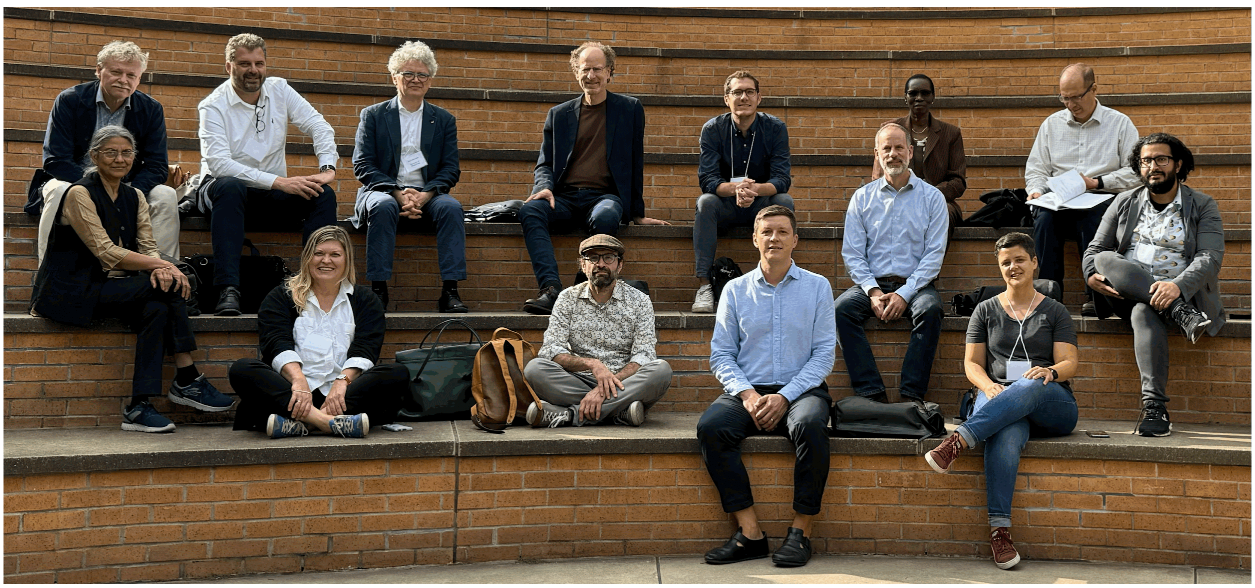
Summary report from the International Research Seminar on Modeling Urban Pedestrian Mobility at MIT.

Draft, January 15, 2024

Abdulaziz Alhassan, Andres Sevtsuk.
Massachusetts Institute of Technology



Contents

1. Introduction

This report summarizes the results of the International Research Seminar on Modeling Urban Pedestrian Mobility held at the Department of Urban Studies and Planning at the Massachusetts Institute of Technology (MIT) in October 2023. Organized by Andres Sevtsuk, Associate Professor of Urban Science and Planning at MIT and director of the MIT City Form Lab, with financial support from the Volvo Research and Educational Foundations (VREF), the seminar convened a group of international mobility experts working on modeling pedestrians or using pedestrian modeling applications in planning and policy work. The aim of the workshop was to chart the present state and future frontiers of pedestrian modeling, and to identify common challenges and priorities for upcoming research initiatives that can inform urban design, planning, and policy around pedestrian mobility in cities globally.

Motivation and Background

A growing body of research at the nexus of transportation and urban planning indicates that a shift to sustainable modes of urban travel (i.e. walking, biking, and public transit) is necessary to reduce urban carbon emissions, address public health crises, and to make cities more livable places for all. Although still in the minority, some municipal and state agencies have started addressing non-motorized travel more rigorously, such as requiring pedestrian mobility to be included in travel-demand models and development impact reviews. However, mainstream transportation modeling approaches have historically focused on capturing the dynamics of vehicles and public transport, and many still do not know that pedestrian mobility can even be modeled with scientific rigor. While most travel-demand models tend to ignore pedestrian trips, the few that do consider pedestrians as a mode of transport tend to focus on aggregate pedestrian trip volumes, not their geographic distribution along city streets. Yet, pedestrian flows are not evenly spread throughout neighborhoods. Understanding their geographic distribution along city streets and developing models to explain how the built environment shapes foot-traffic in cities is key to designing policies and plans that can increase the mode-share of non-automobile travel options. A renewed policy emphasis on better pedestrian environment has thus triggered a need to better understand how pedestrian flows are shaped by the built environment in general, and how building and infrastructure developments might affect foot-traffic on surrounding streets in particular. This is critical for prioritizing investment in pedestrian infrastructure as well as understanding how zoning and urban design can be leveraged to increase foot-traffic and improve pedestrian experiences.

