A Data-Driven Study on Pedestrian Walking Behaviour as Transitioning Different Spaces

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Abstract. Pedestrians' daily walking behaviours involve transitioning urban spaces with different functions in the pedestrian transportation. Current research has extensively investigated different pedestrian walking behaviours. However, beyond the influence of physical disturbances and structure on pedestrian behaviour, current research lacks an understanding of the impact and role of space itself on pedestrian behaviour from the perspective of spatial changes, and similarities in the behaviour of pedestrians as they transition different spaces. This study uses real-world datasets to conduct a data-driven study on the impact of spaces (open space, sidewalk, and crossing) on pedestrian walking speed. The results show that, pedestrian speed changes statistically significantly near the connection line between two spaces. The location of this significant change in speed depends on the type of connected space. Also, the magnitude of speed change in this area depends on the type of adjacent space and the movement direction. We also study the extent to which the turning behaviour of pedestrians as they transition in different directions of movement affects the speed. Furthermore, We investigate the correlation between the rate of speed change as pedestrians transition in different directions and through different spaces. We regard our results can benefit the realistic pedestrian walking simulations, behaviour prediction, and speed based knowledge.

Keywords: Walking Behaviour · Different Spaces for Urban Traffic · Pedestrian Walking Behaviour Knowledge

1 Introduction

Pedestrians exhibit a wide range of walking behaviours in complex urban traffic. Considering the relationship and influence between pedestrians and spaces has become an important topic in urban research, practice, and application [20], as researchers seek to better understand the complex interactions between pedestrians and space especially when influences change. Studying the link between real-world pedestrian behaviour and space is crucial since it enhances the realism in modeling pedestrian behaviour in scenarios such as Open-World Games [17], and refines predictive accuracy in pedestrian behaviour [8]. Additionally, it offers

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valuable perspectives in social and behavioural sciences, aiding in understanding human responses to the built environment [5].

In daily walking, pedestrians often transition various urban outdoor spaces which have different functional uses or purposes for which land is designed to be used [7], such as crossings, sidewalks, and open spaces. Current literature has listed the factors influencing pedestrian movement in spaces [15] and general behaviours in different spaces [6]. However, there is a knowledge gap regarding how pedestrians spontaneously adapt their behaviours and habits in transitioning between connected spaces, as well as in understanding the differences and commonalities in pedestrian behaviour within mixed traffic and exclusively pedestrian spaces, which vary in safety awareness levels [14].

In particular, we ask: is there a significant difference in the speed of pedestrians when they transition different spaces? If so, where do these changes usually occur? Are there any similarities between these changes in different spaces and movement directions? Given the above context, we use two real-world datasets [13,22] which recorded pedestrian trajectories when transitioning spaces to investigate and analyze the walking speed, with speed being considered an important reference for most walking behaviour simulation models [18]. We elucidate the effects of urban space transitions on pedestrian walking speed, which helps to better understand pedestrian walking habits. The expected contributions are the understanding of spontaneous walking speed as pedestrians transition different spaces, and the understanding of the similarities and differences of speed trends when transitioning different connected spaces and in different movement direction.

2 Background Knowledge and Related Works

In this study, the urban spaces focus on are outdoor public lands and built environment on which they are designed for different transport purposes [2]. The spaces in this research are public outdoor spaces between buildings which are represented by transport infrastructures [4], and pedestrian-oriented with a pedestrian scale. In this research, We consider open space, crossing, and sidewalk which are generally considered common separable urban public spaces as our scope.

Pedestrian behaviour, influenced by environmental and crowd factors, is often studied through simulation models [1]. Various methods have been used to analyze walking behaviours in different settings, utilizing kinematic equations and behavioural rules [12]. Although behaviour-based investigations are emerging, the application of space-pedestrian relationship knowledge in modeling remains limited, often focusing on specific structures or environmental factors [3]. Further research is needed to understand pedestrian walking habits across different spaces and the impact of spatial variation on walking speed.

