SHARED PATHWAY ANALYSIS FOR PEDESTRIANS, CYCLISTS AND EPMD USERS

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Abstract. To facilitate the increase of urban cycling and electronic personal mobility device (ePMD) ridership, pedestrian footpaths have become shared spaces for riders to traverse and this has raised safety concerns regarding the risk of collisions. This study aims to provide a method of assessment for a network of shared pathways within a building estate, via the analysis of a graph network generated from Building Information Modelling (BIM). First, path width is used as a marker for the capacity of the pathway, and modes of mobility for riders are determined for each segment across the network. Using betweenness centrality, high-traffic zones are mapped, and potential pedestrian-rider conflict zones are highlighted. Finally, recommendations are made as to which segments should be widened for an impactful improvement to the capacity of the network.

Keywords. Urban Cycling, Cyclist and Pedestrian Conflict, Shared Pathway, Network Analysis.

1. Introduction

In recent years, urban cycling has experienced a significant surge in popularity with a notable annual increase in cycling distance per capita recorded across several countries between 2000 and 2009 (OECD/International Transport Forum, 2013). Motivations behind this growing trend include a desire to mitigate the risk of chronic diseases (Celis-Morales et al., 2017), enhance environmental conditions within urban areas (Zahabi et al., 2016), and facilitate first-and-last mile mobility in conjunction with the use of public transportation (Che et al., 2021). In response to the growing prevalence of cycling as a mode of transportation, many countries are actively engaged in developing infrastructure to create an environment conducive to their safe and efficient mobility (Infrastructure Canada, 2021; Land Transport Authority, 2020).

Several studies have indicated that cyclists have the highest preference for dedicated off-road bicycle paths (Broach et al., 2012; Chen et al., 2017; Scott et. al., 2021). The desire for physical separation is also mutually expressed by pedestrians, with speed differentials emerging as a primary contributing factor to conflicts in their coexistence with cyclists (Che et al., 2021; Li et al., 2012). Although it is crucial to

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provide off-road cycling options, to decrease the risk of motor-vehicular collision (Kapousizis et al., 2021), the existing built environment in some areas of cities makes it challenging to accommodate the expansion of dedicated bike paths alongside roads (Hatfield and Prabhakharan, 2016). Consequently, pedestrian footpaths are converted into shared pathways to provide an off-road option for cyclists.

There is an increased demand for space to accommodate the diverse mobility patterns of not only cyclists and pedestrians but also a growing number of electronic personal mobility devices (ePMDs) users on shared pathways (Liang et al., 2021). The presence of cyclists and ePMD users is also prevalent within building parcels, where there are bicycle facilities such as parking lots. This situation has caused much discomfort to pedestrians, as they perceive the presence of these riders as an invasion of safety in a space originally intended for pedestrian use (Bigazzi et al., 2021; López and Wong, 2017). As a result, ensuring the comfort and convenience of all users in this shared environment has become increasingly important for architects and planners.

To address this challenge, this study bridges BIM to Geographic Information System (GIS) for a comprehensive analysis of interactions within a shared circulatory network. By prioritising factors such as path size, the study presents a novel approach to understanding circulation patterns within and around building parcels. The analysis tool aims to provide architects and planners with an improved understanding of network dynamics, leading to more informed decision-making processes to encourage the seamless coexistence of pedestrians, cyclists, and ePMD users, while also prioritizing safety, efficiency, and equitable access to shared pathway infrastructure.

2. Relevant Work

The phenomenon of cyclists and ePMD users riding on footpaths has had a notable increase in various countries, including China, Denmark, Singapore, and the US (Che et al., 2021; Kang and Fricker, 2016). In the study of patterns and attitudes of cyclists, ePMD users and pedestrians, researchers employ various methodologies. These methodologies can be categorised as (a) Empirical studies based on field observations and statistical modelling and (b) Network analysis based on graph theoretic concepts.

