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Prioritising Street Shade Intensification to Support Pedestrian Accessibility to Public Transport: A Data-driven Approach

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Abstract: This article presents a new methodology for urban-scale prioritisation of shade-inducing operations by quantifying the gap between the use intensity of public transport stops and the solar exposure of the streets leading to them. By cross-referencing a high-resolution dataset of travel ticket validation with shade maps quantifying the average street shade provision, we were able to calculate a new metric, the Shading Priority Index, which quantifies the relative importance of adding street shading in each statistical zone. The method was applied to Tel Aviv-Yafo, a major city in Israel. The calculation of the **Shading Priority Index** at the scale of a statistical zone in the city made it possible to expose significant differences between each zone, both in passenger quantities and outdoor shading conditions in the routes leading to transportation stops, and to identify key weak points in the climate-related accessibility of pedestrians to public transport.

Keywords: big-data analysis; climatic urban policy; shade maps; urban human behaviour; urban microclimate

1 INTRODUCTION

Accessible and readily available public transport is perceived today as an essential component in securing urban quality of life and as one of the central goals of any urban sustainability vision. However, accessibility to public transport is often presented as depending mainly on the walking distance between users' starting points (e.g., places of residence or work) and transportation stops, alongside the availability of convenient physical infrastructure for walking [1-4]. This approach, while focusing on the network properties of public transport infrastructure and the morphological aspects of urban design, does not consider the need to secure comfortable thermal conditions along the footpaths leading to the stops.

Although several studies from recent years have examined the relationship between thermal comfort at bus stops and their use, these studies were limited to thermal comfort at the stops themselves and did not address the conditions along the walking routes leading to them [5-7]. In Israel and other hot-climate countries, it is known that the lack of outdoor shade can result in severe heat stress among pedestrians, as studies from Tel Aviv-Yafo [8] and Tempe, AZ [9] demonstrated. It is, therefore, expected that access routes to transportation stops that are more exposed to the sun would reduce the willingness to use public transport. A recent study from Boston, MA [10] has also suggested, based on a large dataset of pedestrian routes, that heat stress significantly affects the "perceived walking distance" and can thus negatively limit access to common points of interest like public transport destinations.

The evidence found in studies on urban climate indicates that the lack of "climatic accessibility" to public transport, i.e. the provision of comfortable climatic conditions along the routes to public transport stations and stops, should also be considered an impediment to public transport travel. Yet, until now, little attention has been given to methods that will enable us to highlight urban areas where the climatic accessibility to public transport is poor and prioritise actions for improving it based on standardised indices. This study was intended to provide an initial response to this gap by developing a method for prioritising improvements to the climatic accessibility of transportation stops based on urban-scale, high-resolution quantitative data.

2 METHODS

The goal of this study was to develop a metric that would facilitate the identification of the most extreme climatic vulnerabilities in a city's network of transportation stops. This metric uses large datasets of various inputs (geographic, climatic, and functional) that enabled us to quantify the intensity of use of urban transportation stops alongside the degree of exposure to solar radiation of the street network leading to them. The study focused on the city of Tel Aviv-Yafo, a city of about 475,000 residents (2023 figures, Israel's Central Bureau of Statistics) covering an area of 52 km^2 and the centre of Israel's main population conurbation (Gush Dan). The city's morphological complexity and its role as a central economic hub enabled us to calculate the metric for a variety of urban contexts that differ from each other in the spatial distribution of the transportation stops, the intensity of their use, the structure of the urban street network, and the level of exposure of the street network to solar radiation.

The study was based on the analysis and cross-referencing of two main databases: a national database of travel ticket validation at transportation stops that is maintained by Israel's Ministry of Transport (https://data.gov.il/dataset/tikufim_station_2022) and a zone shade map of Tel Aviv-Yafo. We produced the shade map according to a unique method we developed previously [11] by processing digital surface models and tree canopy mapping provided by the Survey of Israel. Using these two datasets, we calculated a new metric that quantified the importance of additional shading as a product of the average outdoor shading level of streets and the average daytime public transport passenger numbers in all the statistical areas of the city.