In addition to modelling, the pedestrian-space relationships are crucial for trajectory prediction models used in applications such as autonomous vehicles [21]. These models incorporate space as a key feature to predict navigation and pedestrian-space interactions [10]. Despite their potential, challenges of computational intensity and data scarcity make it hard to balance model complexity and prediction accuracy [23]. Knowledge of spatially relevant spontaneous behaviour can enhance model training and improve accuracy. Further, while space significantly influences walking speed [19], more research is needed to understand speed variations during space transitions, particularly between mixed traffic and pedestrian spaces.

3 Methods

We investigate pedestrian speeds when transitioning through: (1) in an entirely pedestrian space consisting of sidewalk and open space orthogonally connected, and (2) in a mixed traffic space consisting of open space, crossing and sidewalk connections.

We emphasize the assumptions in this study, as follows:

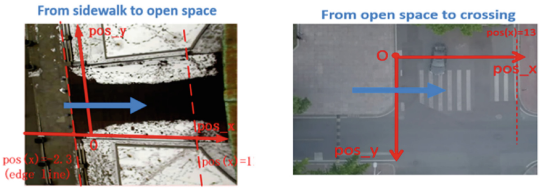
- All pedestrians in our study behave in similar way and have the same perception of the space. We do not consider specific individual behaviours.
- Possible interactive and conflicting behaviour between pedestrians does not have a significant impact on speed and have been ignored [9].
- Frictional resistance of pavement construction materials is similar. Possible ground landscaping and differences in pavement height do not have a significant impact on pedestrian speeds and have been ignored.
- The curb between a sidewalk and mixed traffic has a temporary and minor impact on speed, primarily due to the low curbstone height.
- Our study is on pedestrians who walk for commuting purposes, excluding those who walk to the scenario edge.

3.1 Dataset Description

To study how walking speed varies across spaces, datasets with human trajectory data and spatial information for at least two different spaces are needed. The BIWI Walking Pedestrians Dataset (BIWI) and Vehicle-Crowd Interaction - DUT Dataset (DUT) are two popular choices whose backgrounds are shown in Fig. 1, both featuring at least two types of spaces and reflecting low to medium pedestrian density scenarios [9].

BIWI Dataset: This dataset captures pedestrian movements in front of ETH Zurich's main building, providing a bird's eye view [13]. Although there is another scenario in this dataset (seq_hotel), it only features one space type and is thus excluded. The BIWI dataset includes an open space and a sidewalk, where pedestrians mainly commute between. Outside the sidewalk is a mixed-traffic space.

DUT Dataset: This dataset features everyday campus scenarios at Dalian University of Technology, focusing on an intersection scenario [22]. It includes open space, non-signal crossing, and a sidewalk, where the pedestrian flows mainly between. Some scenarios (1–3, 4, 6, 10–14, 16, and 17) are excluded due to low trajectory numbers, vehicle interference, group gatherings.



(a) Background information of BIWI data (moving from sidewalk to open space)

(b) Background information of DUT dataset (moving from open space to crossing then to sidewalk)

Fig. 1. Background information of BIWI dataset and DUT dataset (with moving directions).

3.2 Data Processing

Our data processing includes two main steps:

1. Data Cleaning: We pre-process the data to eliminate outliers, retaining only trajectories within three standard deviations of the mean speed, based on a normal distribution estimation.
2. Trajectory Filtering: To analyze speed variations across different spaces, we ensure the trajectories traverse at least two spaces:
   – Retain trajectories with endpoints on opposite sides of the edge line between two spaces.
   – For trajectories with endpoints on the same side of the edge line, split and retain them if they cross the edge line.
   – Exclude trajectories if the perpendicular lengths of both endpoints to the edge line are less than twice the average step length, ensuring only deliberate crossings with a slight crossing angle are retained.
   – In the DUT dataset, due to a parked car on the crossing in some scenarios, retain only trajectories below the parked vehicle.

The filtered trajectory data is summarized in Table 1. Acknowledging that turning affects speed due to human joint kinematics [11], we categorize BIWI dataset pedestrians into turning and non-turning groups.