To understand the preferences and aversions towards different physical route attributes, most researchers employ one of the two empirical data collection methods: Stated Preference and Revealed Preference. Stated Preference studies involve gathering data from individuals using questionnaires administered to the public or focus group interviews and discussions. These studies have consistently found that pedestrians display a lower tolerance towards sharing pathways with cyclists and ePMD users primarily due to safety concerns (Bigazzi et al., 2021; Kang and Fricker, 2016). There is a positive correlation between path size and comfort, with wider paths associated with increased comfort levels and lower occurrences of conflict (Bhat et al., 2015; Haworth et al., 2014). Therefore, pathway size can serve as an indicator to assess the ability of shared pathways to facilitate comfortable interactions between users.

In contrast, studies utilising Revealed Preference data employ GPS-collected travel data and generated route alternatives, to examine the influence of different route attributes on cyclist route choice. It is widely acknowledged that cyclists would take a circuitous route for a safer and more comfortable journey (Broach et al., 2012). For example, cyclists will detour to avoid high-traffic streets and intersections (Ghanayim and Bekhor, 2018; Lowry et al., 2016). However, a study found that cycling trips are on average only 13.5% longer than the most direct possible route (Park and Akar, 2019), indicating that there is limited tolerance for the additional distance taken for comfort (Fitch and Handy, 2020).

GIS network analysis used in studies focused on safe and comfortable route finding can also be applied to pedestrians but requires additional inputs (Sohrabi et al., 2022). In a comparative study of pedestrian network connectivity, it was observed that accessibility measures within a 5-minute walk radius differed greatly between an open-source GIS dataset and a modified network focusing on pathways relevant to pedestrians (Tal and Handy, 2012). Another study in Italy made adjustments to a software-generated GIS network before using it as a tool to guide footpath improvement schemes (D'Orso and Migliore, 2020). Therefore, it is essential to appropriately modify the network used for analysis in this study.

In conclusion, the interaction between cyclists, ePMD users and pedestrians in a shared space has garnered significant research attention, which has shed light on the complexities of this dynamic relationship. The methodology employed in these studies encompasses network analysis and empirical data collection to understand travel patterns and the impact of physical route attributes. GIS network analysis proves effective in evaluating pedestrian walkability and prioritizing improvement efforts, while empirical data collection methods and corresponding simulations, provide valuable insights into user perceptions and route choices. Moving forward, this study aims to contribute to this body of knowledge by developing a tool that utilises GIS network analysis to assess the condition of shared footpaths, offering valuable guidance for architects and planners.

3. Methodology and Results

With the adoption of BIM for building documentation and regulatory submissions around the world (Luo et al., 2022), high-resolution data is available and can be used in the generation of GIS networks for analysis and evaluation. In this study, the GIS network used is from the residential parcel of a university campus consisting of two point blocks and three linear blocks with bicycle and ePMD parking lots. The following sections focus on: (a) Spatial Network Generation: Polygons in the GIS are translated into detailed graphs that depict circulatory networks of buildings and the graphs undergo post-processing for analysis purposes; (b) Support Capability Assessment: The edges of shared pathways are classified based on the ability to accommodate users and subsequently grouped into segments with assigned recommended modes of mobility for riders across the network; and (c) Conflict Analysis: Identification of potential high conflict zones by analysing the betweenness centrality of the network.

3.1. SPATIAL NETWORK GENERATION

The analysis framework uses BIM to extract circulatory information. This is supported by tools developed to process 3D models and create 2D plan representations comprised of labelled polygons as per GIS. The information associated with the polygons is categorical as well as numerical. The categorical information includes classifications such as space type (e.g., rooms or walkways), visual type (e.g., walls), and access type (e.g., doors). Space types define areas where network graphs are mapped, visual types represent obstacles that restrict the passage of the network, and access types facilitate connections between separate graphs of adjacent spaces, enabling the formation of a functional network of the architectural BIM model. The specific functionalities of each polygon type help in accurately representing and analysing the network.

Translating plan areas represented as polygons into circulation paths is approached via a skeletonisation method known as the Medial Axis Transform (MAT). This method creates a geometrically and topologically sound representation in the form of a graph, that contains nodes and edges (Tagliasacchi et al., 2016). The nodes are spatially situated in the centre of spaces and contain both metric and semantic information associated with the polygon they are situated in, while the edges represent connections between nodes and contain information such as distance between nodes.