2.1 Travel Ticket Validation Dataset

Since 2022, Israel's Ministry of Transport has opened to the public a database containing data on public transport travel validation at every urban transportation stop in Israel. The source of the data is the online ticket validation system installed on all the public buses in Israel. The data is distributed as a table in a CSV format, in which the following fields are listed: unique stop ID number, stop name, period for which data was received, year, month number, and date number. For each day, the validation data is divided into seven unequal periods, allegedly representing peak and low times in the use of public transport, as follows: 00:00-03:59 ("night low"); 04:00-05:59 ("morning low"); 06:00-08:59 ("morning peak"); 09:00-11:59 ("daytime low 1"); 12:00-14:59 ("daytime low 2"); 15:00-18:59 ("evening peak"); and 19:00-23:59 ("evening low"). These somewhat rigid definitions do not represent the actual daily fluctuations in each city and were presumably adopted by the Ministry to establish a uniform common denominator for data from all over the country.

In this study, we used the complete ticket validation dataset for the year 2023, from which we extracted data from the stops located within the boundaries of Tel Aviv-Yafo. As part of the work process, we filtered out data from Fridays and Saturdays due to the partial public transport service on these days in Israel. Using the remaining data, we calculated **monthly and weekly averages of the total hourly number of passengers** in each city to examine daily and seasonal passenger trends. Since we wanted to develop an index relating to heat stress caused during the hot season's daytime hours, we further processed the data to calculate the **daytime average number of hourly passengers** in each statistical zone from 1 May to 31 August (four months, between 06:00-19:00). This metric makes it possible to assess and compare neighbourhood-level use of public transport during the hot season.

2.2 Urban Shade Maps

Urban shade maps are maps that depict the levels of outdoor shading conditions at a high resolution based on the calculation of a Shade Index (*SI*) that describes, on a scale from 0 to 1, the extent to which ground-level insolation is blocked during a typical summer day [11]. More specifically, the SI is based on calculating the **cumulative exposure** of the ground between 08:00 and 17:00 (daylight saving time) on 6 August, which is the middle day between the longest day of the year (21 June) and the autumn equinox (22 September) and represents the seasonal peak in local heat stress intensity. In that sense, the *SI* considers the variation in the intensity of global solar radiation throughout the day, comparing the blocked insolation at ground level at a certain location and the maximum insolation of an unobstructed horizontal surface at the same time and location. The higher the *SI* value, the higher the shading. This indicator considers shade produced by all elements in an urban environment: buildings, trees, and other shade-giving elements. It can be formulated as follows:

$$SI_{\mathrm{p}} = 1 - \left(\frac{Insolation_{\mathrm{p}}}{Insolation_{\mathrm{r}}} \right), \tag{1}$$

where SI_{p} is the Shade Index at a certain point, and $Insolation_{\mathrm{p}}$ and $Insolation_{\mathrm{r}}$ represent the intensity of incident solar radiation at that point and at an unobstructed reference point respectively. Roughly speaking, the level of SI can be evaluated as follows: below 0.1, acute shortage of shading; between 0.1 and 0.2, significant lack of shading; between 0.2 and 0.4, shading requires improvement; between 0.4 and 0.6, good shading; above 0.6, excellent shading.

For a high-resolution calculation of the SI in a city, we apply an enhanced process based on the insolation calculation module available in the Urban Multi-scale Environmental Predictor (UMEP) plugin [12] for QGIS. This tool uses high-resolution Digital Surface Model (DSM) and Digital Terrain Model (DTM) data to calculate horizontal insolation and requires the generation of separate DSMs for buildings and tree crowns. To extract the tree crown data from the input DSM, we used an urban crown contour mapping from 2022 that was produced by the Survey of Israel based on machine vision analysis of aerial photographs [13]. The input DSMs and DTM of Tel Aviv-Yafo that we used in this work were produced by the Survey of Israel in 2022.

To generate the shade maps, the input spatial data was processed at the resolution of 50 cm per pixel, resulting in a raw layer of SI values for each input pixel. Based on this layer, we then calculated an average SI value for the entire street area of each statistical zone in Tel Aviv-Yafo based on input land use vector layers provided by the municipality. The SI for each statistical area, therefore, represents the average level of shading throughout the entire street network contained within that statistical area. A city-scale shade map thus provides a good indication of the level of exposure to heat stress of public transport passengers during daylight hours in different parts of the city.