Table 1. Trajectory information after filter

	Datasets		
	BIWI dataset		DUT Dataset
	From sidewalk to open space	From open space to sidewalk	From open space to crossing, sidewalk
Speed Standard Deviation (m/s)	0.29	0.29	0.25
Speed Mean Value (m/s)	1.46	1.46	1.21
Speed Range (m/s)	(0.59, 2.33)	(0.59, 2.33)	(0.45, 1.96)
Number of total pedestrian ids	184	140	405
Number of filtered pedestrian ids	82	43	105
Number of trajectories with turning behaviour	21	16	–
Number of trajectories without turning behaviour	61	27	–

4 Results and Discussion

4.1 BIWI Dataset

BIWI Dataset Results. We use a mixed-effects regression analysis to model the relationship between space and speed, while accounting for the presence of clustered or correlated data. Here, in the regression model, we include the pedestrian identifies as a random effect to account for the difference in initial speeds and comfortable speeds among pedestrians. The parameters in the mixed effect regression analysis are listed in Table 2.

We notice that the p-values are almost 0 for both moving directions in Table 2 which makes us confident that the differences in speed versus positions is not by chance, but significantly related.

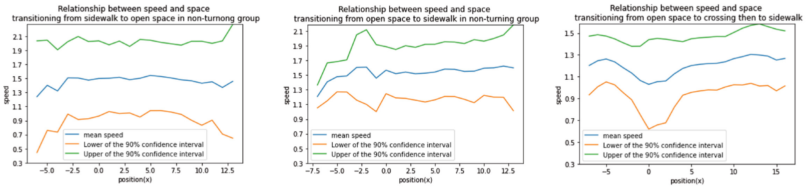
Table 2. Mixed effect regression analysis results of BIWI Walking Pedestrian Dataset and DUT dataset (with moving directions)

Datasets	Direction	Stages	Mean speed change	Mean standard deviation change (m/s)	Estimated change of mean speed within SVA
BIWI dataset	Sidewalk to open space	Sidewalk to SVA	−1.86%	0.04	−5.77%
		SVA to open space	6.74%	0.03	14.08%
	Open space to sidewalk	Open space to SVA	−2.05%	0.06	−6.95%
		SVA to sidewalk	−2.37%	−0.06	10.35%
DUT dataset	Open space to crossing then to sidewalk	Open space to SVA1	−11.82%	0.05	−18.54%
		SVA1 to crossing	9.01%	−0.08	14.29%
		Crossing to SVA2	−2.47%	−0.00	−3.54%

Non-turning group We first analyse the data in the direction from sidewalk to open space in BIWI dataset.

To eliminate brief, unrepresentative fluctuations while preserving detail and capturing the real walking patterns of pedestrians, we calculate the mean and standard deviation of speed in intervals defined by an average stride length of 1 m [16]. We then plot upper and lower bounds of a 90% confidence interval around the mean speed, using a Z value of 1.645. Although our observations are made within this confidence interval, it is important to note that our statistical analyses are based directly on the pre-processed data, not within this interval.

Since there are only a limited four data records in the initial interval from −7.76 m to −6.24 m in Fig. 2(a), we exclude it to maintain data reliability. Aligning position(x) with real-world locations based on the dataset, where the edge line is at about −2.3, we distinguish the sidewalk (less than −2.3) from the open space (greater than −2.3), setting the stage to share our findings:



(a) Transitioning from sidewalk to open space (b) Transitioning from open space to sidewalk (c) Transitioning from open space to crossing then to sidewalk

Fig. 2. Relationship between position(x) (meter) and speed (m/s) in filtered trajectories using mean value and standard deviation.

- As the pedestrians transition from the sidewalk to the open space, their originally rising speed changes before the edge line. In the area from approximate -5m to -3m, the mean speed curve and 90 percent confidence interval both show a near V-shaped change.
- When pedestrians approaching the exit of the open space on the right, the area after approximate 11m in 90 percent confidence interval is becoming wider indicating there is a high degree of variability or uncertainty in the overall speed estimates, meaning that the difference in speed between pedestrians becomes greater here, with some accelerating and others decelerating.

