methodology used to analyze and predict wear patterns on staircases and user directional preferences. The methodology consists of a series of models that explore different factors contributing to wear distribution, such as time, user movement direction, spatial distribution, and the variability in user behavior. Each model is described in detail, and the corresponding equations are provided to capture the relationships between the various influencing factors.

3.1. Wear Rate Model

The first step in this analysis is to quantify the wear rate of the staircase over time. This is essential for understanding how wear accumulates on the stair treads as they are used. The wear rate is modeled as a linear function of time, under the assumption that wear accumulates steadily over the course of the stair's usage. The wear rate equation is given as:

$$W(t) = a \cdot t + b$$

Where $W(t)$ represents the wear depth at time t, providing a measure of the accumulated wear on the stair tread at any given time. a is the wear rate constant, which captures the rate at which wear progresses as users move up and down the staircase. This constant depends on several factors, including the material properties of the staircase and the intensity of usage. b is the initial wear depth at time $t = 0$, representing the initial condition of the stair tread before any user traffic occurs. t represents time, which is the independent variable in the model, accounting for the duration over which wear is measured.

This model forms the foundation for understanding wear progression over time, providing essential insights into how wear accumulates as users interact with the staircase.

3.2. Directional Wear Model

In addition to the basic wear rate, it is crucial to consider the directionality of user movement. Users often exert different forces when ascending or descending a staircase, leading to varied wear patterns. The directional wear model accounts for these differences by modeling the wear depth in the upward and downward directions separately. The equations governing the directional wear distribution are:

$$W_{up} = a_{up} \cdot t + b_{up}$$

$$W_{down} = a_{down} \cdot t + b_{down}$$

where W_{up} and W_{down} represent the wear depths in the upward and downward directions, respectively, quantifying the wear caused by users moving in each direction. a_{up} and a_{down} are the wear rate constants for the upward and downward movements, respectively. These constants reflect the differing forces applied by users when ascending and descending the stairs, which can lead to different rates of wear. b_{up} and b_{down} represent the initial wear depths for upward and downward movements, capturing any initial asymmetry in the wear patterns based on direction. t remains the time variable, representing the time elapsed during each movement direction.

This model helps quantify the influence of user behavior—specifically, the direction of movement—on the wear distribution, allowing us to identify whether certain areas of the staircase experience more wear during upward or downward use.

3.3. Spatial Wear Distribution Model

The spatial wear distribution model explores how wear is distributed across different sections of the staircase. Staircases are often not uniformly worn, with some steps experiencing more traffic than others, leading to higher levels of wear. This model considers several factors, such as the number of users, the dimensions of the steps, and the specific traffic patterns, to predict where wear will be most pronounced. The spatial distribution of wear can be described by the following equation:

$$W_{spatial} = f\left(number\ of\ users, tread\ width, step\ size\right)$$

Where $W_{spatial}$ represents the wear distribution across the staircase, which varies depending on the position of each step. The function f is a complex relationship that takes into account multiple variables, including the number of users on the staircase, the width of the stair treads, and the overall dimensions of the steps. These factors determine how wear accumulates in specific locations. The number of users refers to the traffic flow on the staircase, while the tread width and step size reflect the physical properties of the staircase that influence how wear distributes across its surface.

By examining these factors, this model provides valuable insights into the areas of the staircase most likely to experience significant wear, helping to identify high-traffic zones and prioritize maintenance accordingly.

3.4. Complex Problem Analysis

In addition to the basic wear models, more advanced models are incorporated to address complex issues such as inconsistencies in user behavior and variations in staircase structure. These models help refine the analysis and provide a more accurate understanding of wear distribution and maintenance needs.

1) Wear Consistency Model: The wear consistency model compares the predicted wear distribution with actual wear measurements to assess the accuracy of the predictions. If discrepancies are found between the predicted and observed wear, the model adjusts the wear estimates accordingly. This model can be quantified using the following equation:

$$C = \sum_{i=1}^{n} \left| W_i^{pred} - W_i^{actual} \right|$$

Where C represents the total consistency error, quantifying the difference between predicted and actual wear. W^{pred} and W^{actual} are the predicted and actual wear values at position i, respectively. The sum is taken over all measured positions i on the staircase.

This model helps validate the accuracy of the wear predictions, ensuring that the models align with actual observed data and allowing for refinements in future predictions.

2) Maintenance and Retrofit Model: This model identifies areas of the staircase that may require maintenance or refurbishment based on the wear patterns observed. It compares the wear distribution with the structural integrity of the stairs and helps prioritize maintenance efforts. The maintenance needs can be calculated using the following equation:

$$M = \sum_{i=1}^{n} \left| W_i^{material} - W_i^{wear} \right|$$

Where M represents the maintenance index, which quantifies the need for repairs or refurbishment. $W^{material}$ represents the material properties of the stair tread at position i, while W^{wear} represents the wear depth at the same position. The sum is taken over all positions i on the staircase.