2.3 The Shading Priority Index

Based on the average hourly passengers and the SI values for the statistical zones, we calculated a Shading Priority Index (*SPI*) for each zone with the aim of using it to locate key areas in the city where concentrated activity is required to improve shading throughout their street network. This metric highlights areas where poor street shading conditions exist alongside a relatively high number of public transport users. A zone SPI (*SZ_SPI*) is calculated according to the following formula:

$$SZ\_SPI = \left(1 - SZ\_SI\right) \times \frac{SZ\_APh - APh_{\min}}{APh_{\max} - APh_{\min}}. \tag{2}$$

where *SZ_SI* is the zone's SI, *SZ_APh* is its average daytime hourly number of passengers (*APh*) during the hot season, $APh_{\max}$ is the highest *APh* among all statistical zones, and $APh_{\min}$ is the lowest. The *SZ_SPI* thus describes, on a scale of 0 to 1, the importance of improving the shading conditions in areas attracting a high number of public transport passengers, with importance increasing as the value approaches 1.

3 RESULTS

The results were analysed in two stages: first, we calculated average hourly ticketing events at the city level, looking for general trends that could indicate whether the use of public transport is significant enough during all daytime hours. We assumed that if certain periods during the daytime show significantly low ridership, they may not be accounted for when prioritising shading actions. The second analysis stage consisted of calculating outdoor shade levels and the Shading Priority Index according to the abovementioned method and using it to map priority zones for increasing street shading.

3.1 Public Transport Passenger Trends

The city-scale analysis of the ticket validation dataset (Fig. 1) presents no significant seasonal changes in the quantities of public transport users throughout the year. However, a sharp decline in public transport rides occurred in October 2023, which can be attributed to the war that erupted in Israel on 7 October, resulting in a partial closure of workplaces and the education system. Additionally, in April and September, which are months of holidays and vacations in Israel, there was a slight decline in the weekly passenger averages. It can therefore be argued that the demand for public transport is more or less constant throughout the year, although there is a slight increase in the use of public transport during the hot season, starting in May. This hard demand is also apparent from the recurring daily pattern of passenger peaks and lows, which was similar throughout most of the year. In Tel Aviv-Yafo, the peak number of public transport passengers is between 15:00 and 19:00 and is relatively higher than in the other daily analysis periods. Nevertheless, it can be argued that passenger quantities were relatively high during all other daytime hours (06:00-15:00) when compared to the evening and night periods. This finding supported our decision to include all daytime hours (06:00-19:00) and not only the peak afternoon when calculating the Shading Priority Index since significant numbers of passengers still use public transport even outside the peak afternoon period.

3.2 Mapping Shade and Passenger Geographic Distribution

The Tel Aviv-Yafo zone shade map (Fig. 2) shows significant differences in street shading levels in different parts of the city. The dense street network in the city's historic centre is mostly well-shaded and generally provides very good climatic accessibility to transportation stops. At the same time, other central areas of the city suffer from a significant lack of shading, and this is especially evident in the area of the main central business district (CBD) along Begin Road, in the south-eastern parts of the city, as well as in the area of Tel Aviv University and the exhibition grounds ("Expo Tel Aviv").

