12th International Conference on Pedestrian and Evacuation Dynamics (PED 2025)
Prague, Czech Republic – September 9-12, 2025

Understanding Pedestrian Congestion in Merging Corridors: A Speed and Velocity Variance Approach

Jiawei Zhang*[1], Sakurako Tanida[1], Xiaolu Jia[2], Claudio Feliciani[1], Daichi Yanagisawa[1], and Katsuhiro Nishinari[1]

[1]School of Engineering, The University of Tokyo, Tokyo, Japan
[2]Beijing Key Laboratory of Traffic Engineering, Beijing University of Technology, China

Abstract Crowd dynamics in high-density scenarios challenge congestion analysis and risk mitigation. This study introduces speed and velocity variances as metrics to quantify movement irregularity and assess congestion. Experiments in a T-shaped corridor show that velocity variance detects directional disruptions at turning corners, while speed variance identifies congestion near merging points. Their distinct probability distributions provide deeper insights into localized movement instabilities, improving congestion assessment.

Keywords Pedestrian dynamics, Collective behaviors, Interactions, Voronoi diagram

Introduction

Collisions in crowded environments highlight the need to accurately assess congestion as a key characteristic of crowd dynamics. Although density, which measures the number of pedestrians per unit area, is the most common crowding indicator, it often overlooks critical factors such as individual behavior, localized interactions, and emergent turbulence in high-density conditions. Traditional models like Fruin's level-of-service [1] rely on density, flow, and speed thresholds but fail to capture multidirectional flows, self-organization, and turbulence in pedestrian movement.

T-shaped merging corridors, common in train stations, stadiums, and event venues, create natural "pinch points" where converging pedestrian streams lead to sudden congestion and disruptions. The interplay of turning angles and varying densities makes movement patterns highly complex, posing challenges for congestion assessment.

Existing metrics struggle to fully capture these dynamics. Congestion Number (CN) further quantifies flow disruptions and transitions to disorganized states [2], but do not account for directional conflicts in merging flows, and its data and computation demands limit real-time application. Entropy-based measures assess disorder [3] but may miss localized interactions crucial in confined merging spaces.

To address these limitations, we propose a new metric specifically designed for T-shaped corridors, offering a complementary perspective on pedestrian dynamics and contributing to more effective risk mitigation strategies.

Model and Methods

This study proposes two indicators: speed variance and velocity variance, which capture both magnitude and directional fluctuations in pedestrian movement. Speed variance (V_s) measures how an individual's

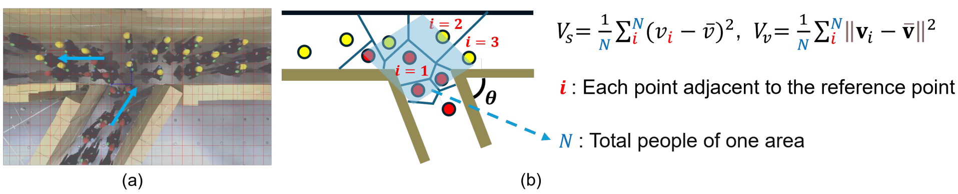

Figure 1: (a) Real-experiment setup of merging corridor (b) Concept of calculation

*Email of the corresponding author: `zhang-jiawei@g.ecc.u-tokyo.ac.jp`

scalar speed deviates from the local average, while velocity variance (V_v) incorporates direction by treating speed as a vector quantity. Voronoi diagrams facilitate detailed spatial assessments of local congestion by adaptively partitioning pedestrian space.

These indicators were tested in a T-shaped corridor experiment (Fig. 1), designed to simulate pedestrian merging flows under different turning angles and crowd sizes.

Result and discussion

Heatmap analysis of density and speed/velocity variance reveals congestion hotspots. Density increases after merging (Fig.2(a)). Figure 2(b) shows a 120° merging corridor where speed variance is concentrated after the turn, highlighting abrupt accelerations and decelerations due to interactions. In contrast, velocity variance peaks at the turning corner (Fig.2(c)), capturing directional disruptions at sharp turns. This distinction suggests that velocity variance detects pre-collision shifts, while speed variance marks collision-prone zones.

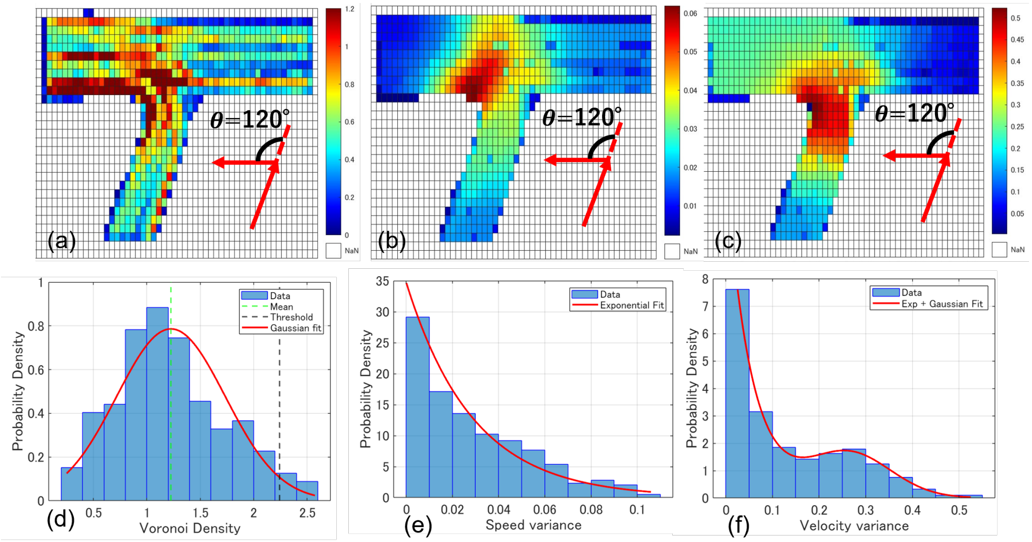

Figure 2: Heatmap of (a) Density, (b) Speed variance, (c) Velocity variance; Distribution of (d) Voronoi density, (e) Speed variance, (f) Velocity variance.

To further understand crowd behavior, we examine the probability distribution functions (PDFs) at the merging point. Voronoi density follows a Gaussian distribution (Fig.2(d)), indicating moderate crowding symmetry. Speed variance exhibits an exponential decay (Fig.2(e)), meaning small fluctuations dominate, but occasional large variations occur due to collision avoidance. Velocity variance (Fig. 2(f)) follows a mixed exponential-Gaussian pattern, suggesting that while minor directional changes are common, sharp turns cause significant disruptions. Thus, Voronoi density reflects overall crowding, while speed and velocity variance capture critical movement instabilities essential for collision risk assessment.

Summary

This study examines pedestrian congestion using speed variance and velocity variance as indicators of movement irregularity. Heatmap analysis in a T-shaped merging corridor demonstrates that velocity variance is highly sensitive to turning angles, effectively detecting directional shifts before collisions, while speed variance identifies congestion zones near merging points, where sudden speed fluctuations occur.

References

[1] Fruin.J., *Pedestrian Planning and Design*, Metropolitan Association of Urban Designers and Environmental Planners, 1971.

[2] Francesco.Z et al., *A pure number to assess "congestion" in pedestrian crowds*, Transp. Res. C, **148**, 104041, 2023.

[3] Yiping.Z et al., *Entropy analysis of the laminar movement in bidirectional pedestrian flow*, Physica A, **566**, 125655, 2021.