With the plethora of information available and the fine granular detail of the graph generated, it is necessary to engage in post-processing for a more concise dataset. The initial graph generated may contain extraneous information that is not relevant to the analysis, such as connections to the nodes at extreme corners of spaces which are not necessary for determining the paths of users. Therefore, nodes that are not essential for the analysis of shared pathways are removed, streamlining the graph and focusing on the critical connections. Figure 1 shows how these adjustments result in a more simplified graph from the originally generated graph. This allows for a more accurate analysis of the network's traversal patterns for cyclists, ePMD users and pedestrians.

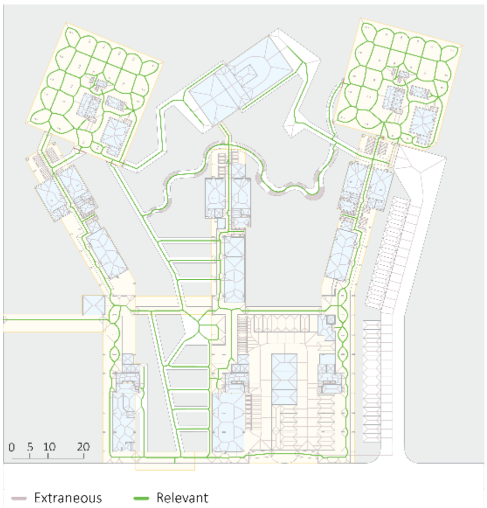

Figure 1. Medial Axis Transform (MAT) graph: Extraneous edges that will not be used are in grey and edges to be used for analysis are in green.

3.2. SUPPORT CAPABILITY ASSESSMENT

The overall capability of a network to support cyclists, pedestrians and ePMD users is related to the physical size of shared pathways and governmental regulation. Wider pathways correspond to increased comfort levels, as evident in studies that found that pedestrians are observed to be significantly more tolerant of sharing a footpath with cyclists when the distance between them is 1.5m during a passing event (Haworth et al., 2014; Kang and Fricker, 2016). Furthermore, different governmental bodies have various standards and allowances for these shared spaces. In Singapore, cyclists are permitted to ride on shared pathways that are at least 1.5m (Urban Redevelopment Authority, 2018). Hence the assessment of the overall ability of a network to comfortably accommodate all users should not only consider the size of pathways but should also be adjusted to suit the local context of the study, considering factors such as local regulations and user preference.

To evaluate the potential of a network to support cyclists, pedestrians and ePMD users, the edges in the network were first classified into three distinct categories, namely “Inadequate”, “Adequate”, and “Exceptional”, based on the pathway size. In this study, sections of the shared pathway where the width was below 1.5m are considered inadequate while areas with path width above 3m are considered exceptional, a value derived by adding the critical distance identified (1.5m).

Figure 2 shows the classification of the edges of the residential parcel. While most external pathways are made up of adequate and exceptional edges, there are a few short stretches of inadequate edges (A1). Some corridors have exceptional edges (A2), and others have inadequate edges interspersed amongst satisfactory edges (A3). Overall, the adequate and exceptional edges make up 80% of the total length of the network, hence the parcel has a high capability to comfortably support riders and pedestrians.