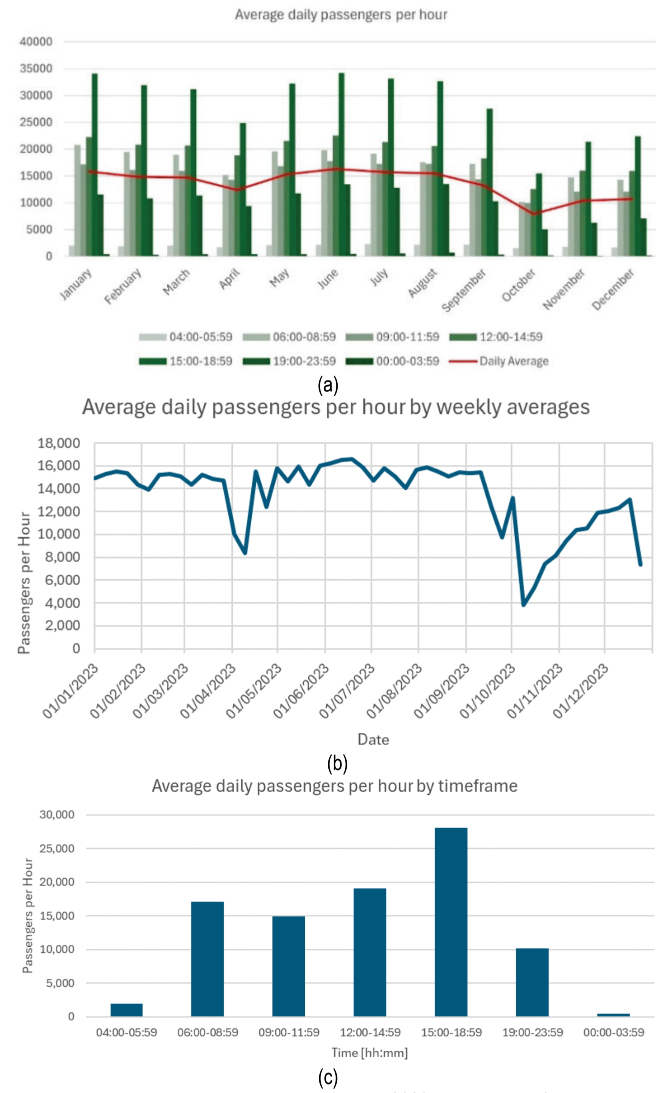

Figure 1 Hourly ticketing events throughout 2023 in Tel Aviv-Yafo: Monthly averages, divided into seven daily periods (a); weekly averages (b); and annual averages, divided into seven daily periods (c).

Mapping the average hourly number of daytime passengers in statistical zones (Fig. 3) reveals the effect of Tel Aviv-Yafo's four train stations on public transport use in the city. The average hourly passenger number during daytime from transportation stops in zones containing a train station was above 1,000, a number significantly higher than in most other parts of the city. These numbers do not include train rides but only urban bus rides. By comparing the shade and passenger mapping, it becomes evident that the zones attracting the highest numbers of passengers also suffer from low levels of street shading.

What seems to be visually apparent from comparing the shade and passenger maps becomes much more pronounced when calculating and mapping the *SPI* for each of the statistical zones (Fig. 4). The map highlights three distinct areas with the highest SPI, each consisting of several zones, and all of them located around the city's four train stations. Nevertheless, the index helps to differentiate between the shading priority of each of these areas, reflecting the centrality of the CBD area and the high need for shade in its streets (*SPI* = 0.64 to 0.91) compared to the areas around the northern (*SPI* = 0.4) and southern (*SPI* = 0.38) train stations. The map also shows very low *SPI* values (less than 0.1) in most of the city's other statistical zones.