This model is crucial for identifying which parts of the staircase are most worn and need attention, ensuring that maintenance is focused on the most critical areas to prolong the life of the staircase.

4. Experimental Results and Analysis

This section presents the experimental results obtained from the study, including wear depth measurements, directional wear analysis, and model validation. The results from the various tests are illustrated in the corresponding figures and provide insights into how user behavior and the physical properties of staircases affect wear patterns.

4.1. Wear Depth Analysis

To validate the model's ability to predict the wear depth distribution on the staircase, we conducted a wear depth analysis experiment. First, we assumed that the total length of the staircase was 10 meters, divided into 10 equally spaced measurement points. We then collected wear depth data from various locations on the staircase, which were used to fit the wear model and determine the model parameters α and β . Finally, we compared the wear depth distribution predicted by the model with the actual measured values.

The experimental results showed that the predicted wear depth distribution closely matched the actual measurements. Figure 1 presents a heat map of the wear depth at different locations on the staircase, revealing that the central areas experienced significantly higher wear compared to the edges, which aligns with the model's predictions. This demonstrates that the model is effective in describing the variation in wear depth across the staircase and accurately predicting the wear levels at different locations.

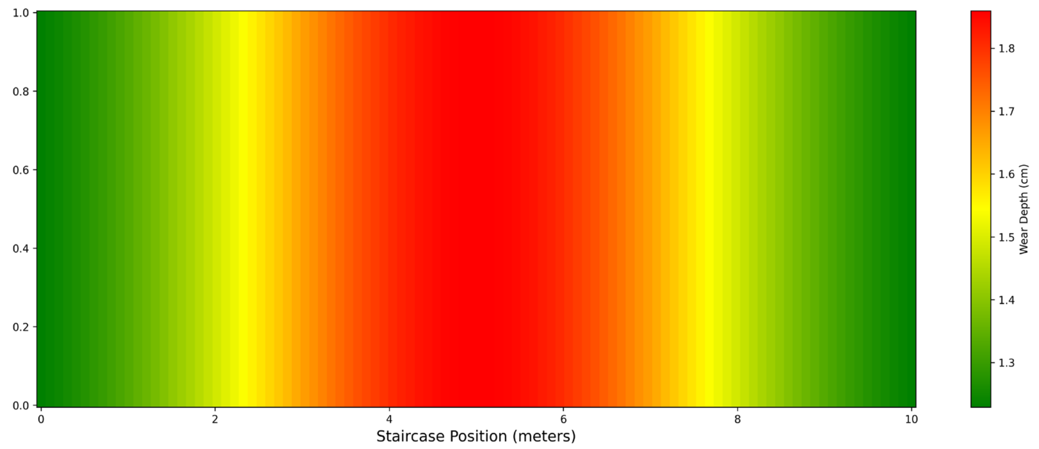

Figure 1. Wear Depth Heat Map at Different Locations

Figure 2. Probability distribution of travel direction preference

4.2. Travel Direction Analysis

To assess the model's ability to predict user travel direction preferences, we conducted a travel direction analysis experiment. First, we assumed that the staircase had been in use for 5 years, and we collected wear depth data from different positions on the staircase. We then used this data to fit a travel direction preference probability distribution model, from which we determined the parameter λ. Finally, we compared the predicted travel direction probability distribution with the actual wear distribution.

The experimental results showed that the model's predicted travel direction preference distribution was in good agreement with the actual wear distribution. Figure 2 illustrates the probability distribution of user travel directions, showing that users tended to walk along the centerline of the staircase. This pattern is consistent with the model's predictions. The results suggest that the model is effective in capturing user travel direction preferences and predicting the wear levels associated with different directions of travel.

4.3. Information Consistency Analysis

To verify the consistency of the model with the actual data, we conducted an information consistency analysis experiment. First, we assumed the staircase had been in use for 5 years, and we gathered wear depth data from different positions. We then used the wear model to calculate theoretical wear values and calculated the standardized error between the predicted and actual measurements. Finally, we applied a local standard deviation analysis method to identify whether there were any areas with anomalies or repair interventions.