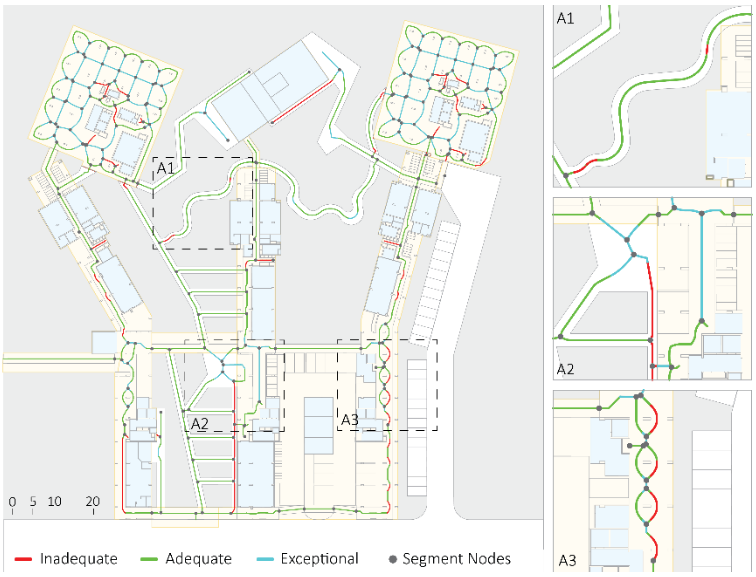

Figure 2. Classification of network edges into three distinct categories

However, relying solely on width measurements does not present the complete picture. To encourage harmonious interaction among users, the locational context of the edges is considered and segments across the network are assigned suitable modes of mobility for riders. Figure 3 shows an analysis of the graph with identification of restricted zones, dismount zones and ride zones.

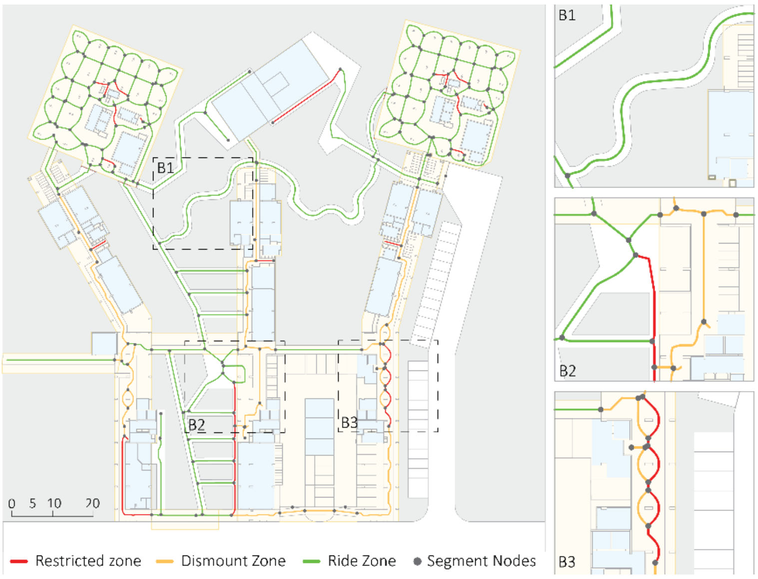

Figure 3. Segmentation of network and classification according to modes of mobility

Despite having similar edge classification profiles, most external pathways are designated as ride zones while corridors are assigned as dismount zones. There are distinct implications for user comfort associated with either space. Outdoors, there is ample space for riders or pedestrians to swerve or move away from one another, including the possibility of using adjacent grass areas. Hence, even with small amounts of inadequate edges (A1), it is acceptable to designate external pathways as ride zones (B1). Conversely, corridors offer limited manoeuvring space, hence greatly increasing the discomfort of all parties in a passing event between riders and pedestrians. Hence for the safety and comfort of all, corridors should be designated as dismount zones even if it is exceptionally wide (B2). Moreover, corridors with alternating inadequate edges should be avoided by riders (B3). Ride zones constitute 72% of the total network length, further supporting the assertion that this parcel effectively accommodates rider and pedestrian movement, providing comfortable passing distances for users.

While the categorisation of edges provides an initial understanding of capacity, further consideration of widths and their implications for different contexts is indispensable in enhancing the overall usability and experience of the shared spaces in the network. Aside from looking at a network categorically, the next section explores the traffic flows of different user groups and potential conflict zones which may have implications for the mobility allowance of each segment.

3.3. IDENTIFICATION OF CONFLICT ZONES

The risk of a conflict between riders and pedestrians is not only affected by pathway width but also the volume of rider and pedestrian traffic (Nikiforiadis et al., 2020). Hence, critical connectors in the network are identified by studying the traffic flow of riders and pedestrians across the parcel and are assessed to determine if they are wide enough to support the high volume of users.