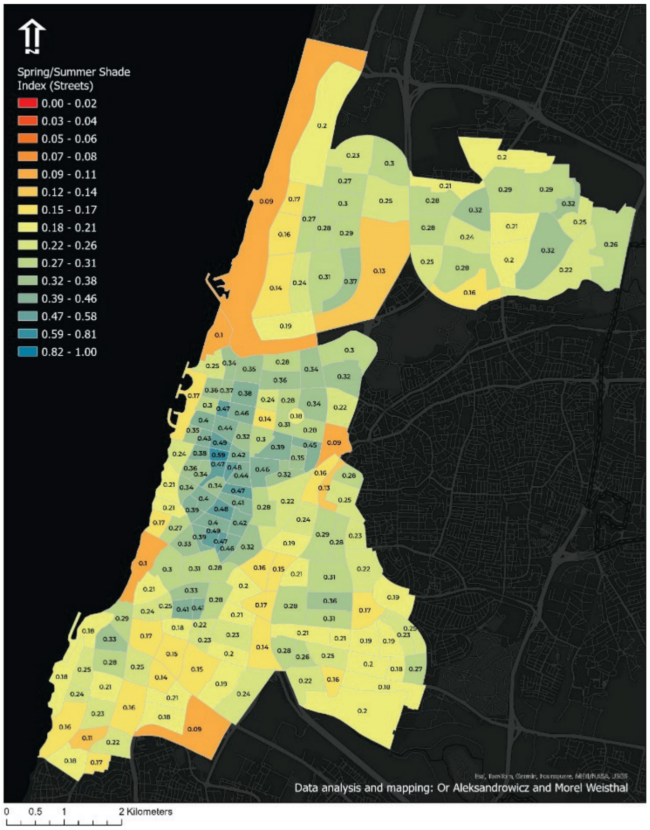

Figure 2 Shade map of statistical zones (average Shade Index in streets in each area) in Tel Aviv-Yafo, 2022. Data processing and mapping: Or Aleksandrowicz and Morel Weisthal.

4 DISCUSSION

Shade mapping based on a quantitative index like the SI can be regarded as the first step in allocating resources to outdoor shading improvements. However, in most cases, one cannot depend only on SI values to highlight urban areas where additional shading is particularly urgent and requires high prioritisation, especially in cities where many parts of the city suffer from a significant lack of shade. Prioritising shading actions usually depends on choices and preferences prevalent among the municipal planning and executive bodies, but these are rarely formulated based on quantitative evidence. Rather, they rely on accumulated experience and close familiarity with city life. However, data-driven prioritisation has stronger explanatory power, assuming we have the relevant data at hand, as well as the potential to direct actions in the most efficient and effective way.

The ticket validation dataset provided by the Ministry of Transport could significantly assist in adopting an evidence-based shading prioritisation policy since it reflects how certain populations use urban space. In the context of public transport, some of these populations are usually the most vulnerable to heat stress (children, the elderly) and, therefore, need closer attention with respect to additional shade provision. However, beyond that, it should be recognised that less vulnerable populations also use public transport daily and that policies which serve to increase their numbers can reduce the use of private vehicles in cities. Therefore, prioritising shading on the way to transportation stations is not only important for reducing exposure to heat stress and improving walkability but can also be seen as a complementary planning measure to encourage the transition to public transport and to pursue benefits ranging from improved health and safety to long-term environmental sustainability.

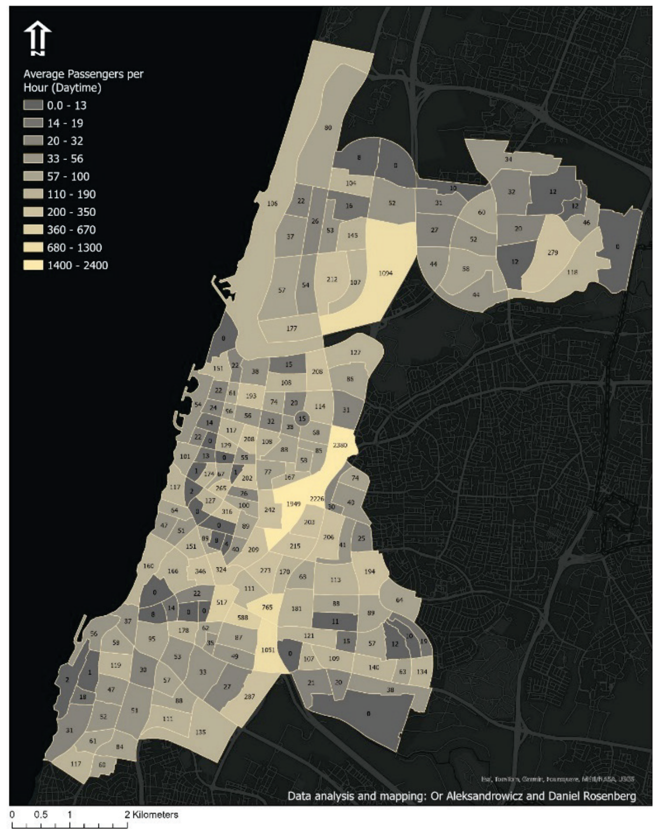

Figure 3 Map showing the average number of hourly daytime passengers from May to August in each statistical zone in Tel Aviv-Yafo (2023 data).