Developing models of pedestrian mobility as part of land use-transportation interactions has gained traction with several research groups across the world over the last couple of decades. Three modeling approaches can be broadly distinguished as follows:

- First, "sketch planning", "factoring methods", and "direct demand models" approximate pedestrian demand based on comparative analysis of locations and their pedestrian activity levels [1]. This typically involves regressing observed pedestrian counts against land use mix, density, demographic, street-type or other built environment variables and applying regression coefficients to predict pedestrian activity in a comparable area [2-4]
- Second, pedestrian movement has been spatially distributed in agent-based simulations that generate movements of individual people (agents) based on origin–destination pairs and a set of behavioral assumptions [5,6]. Such simulations can offer high-resolution results where each individual trip is spatially visualized. However, a high degree of specificity and extensive setup requirements have also limited the applicability of agent-based pedestrian models to fairly small sites, such as airports, transit stations, or a few downtown blocks [7]. MatSim, an agent based framework discussed below, and MoPed, a pedestrian-specific travel demand model that works in conjunction with MatSim, constitute exceptions and have been applied at the urban scale.
- And third, large-scale pedestrian flow prediction has emerged in network-based models, such as PedContext, Urban Network Analysis, sDNA, Depthmap, Urbano, and Multiple Centrality Analysis (MCA), which also estimate trip-level pedestrian trajectories but do so mathematically, without visualizing individual agents' journeys [8-18]. Instead, the number of trips traversing each network link is estimated using graph theory methods, computing results faster and for significantly larger study areas than agent-based approaches. This makes network analysis an attractive option for planners and urban transportation consultants, who tend to work at the neighborhood-scale with a significant amount of complexity [12;19-21].

Though different approaches have moved the field forward and helped shed light on the need to explore pedestrian mobility with models, their methodological heterogeneity has also hindered the comparison of results and made it difficult to examine built environment and walking interactions in a consistent manner.

In order to promote knowledge sharing, accelerate capacity building, and chart the current and future frontiers of pedestrian modeling, the seminar organizers invited a group of international pedestrian modeling experts to participate in a joint presentation and discussion event at MIT. Invited participants were asked to present their current methodological approaches for modeling urban pedestrian mobility and demonstrate the relevance of these approaches for applied policy and planning.

2. Seminar Outline and Structure

A two-day seminar, held on 5-6 October 2023, Researchers and policy-engaged academics and practitioners with interest in pedestrian mobility, behavior and modeling were invited to present and participate in discussions centered around state-of-the-art pedestrian modeling and simulation. The first seminar day was dedicated to presentation panels, and the second was designed as a discussion workshop to identify strengths and weaknesses of existing pedestrian modeling frameworks. Each framework was critiqued and evaluated with respect to elements of the four-step transportation model. Appendix A provides an overview of the workshop schedule and presentations. Takeaways from the two days are summarized in Sections 3 and 4. Section 3 summarizes each of the pedestrian modeling frameworks that were presented at the workshop, and section 4 provides a summary of discussion around a wide array of topics concerning future directions for pedestrian modeling and policy-relevant application work.

A detailed program of the event and biographies of participants are available in the [program page: cityform.mit.edu/projects/modeling-pedestrian-mobility-seminar-2023](https://cityform.mit.edu/projects/modeling-pedestrian-mobility-seminar-2023)

3. Description of Existing Models

Urban Network Analysis (UNA)

Urban Network Analysis is a network-based modeling framework for estimating pedestrian or bicycle mobility. Edges represent route connections and nodes represent either origin or destination points. UNA handles all steps of the four-step model, with a simplified mode choice approach that is addressed in the model calibration phase..

Trip Generation

Trips generated from origin points (often address level), weighted by an attribute of that point, which informs its trip generation rate. Trip generation levels are elastic to destination accessibility–in areas with better destination availability within walking range, more pedestrian trips per capita are generated to such destinations. Data needed for trip generation include assumptions about trip trip types that are expected to occur during different time periods, and data about trip generation locations and their relative magnitudes: census blocks, jobs, establishments, parks, schools, transit stations, institutions, other POI (e.g. tourist sites). Person characteristics haven't yet been factored into trip distribution, but if trip generation heterogeneity between different demographic groups is known, it can also be incorporated into trip generation.