Using betweenness centrality analysis, all shortest paths from source nodes to target nodes are run and the centrality value of each segment is the sum of the shortest paths that run through it. Higher centrality values correlate to segments that are more frequently traversed and therefore represent higher pedestrian or rider traffic flow. The target nodes for both pedestrian and rider traffic flow analysis are the Entry-Exit points of the parcel. The source nodes of the former are doors that provide entry into an indoor space or a lobby, and they represent points of implicit pedestrian circulation. The source nodes of the latter are bicycle parking areas.

Provisions have been implemented to address the nuances in user traffic flow. For the pedestrian analysis, the number of pedestrian units per door is calculated based on the occupancy load of its corresponding room as rooms with distinct functions experience varying levels of foot traffic. In the rider analysis, an extra penalty is applied to the weight of segments to accommodate the diverse preferences of riders as they navigate different mobility zones with varying pathway widths.

Figure 4 shows that most of the high rider traffic flow areas (in red) and the pedestrian traffic flow areas (in blue) do not overlap, with the former occurring at ride zones of external pathways and the latter in corridors. Critical connectors of the network in Figure 4 can be identified by discerning areas with both high cyclist and pedestrian traffic flow. They are highlighted and assessed to determine if the path is wide enough to account for the higher traffic volume.

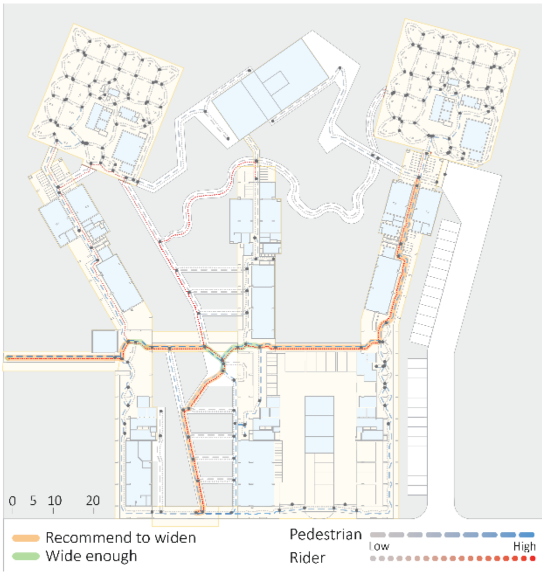

Figure 4. Pedestrian-Rider Traffic Flow Map with critical connectors highlighted

In Singapore, inter-town shared pathways are usually 4m wide as opposed to arterial pathways that are 1.5m wide. In this study, the threshold for critical connectors can be taken as the width identified as "exceptional", that is 3m. In Figure 4, areas that have been identified as critical connectors and have exceptional edges are highlighted in green. Areas recommended to be widened due to lack of space to support heavy pedestrian and rider traffic flow are highlighted in orange.

The ability to analyse pedestrian traffic flow and cyclist traffic flow in the network provides valuable insights into the structure of the network, such as the identification of main arterial roads and possible provisions required. This informs the decision-making process as planners seek to mitigate conflicts between cyclists, ePMD users and pedestrians, and enhance the overall usability and safety of shared pathways.

4. Conclusion

This paper is intended to be a guide to aid architects and planners in assessing pathways for shared usage between cyclists, ePMD users and pedestrians. The efficacy of a shared pathway network is assessed by employing path width as an indicator in supporting comfortable pedestrian-rider interactions. This subsequently informs the classification of the different modes of mobility for riders across the network. Analysis of rider and pedestrian traffic flows through the network provides insights into which segments of the network are critical connectors. Planners should prioritise such segments and ensure they are wide enough to support the heavy traffic flow.

The parcel presented in this study is specific to a residential area of a university campus and limits the study in terms of the size of the network. Hence, similar analyses have been conducted on other parcels of different sizes and estate typologies.

The numbers used to define the adequacy of pathway width are dependent on local context and extrapolation from previous studies. Field studies in the local environment should be conducted in conjunction with this analysis for an increased understanding of the comfortable pedestrian-rider distance in both low and high-traffic situations, thereby establishing the actual adequate pathway width required in the different situations. Such data increases accuracy for the categorisation of network edges and provides more appropriate recommendations for planners and architects.