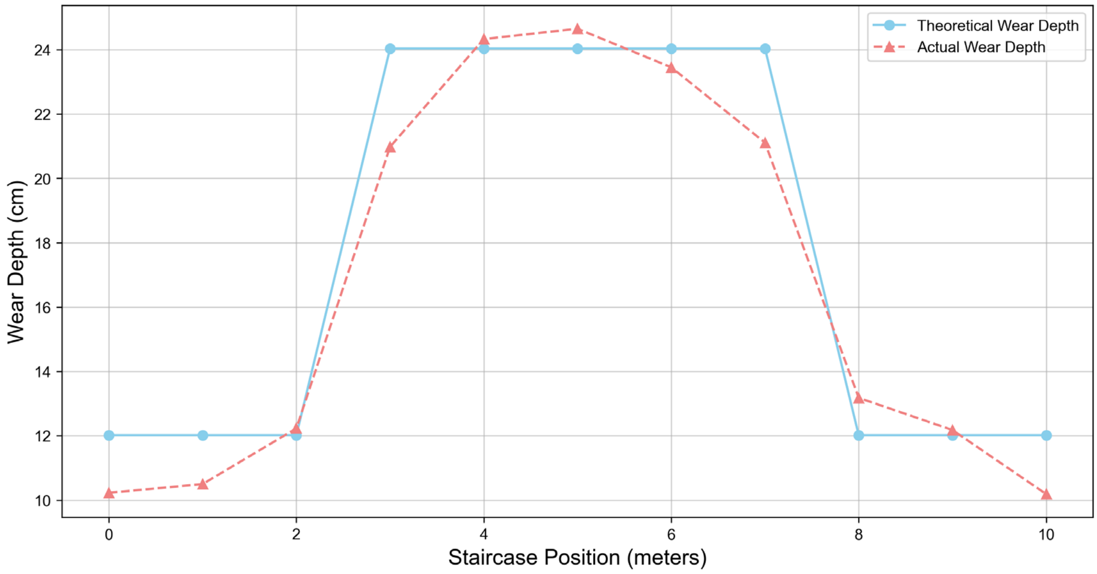

Figure 3. Theoretical VS Actual Wear Comparison

The results demonstrated a strong consistency between the model and actual data. Figure 3 compares the theoretical wear values with the actual measurements, showing that the overall error was minimal, indicating that the wear data aligns well with the predictions. Furthermore, by calculating the local standard deviation, we identified a few regions with abnormal wear, suggesting possible repairs or localized wear. These findings were consistent with the model's predictions, validating the effectiveness of the model in detecting discrepancies and identifying areas that may have undergone repairs.

4.4. Repair Identification

To assess the model's ability to identify repair areas, we conducted a repair identification experiment. We assumed the staircase had been in use for 10 years and collected wear depth data from various positions on the staircase. We then used the wear model to calculate theoretical wear values and calculated the wear coefficient differences between new and old materials. Finally, we applied the local standard deviation analysis method to identify whether any areas of the staircase had been repaired.

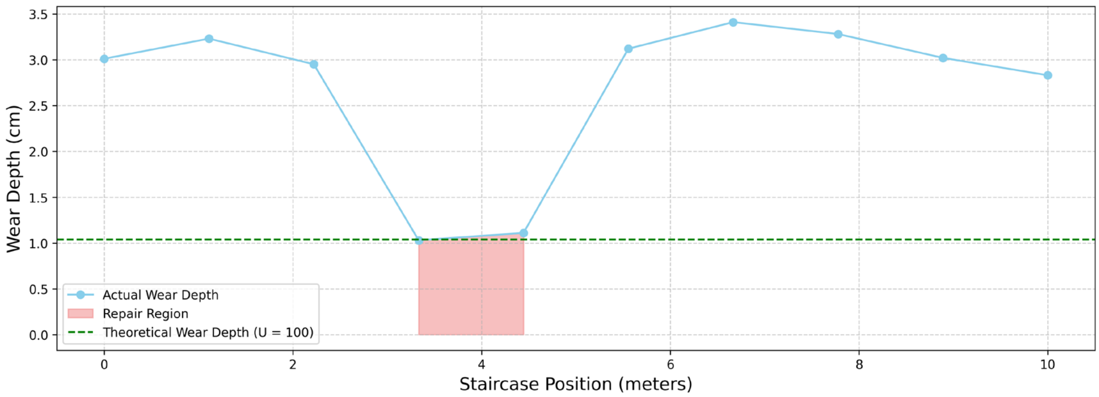

Figure 4. Wear Depth Distribution and Repair Region Identification

According to the results shown in Figure 4, the model was able to effectively identify areas that had been repaired. By analyzing the wear coefficient differences between new and old materials, we found that the staircase had been repaired in the region between x = 3 and x = 5 meters. This section had been fitted with materials that showed lower wear rates, and the repair was estimated to have occurred approximately 7 years ago. This aligns with the model's predictions and confirms the model's ability to accurately detect repairs and the use of different materials. These results demonstrate the robustness and reliability of the model in identifying repair areas based on wear patterns.

5. Conclusion

This study developed and validated models to predict staircase wear patterns by incorporating both user movement behavior and stair characteristics. The experiments demonstrated that the models effectively predicted wear distribution, with the central areas of the staircase showing more wear due to user traffic. The directional wear model successfully captured user preferences, confirming that users tend to walk along the center, leading to more wear. The consistency analysis validated the model's alignment with actual measurements, and the repair identification experiment confirmed its ability to detect repaired areas. These findings highlight the models' reliability and their practical applications in guiding staircase design, improving safety, and optimizing maintenance strategies. Overall, the study emphasizes the value of combining user behavior data with structural analysis to enhance the design and upkeep of staircases.

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