Trip Distribution

The UNA framework uses the Huff destination choice model for trip distribution. Destination probabilities depend on destination accessibilities, which in turn depend on destination weights and travel costs. Each destination within a given radius is given a unique probability, while the probabilities sum to one. UNA is a trip-based model that does not incorporate an activity schedule. Pedestrian tours are therefore not estimated (e.g. walk from home to metro, then metro to work, work to metro and back from metro to home). Instead, home to metro trips are modeled separately from metro to work trips etc. It is a sequential model where non-home based trips do not guarantee that people are returned home at the end of the simulation. Person characteristics don't factor into trip distribution, but could be added in the future.

Mode Choice

UNA models pedestrian or cycling trips, and does not explicitly include a mode-choice model. Since model results are calibrated to match observed pedestrian counts in a defined time interval, mode choices are derived in model calibration phase, based on observed pedestrian counts.

Route Choice

The UNA model is unique in routing trips to multiple destinations at the same time according to the Huff destination probability model, and finding all 'plausible' routes between each origin-destination pair: routes that are up to a given percent costlier than the lowest cost route. Additionally, the UNA framework operates with either geometric route lengths, which require no route attribute data from users, or 'perceived' route lengths, which are interpreted as distance-equivalent costs, given by the user, for network segments. The 'perceived' edge costs can account for a wide variety of route segment characteristics (e.g. sidewalk widths, amenities, greenery, shade, traffic volumes, etc.), all of which are translated into a single 'perceived cost' value using a linear equation and coefficient estimates from pedestrian route choice studies.

Challenges

The model does not generate non-trip activities, such as recreational walking or movements in public spaces. UNA lacks a proper mode choice model—mode choices, and corresponding pedestrian trip generation levels are instead computed at the model calibration phases, based on observed pedestrian counts. Due to its high spatial resolution (address level origins and destinations, accounting for street characteristics in route choice), it can be challenging to obtain data for the model.

Using the Model

UNA is available for free as a plug-in for Rhino (Project Page: cityform.mit.edu/projects/una-rhino-toolbox - User Manual: unatoolbox.notion.site/) UNA also provides a python version as part of the Madina Package (Github: github.com/City-Form-Lab/madina - Documentation: madinadocs.readthedocs.io/)
The Rhino version provides a more interactive experience with a strong visual interface that is suited for smaller analysis projects and more friendly in a learning environment. The Python version is more suited for producing reusable scripts and running large-scale analyses.

Selected Case Studies:

- Sevtsuk, A., Kollar, J., Pratama, D., Haddad, J., Basu, R., Alhassan, A., Chancey, B., Makhlouf, R., Halabi, J., & Abou-Zeid, M. (2023). Pedestrian-Oriented Development in Beirut: A Framework for Estimating Urban Design Impacts on Pedestrian Flows through Modeling, Participatory Design, and Scenario Analysis. *Cities*, *(in review)*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4618238
- Sevtsuk, A., Basu, R., & Chancey, B. (2021). We shape our buildings, but do they then shape us? A longitudinal analysis of pedestrian flows and development activity in Melbourne. *PLOS ONE*. https://doi.org/10.1371/journal.pone.0257534

- Sevtsuk, A. (2021). Estimating pedestrian flows on street networks: revisiting the betweenness index. *Journal of the American Planning Association*, *87*(4), 512–526. https://doi.org/10.1080/01944363.2020.1864758

Multi-Agent Transport Simulation (MATSim)

MATSim is an agent-based transportation model that utilizes travel and time use diary data to produce populations of synthetic agents. This model is capable of simulating vehicular traffic, bikes, pedestrians and public transportation.

Trip Generation

Agents in MATSim generate trips using an activity chain derived from time-use and travel diaries that are extrapolated to a synthetic population of agents. Based on the activity chain, agents are assigned a sequence of time-based trips from one point to the next. These points could be at a fine geographical resolution when high granularity data is available. Origins are not assigned weights explicitly, but multiple agents could originate from the same point which could be interpreted as a point's trip intensity. Total trip generation levels are not elastic to destination accessibility and like other models, MATSim lacks the ability to generate recreational trips, unless explicitly provided in travel diaries. Setting public spaces as destination points enables MATSim to model trips to/from these public spaces, but movement within these spaces is not captured.

Trip Distribution

MatSim offers two options for trip distribution: a) classical, through geospatial fitting and b) advanced, through a discrete destination choice model. However, only unimodal trips are considered explicitly, dependent on (granularity of) activity chains. Trips are explicitly assigned a specified destination, determined through a multinomial logistic choice model, destinations are not assigned partial trips.