In this work, we proposed an index for prioritising shading operations that consider the number of passengers passing through the city's transportation stops alongside the degree of shading in the streets. In examining the mapping we produced, it is evident that it is possible to use this index to pinpoint a small number of areas in the city to which high priority should be given in shading operations. In this respect, the cross-referencing between mapping outdoor shade and calculating the average number of public transport passengers helps to distinguish between different degrees of importance that should be given to shading different parts of the city and to first direct efforts to areas where they are in the utmost need.

Some prioritisation of shading operations is always necessary since municipalities cannot simultaneously improve the shading situation in all parts of the city. A quantitative index calculated for prioritisation can only be effective when it helps highlight a relatively small number of intervention sites. In this respect, the Shading Priority Index that we present here is up to the task because it highlights a relatively small number of areas for action. At the same time, in Tel Aviv-Yafo, the concentration of exceptionally high passenger rates in a small number of areas that are also poorly shaded makes the distinctions revealed by applying the SPI more clear-cut than they would be in cities with a lesser confluence of these two factors.

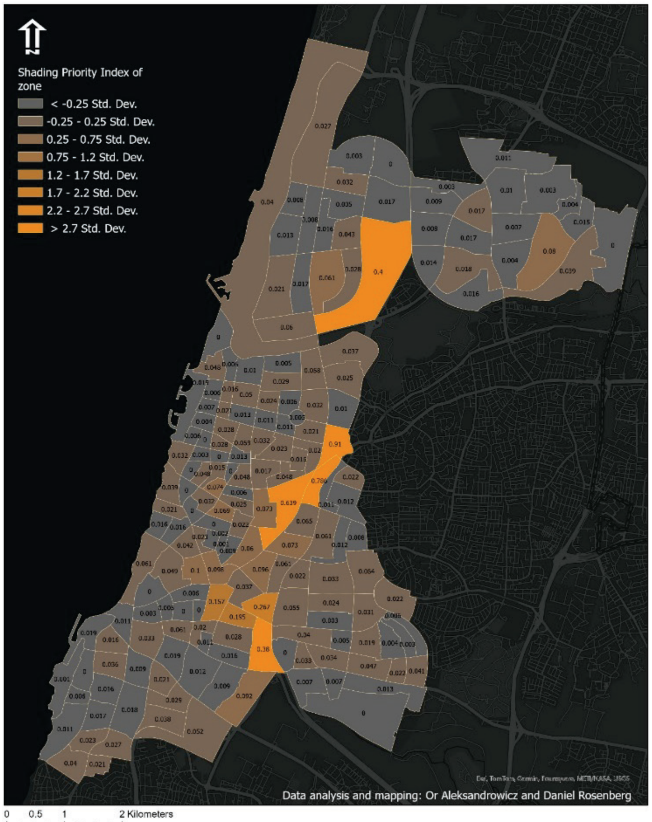

Figure 4 Map of the Shading Priority Index (SPI) in statistical zones in Tel Aviv-Yafo. The three zones with the highest SPI (visible in orange) are adjacent to the city's four main train stations: University Station in the north, Central and Hashalom Stations in the centre, and Hahagana Station in the south.

5 CONCLUSION

This study introduces a method and metrics for quantitatively assessing outdoor shading in streets and prioritising actions to improve shading conditions while considering the geographic distribution of public transport passenger flows during the hot season. These metrics make it possible to conduct a broad assessment of the degree of climatic accessibility of public transport in a city. The proposed Shade Priority Index makes it possible to identify a city's climatic vulnerabilities in public transport access while highlighting the need for a granular level of analysis and mapping to extract insights on the climatic management of urban spaces.

The calculation of the new metric presented in this study combines the analysis of two types of public datasets: a high-resolution, three-dimensional geographic mapping of the urban area from which urban shade maps can be generated and high-resolution ticket validation data at transportation stops. From the ticket validation dataset, it was possible to learn, on the one hand, about substantial differences in passenger numbers during peak and low times and, on the other hand, to conclude that most trips on urban public transport take place throughout the daytime, even during the hot season. This conclusion emphasises the need to secure shading along pedestrian routes to transportation stops.