Analyzing the BIWI dataset for pedestrians moving from open space to sidewalk (Fig. 2(b), right to left), we observe a shift from near-stable speeds to a V-shaped change in the mean speed and 90% confidence interval between 0 m and −2.3 m. Specifically, the upper confidence interval stays constant from −1 m to 0 m, while the lower drops significantly, indicating a predominant deceleration with few maintaining or increasing their speed.

Our analysis of the mean value curve and 90% confidence interval curves in two reverse directions in the BIWI dataset leads to the following findings: As the pedestrians transition between open space and sidewalk, their speed shows a considerable change in short prior to the edge line between the two spaces.

We refer to the locations where the observed near V-shaped speed changes as the Speed Variation Area (SVA). Next, we explore the extent to which the speed within the SVA has changed from the speed in the area before it and whether there is a significant difference.

To understand speed fluctuations in the SVA, we categorize pedestrian data into stages—sidewalk, SVA, and open space—based on their coordinates. We compute and summarize the average speed changes and their variations across these stages, as shown in Table 3. This analysis highlights the average speed differences between the SVA and adjacent areas, as well as the speed increase and decrease ratios within the SVA, correlating with the key points in the V-shaped speed curve in Fig. 2.

In the BIWI dataset, pedestrians consistently slow down when entering the SVA, regardless of movement direction. However, the magnitude of speed change

Table 3. The extent to which the speed within the SVA varies for different spaces of pedestrian transition (in BIWI dataset and DUT dataset)

	Direction	Stages	Mean speed change	Mean standard deviation change (m/s)	Estimated change of mean speed within SVA
BIWI dataset	Sidewalk to open space	Sidewalk to SVA	−1.86%	0.04	−5.77%
		SVA to open space	6.74%	0.03	14.08%
	Open space to sidewalk	Open space to SVA	−2.05%	0.06	−6.95%
		SVA to sidewalk	−2.37%	−0.06	10.35%
DUT dataset	Open space to crossing then to sidewalk	Open space to SVA1	−11.82%	0.05	−18.54%
		SVA1 to crossing	9.01%	−0.08	14.29%
		Crossing to SVA2	−2.47%	−0.00	−3.54%

as they leave the SVA and transition to the next space varies significantly, highlighting a clear link between average speed change and movement direction. Variations in the 'Estimated change of mean speed within SVA' also underscore that speed changes within the SVA are dependent on the direction of movement.

In the case of ignoring the edge line between the open space and the building, the SVAs range include:

- From sidewalk to open space, approximate: $-5 < \text{position}(x) < -3$;
- From open space to sidewalk, approximate: $-2.3 < \text{position}(x) < 0$

To verify that the speed changes in the SVA are statistically significant, we perform Welch's t-tests to compare speeds within the SVA and the previous area for pedestrians transitioning between sidewalk and open space in both directions. Using a bootstrapping strategy with a sample size of 26 pedestrian identities-determined by a prior power analysis-and repeating the process ten times, we obtain average p-values of 0.045 for transitions from sidewalk to open space, and 0.018 for the reverse. These results validate the statistical significance of the observed speed changes in the SVA, affirming a consistent shift in pedestrian speed just before reaching the edge line, regardless of the direction of transition.

Turning Group. To analyze the impact of turning on pedestrian speed within right-angle spatial connections, we compared turning group speeds during turns to their steady speeds. We define turning thresholds using the standard deviation of heading changes in open space for each individual, identifying the start of a turn when position(x) is less than 0 and the heading change exceeds this threshold, and marking the end when the heading change fell below it. The average speeds and speed standard deviations for the pre-turn, during-turn, and post-turn stages are then calculated and presented in Table 4.

It can be seen that pedestrians generally slow down when turning due to the layout of the space. Notably, moving from sidewalk to open space, they hardly accelerate post-turn, showing only a 0.12% speed change- a stark contrast to the evident speed increase seen when transitioning from open space to sidewalk.