Mode Choice

MATSim is multimodal, and uses a discrete choice model for mode choice, with some restrictions. Pedestrians and cyclists are modeled separately from vehicular traffic.

Route Choice

MatSim currently uses least-cost path routing where the modeler is able to define a cost function depending on available data. A discrete route choice model integration is currently being developed. Cost could be an attribute of the path/network like distance, slope, surface type, steps, land-use, turns, amenities, urban greenery, safety/lighting, car traffic. Cost could also factor in agent attributes such as Age, use of strollers, accompanying pets or other agent characteristics. One single lowest-cost route is identified for each trip and mode.

Challenges

A major limitation to using MATSim is its large data requirements where the quantity, quality, and spatio-temporal granularity of the data can influence the model. Travel diaries can be formatted differently across different regions, which poses a challenge on how to properly format them as inputs to the model. Travel diaries are also hard to come by and not readily available for most locations. Pedestrian journeys are handled in a simplified manner in MatSim, where destination choice and route choice are not explicitly modeled.

Using the Model

Documentation, resources and instructions on how to obtain and use MATSim are available in the project's website https://www.matsim.org/ The website also shows a list of case studies across multiple modes and geographic locations.

Selected Case Studies:

- Multiple cities internationally (Axhausen et al 2010; 2016)
- *W Axhausen, K., Horni, A., & Nagel, K. (2016). Chapter 21. The multi-agent transport simulation MATSim. Ubiquity Press.*
- *A first implementation of a pedestrian simulation module for MATSim, which also supports agent-agent interactions, was presented by Lammel and Plaue (2014) introducing a force-base model. Dobler and Lammel (2012) combined the force-based pedestrian simulation module with the multimodal link contribution, creating the opportunity to simulate large-scale scenarios.*
- *Automobile model: Axhausen, K. W., Meister, K., Balmer, M., Ciari, F., Horni, A., Rieser, M., & Waraich, R. A. (2010). Large-scale agent-based travel demand optimization applied to Switzerland, including mode choice. Working paper/Institute for Transport Planning and Systems, 625. https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/152027/eth-1445-01.pdf*

Model of Pedestrian Demand (MoPeD)

A Four step model that is designed to predict daily pedestrian trips and the selection of travel mode within designated "Pedestrian Analysis Zones" consisting of 80 meter by 80 meter grid cells. Core components of MoPed include pedestrian trip generation, distribution and mode choice. Route assignment is not handled within MoPed and can instead be added with other platforms, such as MatSim, UNA etc.

Trip Generation

Trip generation is handled in line with traditional demand models, where a linear regression model is used to determine the number of trips per zone from travel survey data. MoPed requires a finer resolution than traditional traffic analysis zones and depends on household survey data to create a synthetic population of agents. Travel survey data is needed to calibrate trip generation. Pedestrian mode share depends on destination accessibility on foot, but total trip generation levels are not elastic to destination accessibility.

Trip Distribution

MoPeD incorporates a Logit-based destination choice model. With a focus on walking trips with a walking range of 1.5km. Individual pedestrian analysis zones (PAZ) are grouped into Super PAZ where a hierarchical representation happens: trip goes from an origin PAZ which is assigned a super PAZ. Trips are distributed from an origin super PAZ to a destination super PAZ, trips are then split between individual PAZ within the destination super PAZ. Each PAZ is a summary aggregation of destinations within. e.g. : total park space, employment, and other available parameters. Accessibility is handled using a pedestrian index of the environment. This index is a function of employment and households within a network distance from households. MoPed handles trips independently and does not chain trips into a schedule, which does not guarantee that trips return home at the end of the simulation. For trip generation and trip distribution in MoPeD, data on household surveys, pedestrian network, employment and land use, slope (topography) are needed.

Mode Choice

As MoPeD focuses on pedestrian activity. Binary mode choice between pedestrian and non-pedestrian modes is defined as a function of pedestrian access within a distance threshold accounting for individual and household characteristics. Mode choice is determined according to a binomial choice model (Walk vs. vehicle trip) with trip distance and area-specific independent variables. MoPeD does not consider or fully represent factors of behavior besides distance.

Route Choice

MoPed handles trip generation and distribution internally, but delegates route assignment to MATsim or other external route choice estimators.

Challenges

The framework is dependent on large volumes of data, specifically a household survey. The model does not account for trips where walking is a purpose such as recreational walking, or movement in a public space. Egress/access trips from other modes are not represented. When forecasting, there is a challenge with aligning base year with input data. In this formulation, it is hard to answer the question: Should destination choice happen before mode choice, or the other way around? The model faces challenges with non-home based trips as closing the tour back to home is not a guarantee.