Moreover, this study aggregates cyclists and ePMD riders, disregarding the possible differences in how pedestrians perceive them. Disparity in travelling speed is one of the reasons pedestrians feel their safety is compromised by the presence of cyclists on pathways (Liang et al., 2021). While most cyclists are fast, some ePMD riders may travel at lower speeds and are not viewed as safety hazards by pedestrians. Therefore, it is beneficial to distinguish between cyclists and the different types of ePMD riders for future studies.

Finally, mobility patterns due to the weather have not been taken into account in the analysis of pedestrian and rider traffic flows. In the event of good weather, pedestrians may choose to walk at external pathways instead of sheltered areas, potentially increasing the areas of critical traffic volume. Conversely, high rider traffic may be observed in sheltered corridors during wet weather. Hence, more parameters could be put in place during analysis to generate results of traffic flow in different weather conditions.

Overall, this paper is a valuable contribution to improving the safety of shared pathways and encouraging urban mobility. Architects and planners can easily use this tool with the existing BIM technology and adapt the parameters of the analysis to best suit local legislation and preferences.

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References

Bhat, C. R., Dubey, S. K., & Nagel, K. (2015). Introducing non-normality of latent psychological constructs in choice modeling with an application to bicyclist route choice. *Transportation Research Part B: Methodological*, 78, 341–363. https://doi.org/10.1016/j.trb.2015.04.005.

Bigazzi, A., Gill, G., & Winters, M. (2021). Contrasting perspectives on the comfort and safety of pedestrians interacting with other road users. *Transportation Research Record: Journal of the Transportation Research Board*, 2675(3), 33–43. https://doi.org/10.1177/0361198121992272.

Broach, J., Dill, J., & Gliebe, J. (2012). Where do cyclists ride? A route choice model developed with revealed preference GPS Data. *Transportation Research Part A: Policy and Practice*, 46(10), 1730–1740. https://doi.org/10.1016/j.tra.2012.07.005.

Che, M., Raditya, S. J., Dwi Phalita, U., Wong, Y. D., & Lum, K. M. (2021). Cyclists' preference study in using four types of cycling facilities in Singapore. *Case Studies on Transport Policy*, 9(4), 1810–1817. https://doi.org/10.1016/j.cstp.2021.09.005.

Chen, P., Shen, Q., & Childress, S. (2017). A GPS data-based analysis of built environment influences on bicyclist route preferences. *International Journal of Sustainable Transportation*, 12(3), 218–231. https://doi.org/10.1080/15568318.2017.1349222.

D'Orso, G., & Migliore, M. (2020). A GIS-based method for evaluating the walkability of a pedestrian environment and prioritised investments. *Journal of Transport Geography*, 82, 102555. https://doi.org/10.1016/j.jtrangeo.2019.102555.

Fitch, D. T., & Handy, S. L. (2020). Road environments and bicyclist route choice: The cases of Davis and San Francisco, CA. *Journal of Transport Geography*, 85, 102705. https://doi.org/10.1016/j.jtrangeo.2020.102705.

Ghanayim, M., Bekhor, S. (2018). Modelling bicycle route choice using data from a GPS-assisted household survey. *European Journal of Transport and Infrastructure Research*, 18, 158-177. http://dx.doi.org/10.5930/issn.1567-7141.

Hatfield, J., & Prabhakharan, P. (2016). An investigation of behaviour and attitudes relevant to the user safety of pedestrian/cyclist shared paths. *Transportation Research Part F: Traffic Psychology and Behaviour*, 40, 35–47. https://doi.org/10.1016/j.trf.2016.04.005.

Haworth, N., Schramm, A., & Debnath, A. K. (2014). An observational study of conflicts between cyclists and pedestrians in the city centre. *Journal of the Australasian College of Road Safety*, 25(04), 31–40.

Infrastructure Canada. (2021). *Government of Canada announces first federal funds for cycling paths and trails across the country*. Retrieved August 20, 2023, from https://www.canada.ca/en/office-infrastructure/news/2021/03/government-of-canada-announces-first-federal-fund-for-cycling-paths-and-trails-across-the-country.html.