Table 4. The extent to which the speed of pedestrians changes pre, during and post turning in different directions in the BIWI dataset

Direction	Stage	Mean speed(m/s)	Standard deviation(m/s)	Mean speed change
Open space to sidewalk	pre-turn	1.53	0.23	–
	during turn	1.48	0.28	−3.26%
	post-turn	1.55	0.14	4.72%
Sidewalk to open space	pre-turn	1.67	0.20	–
	during turn	1.57	0.20	−5.98%
	post-turn	1.58	0.22	0.12%

BIWI Dataset Discussion. The mixed traffic space next to the sidewalk, described in the dataset's spatial background, might alter pedestrians' walking speeds, leading to patterns different from typical pavement walking. Despite this, our analysis in Fig. 2 shows a pronounced V-shaped change in speed within the Speed Variation Area (SVA), highlighting pedestrians' speed adjustments in response to the space transition, regardless of external influences from the mixed traffic space. This phenomenon is commonly observed in urban areas where sidewalks intersect orthogonally with open spaces and mixed traffic spaces.

We investigate the effects of external factors and space connectivity methods on pedestrian speed by comparing two groups of pedestrians. Particular attention is paid to the need to turn when walking from the sidewalk to an open space. The turning group exhibits an average speed of 1.67 m/s when non-turning on the sidewalk. Their average speed is slightly higher than the non-turning group. To rule out this potential effect, we calculate the relative difference between the average speeds of the two groups of pedestrians in the same open space area, which turned out to be 0.07. This indicates that the potential average speed of non-turning pedestrians not influenced by external factors is about 1.56 m/s. The average speed of the non-turning pedestrians is about 1.56 m/s. The average speed of the non-turning pedestrians is about 1.56 m/s. Compared to the average speed of pedestrians affected by external influences (1.45 m/s), we can conclude that the sidewalk external space could potentially slow down pedestrians by about 7%. Note that our analysis is limited to scenarios with sidewalks orthogonally connected to open spaces with mixed traffic areas outside the sidewalk. We didn't investigate speed variations near the edge line in scenarios with different sidewalk connections or stable pedestrian sources unaffected by external factors.

The potential reason for the obvious difference in the extent of speed change when pedestrians transition from the SVA to the next space in a non-turning manner is thought to be the influence of different spatial characteristics. When pedestrians move from a wide-open space to a narrow sidewalk, they exhibit less deceleration, indicating an early reduction in speed to minimize subsequent slowdowns. Conversely, pedestrians transitioning from mixed traffic spaces to open spaces typically accelerate upon entering the open area, despite a prior deceleration before reaching the edge line between the sidewalk and open space.

Also, we find that turning slows down pedestrians, who tend to accelerate after turning onto a sidewalk. However, the increase in speed may not be as pronounced when turning into open space, possibly because pedestrians prefer to move at a more comfortable speed in open space. In general, pedestrians on sidewalks tend to be slightly faster than pedestrians in open spaces. We acknowledge that our method of detecting turning states may be relaxed for individuals who change direction significantly, which may affect the accuracy of the turning data and our analysis of turning speeds.

4.2 DUT Dataset

DUT Dataset Results and Discussion. We continue to use the same way to plot the relationship between speed and space in DUT dataset, as shown in Fig. 2(c). Then, we summarize the SVAs in Fig. 2(c):

- SVA1: From open space to crossing, approximate $-5 < \text{position(x)} < 4$;
- SVA2: From crossing to sidewalk, approximate $13 < \text{position(x)} < 16$

The statistical analysis results show the average p-values are 0.001 for SVA1 and 0.022 for SVA2, indicating the speed in both SVA1 and SVA2 is statistically different from the speed in the previous areas.

The potential reasons of the findings are due to the safety properties inherent in the crossing which is a mixed traffic space. That is: For safety reasons, pedestrians like to decrease their speed after they reach the next space (sidewalk) rather than on the crossing. It's important to recognize that the SVA's length can vary depending on the characteristics of the connected spaces, including their type, dimensions, and cultural factors. The SVA's length may change as pedestrians transition between different space types and can differ among individuals. This range is a general average, and individual variations are common.