Selected Case Studies:

- Portland, OR, USA (Clifton et al. 2016; Zhang et al. 2022); Munich, Germany (Zhang et al. 2023)
- Zhang, Q., Moeckel, R., & Clifton, K. (2022). Assessing pedestrian impacts of future land use and transportation scenarios. Journal of Transport and Land Use, 15(1), 547–566. https://doi.org/10.5198/jtlu.2022.2117
- Clifton, K. J., Singleton, P. A., Muhs, C. D., & Schneider, R. J. (2016). Representing pedestrian activity in travel demand models: Framework and application. Journal of Transport Geography, 52, 111–122.
- Zhang, Q., Moeckel, R., & Clifton, K. J. (2023). MoPeD meets MITO: a hybrid modeling framework for pedestrian travel demand. Transportation. https://doi.org/10.1007/s11116-022-10365-x

Spatial Design Network Analysis (sDNA)

sDNA is a graph theory based betweenness index with elements of a four-step model.

Trip Generation

Trip generation in sDNA is link-based, sub-link based, POI based, or Land-use based. Origins could be based on address level points, and weighted by any origin attribute. Like most models, sDNA lacks the ability to generate recreational trips and total trip generation levels are not elastic to destination accessibility. Setting public spaces as destination points simulates trips to these public spaces but movement within them is not captured. Lacks the ability to capture latent trips. Demographic characteristics do not factor into trip generation.

Trip Distribution

Destinations can be represented at the addresses or building level of granularity. All destinations of a given type, available within a given access radius, are considered as equal destinations with no probability assignment. sDNA is unable to model pedestrian tours. It is a sequential model where non-home based trips do not guarantee that people are returned home at the end of the simulation.

Mode Choice

sDNA only models pedestrian trips without explicit mode choice model, though pedestrian-specific trip generation levels can be derived in model calibration phase, based on observed pedestrian counts.

Route Choice

sDNA can find the shortest, most direct, or a hybrid (shortest and most direct) route in 2D and 3D networks where it could factor distance, angularity and/or slope but not any other route characteristics. Each trip between an origin-destination pair is assigned one route.

Challenges

Model does not generate non-OD trips, like recreational walking or movements in public spaces nor represent movement in public spaces. There is no destination choice model to differentiate probabilities of trips to different destinations, instead all destinations within a given walkshed distance are treated as equal destinations. Though the route choice model can account for turns, distance and slope, it does not account for street characteristics, such as sidewalk dimensions, the presence of amenities etc.

Using the Model

Documentation and instructions on how to use the framework is available in the project's website: https://sdna.cardiff.ac.uk/sdna/

Selected Case Studies:

- Cardiff, Wales, UK (Cooper et al. 2019; Cooper & Chiaradia 2020)
- Cooper, C. H. v, & Chiaradia, A. J. F. (2020). sDNA: 3-d spatial network analysis for GIS, CAD, Command Line & Python. SoftwareX, 12, 100525. https://doi.org/https://doi.org/10.1016/j.softx.2020.100525
- Cooper, C. H. v, Harvey, I., Orford, S., & Chiaradia, A. J. F. (2019). Using multiple hybrid spatial design network analysis to predict longitudinal effect of a major city centre redevelopment on pedestrian flows. Transportation. https://doi.org/10.1007/s11116-019-10072-0

Place Syntax

Place Syntax is a graph theory based model that measures the relative centrality of network segments, which has been shown to correlate with pedestrian and vehicular traffic volumes, particularly in dense and mixed use urban areas. Place Syntax is thus not a travel demand model and doesn't model trips per se. It is rather a spatial centrality or spatial accessibility model that illustrates how central each street segment is with respect to the rest of the street network in a city or study area, optionally weighted by the land use properties of destination streets. We acknowledge that applying the four-step framework questions to the Place Syntax methodology below is thus conceptually somewhat ill-fitting.

Trip Generation

Origins are all street segments in a study area. Conceptually, Place Syntax does not generate or compute trips. Instead, the Place Syntax, similar to the Space Syntax methodology, computes the centrality of each network segment vis a vis all other network segments around it, weighted by land use volumes on each segment. From each segment, one shortest-distance path or lowest angular-deviation path is extended to each other destination segment. The number of connections extended from each segment thus equals n-1, where n is the total number of segments in the network. The segments are typically not network segments, but "axial lines"--defined as longest lines of sight between buildings on each street. An axial line is not broken up at intersections with other streets into segments, but rather maintained as a single continuos unit of analysis throughout its length. The final centrality measure illustrates the mean centrality of each axial lines to all other axial lines in the system.