Kang, L., & Fricker, J. D. (2016). Sharing urban sidewalks with bicyclists? an exploratory analysis of pedestrian perceptions and attitudes. *Transport Policy*, 49, 216–225. https://doi.org/10.1016/j.tranpol.2016.04.013.

Kapousizis, G., Goodman, A., & Aldred, R. (2021). Cycling Injury Risk in Britain: A case-crossover study of infrastructural and route environment correlates. Accident Analysis and Prevention, 154, 106063. https://doi.org/10.1016/j.aap.2021.106063.

Land Transport Authority. (2020). *Factsheet: Islandwide Cycling Network (ICN) Programme to Improve Safety and Connectivity for all Path Users*. Retrieved August 20, 2023, from https://www.lta.gov.sg/content/ltagov/en/newsroom/2020/3/news-releases/islandwide-cycling-network--icn--programme-to-improve-safety-and.html.

Li, Z., Wang, W., Liu, P., & Ragland, D. R. (2012). Physical Environments influencing bicyclists' perception of comfort on separated and on-street bicycle facilities. *Transportation Research Part D: Transport and Environment*, 17(3), 256–261. https://doi.org/10.1016/j.trd.2011.12.001.

Liang, X., Meng, X., & Zheng, L. (2021). Investigating conflict behaviours and characteristics in shared space for pedestrians, conventional bicycles and e-bikes. *Accident Analysis and Prevention*, 158, 106–167. https://doi.org/10.1016/j.aap.2021.106167.

Lowry, M. B., Furth, P., & Hadden-Loh, T. (2016). Prioritizing new bicycle facilities to improve low-stress network connectivity. *Transportation Research Part A: Policy and Practice*, 86, 124–140. https://doi.org/10.1016/j.tra.2016.02.003.

López, M. C. R., & Wong, Y. D. (2017). Attitudes towards active mobility in Singapore: A qualitative study. *Case Studies on Transport Policy*, 5(4), 662–670. https://doi.org/10.1016/j.cstp.2017.07.002.

Luo, H., Lin, L., Chen, K., Antwi-Afari, M. F., & Chen, L. (2022). Digital technology for Quality Management in Construction: A review and Future Research Directions. *Developments in the Built Environment*, 12, 100087. https://doi.org/10.1016/j.dibe.2022.100087.

Nikiforiadis, A., Basbas, S., Garyfalou, M. I. (2020). A methodology for the assessment of pedestrians-cyclists shared space level of service. *Journal of Cleaner Production*, 254, 120172. https://doi.org/10.1016/j.jclepro.2020.120172.

OECD/International Transport Forum (2013). Cycling, health and safety. *OECD Publishing/ITF*. http://dx.doi.org/10.1787/9789282105955-en.

Park, Y., & Akar, G. (2019). Why do bicyclists take detours? A multilevel regression model using smartphone GPS data. *Journal of Transport Geography*, 74, 191–200. https://doi.org/10.1016/j.jtrangeo.2018.11.013.

Scott, D. M., Lu, W., & Brown, M. J. (2021). Route choice of bike share users: Leveraging GPS data to derive choice sets. *Journal of Transport Geography*, 90, 102903. https://doi.org/10.1016/j.jtrangeo.2020.102903.

Sohrabi, S., Weng, Y., Das, S., & German Paal, S. (2022). Safe route-finding: A review of literature and Future Directions. *Accident Analysis and Prevention*, 177, 106816. https://doi.org/10.1016/j.aap.2022.106816.

Tagliasacchi, A., Delame, T., Spagnuolo, M., Amenta, N., & Telea, A. (2016). 3D skeletons: A state-of-the-art report. *Computer Graphics Forum*, 35(2), 573–597. https://doi.org/10.1111/cgf.12865.

Tal, G., & Handy, S. (2012). Measuring nonmotorized accessibility and connectivity in a robust pedestrian network. *Transportation Research Record: Journal of the Transportation Research Board*, 2299(1), 48–56. https://doi.org/10.3141/2299-06.

Urban Redevelopment Authority. (2018). Walking and Cycling Design Guide. Retrieved August 20, 2023, from https://www.ura.gov.sg/Corporate/Guidelines//media/BD725DB201DB496A93569C8072DD9FD0.ashx.