4.3 Similarities and Differences in BIWI Dataset and DUT Dataset

Our findings highlight areas where pedestrians significantly adjust their speed during transitions between entirely pedestrian spaces (BIWI) and mixed traffic spaces (DUT), often characterized by higher safety awareness. To understand how pedestrian safety awareness affects speed changes during space transitions and the influence of movement direction, we aim to address two key questions: (1) Do speed changes differ when pedestrians exit pedestrian spaces to enter mixed traffic areas compared to the reverse scenario? (2) Does movement direction during transitions in pedestrian spaces impact the rate of speed change?

We use LOESS smoothing to model speed change rates within the SVAs and then create an interpolation function. To assess the quality of this interpolation, we calculate the Mean Absolute Error (MAE) between predicted and actual values at the original data points. The low MAE values in Table 5 indicate that the interpolation function closely matches the original curve, demonstrating its quality as a representation.

Table 5. Quality of the LOESS curves (MAE) and the representative information of the rate of speed change curves in SVAs

Dataset	Moving Direction	SVA (m)	MAE (m/s^2)
BIWI dataset	(1) from sidewalk to open space (without turns)	$-5 < pos\_x < -3$	0.009
	(2) from open space to sidewalk (without turns)	$-2.3 < pos\_x < 0$	0.049
DUT dataset	(3) from open space to crossing	$-5 < pos\_x < 4$	0.001
	(4) from crossing to sidewalk	$13 < pos\_x < 16$	0.001

We describe the relationship between the curves by comparing the two interpolation functions and Pearson's Correlation Coefficient. Figure 3 shows the processed rate of speed change curves for two directions, which should be interpreted in a mirrored manner. In (1) and (2), pedestrians remain within pedestrian spaces, aware of their transition to or from mixed traffic areas. The Pearson value is 0.99, indicating a strong correlation between these two curves. In (3) and (4), we observe pedestrians in mixed traffic areas, with a Pearson value of -0.96, indicating a strong positive correlation between these curves.

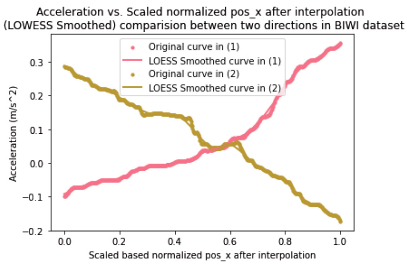


Fig. 3. Speed change rate vs. scaled-normalized pos_x after interpolation in SVAs.

The comparison between (1) and (2) shows that the rate of speed change remains consistent during transitions, regardless of the movement direction. Conversely, the comparison of (3) and (4) indicates that when transitioning from an open space to a crossing, pedestrians first slow down and then gradually accelerate and adapt to the mixed traffic. However, when transitioning from a crossing to a sidewalk, they initially maintain a higher speed and gradually slow down as their perceived threat decreases. Essentially, the trends in pedestrian speed change during different spatial transitions may be inversely related.

5 Conclusions

We carry out a data-driven study using two publicly pedestrian trajectory datasets collected in different countries, in spaces with different safety awareness, and at different times. We find that, pedestrian speeds significantly change near the edge line between mixed traffic and entirely pedestrian spaces, defining a SVA. The SVA's characteristics, including its location, magnitude of speed change, and acceleration/deceleration rates, depend on the space type, movement direction, and pedestrian behaviour, showcasing consistent patterns in non-turning pedestrians transitioning in opposite directions, and contrasting speed change rates in mixed traffic spaces. The potential reasons can be explained by the fact that pedestrians adjust their speed based on the perceived changes in space and their direction of movement, leading to distinct speed variations during spatial transitions. The identified speed characteristics around edge lines enhance our understanding and replication of real-world pedestrian behaviour across different spaces.

Furthermore, we believe that beyond speed, there are other motion characteristics worthy of consideration, and exploring how they can be applied to behaviour prediction is an intriguing research direction. Exploring pedestrian speed variations and rate of speed change in different spatial connections and factors influencing turning behaviour is also an intriguing research direction. Our findings on pedestrian speed changes during space transitions have practical applications in video games, pedestrian behaviour simulations, and data correction. They also shed light on how pedestrians perceive and adapt to various environments, opening avenues for further study.

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