Trip Distribution

All axial lines within a given radius are destinations, optionally weighted by land use characteristics on destination streets characteristics.Since the Place Syntax utilizes a centrality measure not based on trips, it is unable to represent an activity schedule.

Mode Choice

Place Syntax does not model trips and does not model mode choice.

Route Choice

As part of the centrality index, only the shortest lowest cost route is considered to each destination based on topological, geometric or angular distance between segments. This lowest cost route can thus be the shortest route in terms of distance, the most straight route in terms of angular deviations, or the topologically most direct route involving least intermediary axial line crossings.

Challenges

Place Syntax is a spatial centrality model where trips are not modeled. This makes the index relatively easy to compute, requiring substantially less data than the pedestrian travel demand models described in this report. A Place Syntax index can be readily computed numeros city environments to obtain a quick and high-level overview of which streets are most central, and might therefore have relatively more or less pedestrians.

However, a number of challenges and limitations should be kept in mind. First, the resulting index does not estimate the number of pedestrians per segment–it instead returns a centrality index for each segment, which may correlate with pedestrian volumes. While in existing urban areas, it is possible to use a correlation coefficient to re-scale the index to estimate actual pedestrian counts, this may not be readily done in newly planned areas, where observed counts are not available.

Though correlations between spatial centrality and pedestrian volumes have been demonstrated in dense, mixed use, such correlations tend to be smaller in low density suburban or ex-urban areas, where built densities and street hierarchies are less pronounced. Conceptually, axial lines are also ill-defined in low density built up areas, where street edges in the form of building walls are ill-defined.

Due to its reliance on axial lines, which are the longest visible straight lines between building walls on any street, the index favors higher centrality results on long and straight streets. Such long streets do not necessarily have consistently higher pedestrian volumes than shorter axial lines around them.

Using the Model

The Place Syntax tool is provided as a QGIS plugin. Download, documentation and sample data is available on the project's website: https://www.smog.chalmers.se/pst

Selected Case Studies:

- Stockholm, Amsterdam and London (Stahle et al. 2007; Berghauser Pont et al. 2019)
- Berghauser Pont, M., Stavroulaki, G., & Marcus, L. (2019). Development of urban types based on network centrality, built density and their impact on pedestrian movement. Environment and Planning B: Urban Analytics and City Science, 46(8), 1549–1564.
- Stahle, A., Marcus, L., & Karlstrom, A. (2007). Place Syntax- Geographical Accessibility with Axial Lines in GIS. KTH School of Architecture.

4. Workshop Summary and Future Directions

Below is a summary of comments shared during the conclusion of the first day of the seminar. Participants discussed a wide array of topics concerning future directions for pedestrian modeling and policy-relevant application work. These conversations and discussions fit into the following themes:

- The purposes of pedestrian modeling
- Engagement with public agencies
- Policy relevance
- Utilitarian Walking VS Recreational Walking
- Demographic Heterogeneity and Representation of Informal Environments
- Need for more validation data and critical community engagement
- Walkability evaluation metrics
- Modeling complexity and bias

The Purpose of Pedestrian Modeling

What is the purpose of pedestrian models? The answers to this question at the workshop showed that pedestrian modeling has made a great deal of progress as we have more diverse objectives than just traditional demand modeling and forecasting. We still have more work to do around the representation of people and representation of the environments to acknowledge the heterogeneity of populations if we want to capture latent trips and trips in diverse neighborhoods accurately.

When modeling is used in a planning or design context, how do the plans factor into the models? Are planners or designers able to manipulate their intervention proposals in a way that enables representation in a model or iterative testing of outcomes in the model? How could that be achieved in different phases of plans, ranging from early stage concept plans to fully developed detailed plans?

Herein lies an important challenge for pedestrian modeling. Pedestrian models require large amounts of detailed environmental data due to their fine spatial resolution (considerably more detailed than aggregate traffic analysis zones), potentially at an address level of granularity. This poses a challenge when evaluating early-stage design and development proposals. Although models can inform decision-makers most in the early stages of a plan, plans tend to be less specific and lack detailed documentation at such early stages to be used for modeling. When plans are further developed, with considerable monetary and human labor costs, they may produce the required spatial granularity of data needed to specify a pedestrian model, but at that stage, modeling may no longer be able to change anyone's mind about alternative development options–it is simply too late. It thus critical that pedestrian models adopt ways of representing built environments with approximately, fuzzy and high-level information even when detailed information from development proposals is not yet available, since it is the very early stage of development when models can have the biggest impact on decision making.