The mapping we produced during the study also shows that the method we present here can be applied relatively easily in other cities and urban areas where coordinated shading operations are required. Widespread implementation of this method in other cities may also enable decision-makers and planners to identify recurring vulnerabilities in the climatic accessibility to public transport and to conduct a comparative examination of its levels between cities. Cross-referenced with spatial socioeconomic indicators, the index developed in this study may also help expose gaps in climatic accessibility to public transport that particularly affect the access of disadvantaged populations to this public resource.

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6 REFERENCES

[1] Alshalalfah, B. W. & Shalaby, A. S. (2007). Case Study: Relationship of Walk Access Distance to Transit with Service, Travel, and Personal Characteristics. *Journal of Urban Planning and Development, 133*(2), 114-118. https://doi.org/10.1061/(ASCE)0733-9488(2007)133:2(114)

[2] Shaaban, K., Siam, A., Badran, A. & Shamiyah, M. (2018). A simple method to assess walkability around metro stations. *International Journal of Sustainable Society, 10*(1), 1. https://doi.org/10.1504/IJSSOC.2018.092651

[3] Sukor, N. S. A. & Fisal, S. F. M. (2020). Safety, Connectivity, and Comfortability as Improvement Indicators of Walkability to the Bus Stops in Penang Island. *Engineering, Technology & Applied Science Research, 10*(6), 6450-6455. https://doi.org/10.48084/etasr.3849

[4] Taplin, J. H. & Sun, Y. (2020). Optimizing bus stop locations for walking access: Stops-first design of a feeder route to enhance a residential plan. *Environment and Planning B: Urban Analytics and City Science, 47*(7), 1237-1259. https://doi.org/10.1177/2399808318824108

[5] Dzyuban, Y., Hondula, D. M., Coseo, P. J. & Redman, C. L. (2022). Public transit infrastructure and heat perceptions in hot and dry climates. *International Journal of Biometeorology, 66*(2), 345-356. https://doi.org/10.1007/s00484-021-02074-4

[6] Electricwala, F. & Kumar, R. (2016). Impact of green shading on urban bus stop structure. *Proceedings of the 2nd International Conference on Computational Intelligence and Communication Technology, CICT 2016*, 615-622. https://doi.org/10.1109/CICT.2016.128

[7] Lanza, K. & Durand, C. P. (2021). Heat-moderating effects of bus stop shelters and tree shade on public transport ridership. *International Journal of Environmental Research and Public Health, 18*(2), 1-15. https://doi.org/10.3390/ijerph18020463

[8] Aleksandrowicz, O. & Pearlmutter, D. (2023). The significance of shade provision in reducing street-level summer heat stress

in a hot Mediterranean climate. *Landscape and Urban Planning, 229*, 104588. https://doi.org/10.1016/j.landurbplan.2022.104588

[9] Middel, A., Alkhaled, S., Schneider, F. A., Hagen, Bj. B. & Coseo, P. (2021). 50 grades of shade. *Bulletin of the American Meteorological Society, 102*(9), 1-35. https://doi.org/10.1175/BAMS-D-20-0193.1

[10] Basu, R., Colaninno, N., Alhassan, A., & Sevtsuk, A. (2024). Hot and bothered: Exploring the effect of heat on pedestrian route choice behavior and accessibility. *Cities*, 155, 105435. https://doi.org/10.1016/j.cities.2024.105435

[11] Aleksandrowicz, O., Zur, S., Lebendiger, Y. & Lerman, Y. (2020). Shade maps for prioritizing municipal microclimatic action in hot climates: Learning from Tel Aviv-Yafo. *Sustainable Cities and Society, 53*, 101931. https://doi.org/10.1016/j.scs.2019.101931

[12] Lindberg, F et al. (2018). Urban Multi-scale Environmental Predictor (UMEP): An integrated tool for city-based climate services. *Environmental Modelling & Software, 99*, 70-87. https://doi.org/10.1016/j.envsoft.2017.09.020

[13] Shnaidman, A., Aleksandrowicz, O., Renn-poni, D., Hoze, M. & Weisthal, M. (2023). Geo data-based policymaking: National Tree Canopy Cover Example. *FIG Working Week 2023*.

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