Models are not and end themselves. Models are a way of understanding how activities taken by planners and people who intervene in the built environment interact with one another. In urban design, it is common to see teams of urban designers pitching projects to cities and claiming that if their designs were built, cities would see an outcome similar to what the renderings show: e.g. a lot of happy people are walking on busy streets. An informed spatial analysis of such designs could illuminate whether such outcomes are likely. Pedestrian models can capture and describe interactions between land use decisions, infrastructure decisions and urban design decisions at a high spatial resolution. Modelers need to look for ways to engage in capturing such interactions at an early stage of development, where they can best explain how design, planning and land-use interact with one another so we could move towards a city that produces more human interactions, that is healthier, less carbon intensive and more equitable.

There is a potentially powerful use case for reverse-engineered pedestrian models too: working backwards from adopted strategies and targets, to investigate how the built environment needs to be designed/developed to arrive at the goals. What should the built environment of an urban district look like (e.g. land use pattern, density, quality of streets) for the said district to achieve a desired level of pedestrian mode share? Many cities have declared such city-wide mode shift targets. Boston's 2030 sustainable mobility strategy envisions cutting personal driving by 50% [[1]], NYC's by 20% [[2]], and Los Angeles wants 50% of all trips to take place on foot, by bike or by public transit by 2035 [[3]], without clear urban planning and design pathways to get there. Modelers could use such targets as a starting point to identify lan use planning, density, and street configuration scenarios that could potentially lead cities to the stated mode-shift targets, and attempt to articulate the costs and benefits of alternative pathways to reach them. There are potentially infinite pathways to the same goals, and modeling could play a key role in articulating the complexities and costs of different approaches.

[1] https://www.boston.gov/sites/default/files/file/document_files/2019/08/reducing_commuters_driving_alone_to_work_1.pdf

[2] https://www.nyc.gov/assets/sustainability/downloads/pdf/publications/New%20York%20City's%20Roadmap%20to%2080%20x%2050_Final.pdf

[3] https://www.dropbox.com/s/e768n31r3k379w7/the-plan.pdf?dl=0

Engagement with Public Agencies

Modelers tend to get stuck in their own ways of thinking. How can we ensure that what we measure is not only relevant for traffic efficiency, but also fits a larger context of transportation that is an essential part of building a society. Collaboration between modeling efforts and municipal policy-makers should ideally guide progress in modeling, yet an observable gap exists. A substantial portion of current modeling endeavors are driven primarily by modelers and researchers. Recognizing this gap is crucial, as it prompts a reevaluation of the dynamics between modelers and public entities, challenging the status quo of independent research-driven modeling efforts.

To facilitate a more engaging relationship with government agencies, modelers need to pay more attention to the interface between modeling software and practitioners' needs in planning practice. This interface becomes more important as we acknowledge data disparity between data-rich and data sparse communities. Modelers should put more emphasis on creating models that accommodate a wide range of data availability, leveraging both commercially and publicly available data to ensure the inclusivity of diverse urban contexts.

Examining the evolution of the World Bank's project portfolio over the past three decades reveals a noteworthy shift in focus from minimal attention to pedestrian activity to a gradual increase in funding for pedestrian-oriented projects. This shift encompasses initiatives ranging from connectivity-centric endeavors, facilitating movement from point A to point B, to comprehensive projects addressing the concept of complete streets.

Policy Relevance of Models

There seems to be a disconnect between what researchers are trying to achieve through pedestrian modeling, and what is being implemented in the policy realm. When modelers talk about the value of walkability, do they really need to get sophisticated with modeling, when in practice, results could be misused or misinterpreted? This prompts a critical examination of the trajectory in which modeling is heading. There is a growing risk of becoming overly data-driven without ensuring a meaningful translation of sophisticated models into tangible policy and implementation outcomes.

There is an ironic trend, whereby developing cities often start with a high level of pedestrian mobility. As cities then "develop" into more car-centric and car-dependent environments, they loos their pedestrian mode share. At a later stage of development, they recognize this as a loss, and end up trying to regain and repair their level of pedestrian activity. Planning theory must figure out a growth model that is capable of a more intelligent transition, which does not ignore and sacrifice the high level of pedestrian activity in rapidly developing cities under the questionable pretext of consumption- and accumulation-oriented car-centric development.

Utilitarian walking VS Recreational Walking

Despite the multifaceted nature of walking, traditional travel demand models only capture movement between utilitarian origins and destination, neglecting walking as an end itself for health and recreational purposes and pedestrian experiences occurring in civic spaces, squares, plazas and parks. Yet, walking embodies a fundamental, innate need. People's bodies have evolved to engage in a certain amount of exercise on a daily basis, most often in the form of walking. Walking and staying in public space can thus be seen as a social good that supports urban sustainability, physical and mental health, social interactions and local economic development. Spending time in public space, people watching, socializing or simply spending time in a public space constitute pedestrian activities that are often underrepresented, if not completely absent from pedestrian travel models. Yet, such activities can constitute a significant share of all pedestrian activity on main streets, squares and parks, especially during non-work hours and weekends. Incorporating such activities into pedestrian models is not an impossible task—creative approaches can be explored to integrate non-trip pedestrian activities into existing models. While quantification is growingly essential for policy arguments, it is equally vital not to neglect the aesthetic and humanistic appeal inherent in walking, reflecting a more comprehensive understanding of the walking experience in urban contexts.

One participant suggested that "Realizing that walking encapsulates a broader spectrum of human experience, a more fitting name (for VREF's Walking as Mode of Transport) could be "walking as an experience". Walking is not just important as a mode of transport, but also as a way of bringing people together, face to face, in shared urban spaces.

Demographic Heterogeneity and Representation of Informal Environments.

Understanding pedestrian behavior remains a complex challenge, marked by heterogeneity that surpasses vehicular traffic. Current models, while heading in the right direction, fall short in fully encapsulating the diverse decision-making processes and variables inherent in pedestrian movement. The conventional four-step model, designed around car mobility, may not be the most suitable framework for comprehending the intricacies of walking behavior. There is an ongoing need to delve deeper into the nuances of pedestrian behavior and leverage more nuanced insights to refine existing models.

The question on heterogeneity broadens as we attempt to include diverse demographic segments, bringing attention to the increasingly important issue of aging, particularly noticeable in certain Asian communities. As the demographic landscape evolves, understanding how age influences pedestrian behavior becomes a critical aspect in shaping urban planning strategies.

Understanding the heterogeneous nature of walking, where it is both a luxury for some and a necessity for others, underscores the need for more nuanced models. Distinguishing between those who walk rapidly out of situational necessity, and those who walk recreationally due to the luxury of choice, is essential for creating models that accurately reflect the diverse pedestrian needs within urban landscapes. More empirical research of actual walking behavior and habits is needed to clarify how environmental quality around one's place of residence, work or school interacts with diverse demographic walking behaviors.

None of the pedestrian models to date account for demographic particularities of walkers in the trip generation phase. Instead, models assume "typical" pedestrians throughout, all of whom are assumed to behave alike. Future work should incorporate demographic heterogeneity into models to achieve more accurate and truthful representation of walking activity in different urban neighborhoods.

Informality, more pronounced in the global south, remains an under-researched aspect of mobility. Current models inadequately address the informal aspects of urban life, including informal housing, roads, street vending, and transit systems. Incorporating these informal components into models poses challenges for data: how can origins, destinations, paths and trips be accurately represented in such contexts? Shifting perspectives on informality are also notable, challenging traditional approaches that have viewed informality as a "backwards stage." Contemporary thinking recognizes informality as an equal "mode of being," acknowledging its active role in shaping urban dynamics.

Need for more validation data and critical community engagement

Pedestrian models need validation data in the form of empirical pedestrian counts to ensure that they accurately reflect real pedestrian volumes on city streets. Such count data is presently sparse and rarely collected by city governments. Validation data from select pedestrian counting locations helps models explain pedestrian activity on a much broader range of city streets, well beyond the actually counted streets. While most industrialized cities have developed sophisticated infrastructure for vehicle counting on streets and intersections city-wide (in the form of loop-detectors, cameras, and road tubes), equivalent data collection for pedestrians is almost unheard of. One notable exemption comes from Melbourne , Australia, where Victoria government manages and publicly shares hourly data from an automated pedestrian counting system over a website: https://www.pedestrian.melbourne.vic.gov.au/

It is generally rare that we get to see maps of estimated pedestrian flows for city streets. Once we start getting more of these, we need to seek community input to validate their accuracy. Engaging the community in assessing these maps in comparison to their perceptions can offer valuable insights. We could use this knowledge to determine where to install pedestrian counters that help calibrate and refine model outcomes. The current shortage of such counters highlights a critical need for their widespread implementation to enhance the accuracy and reliability of pedestrian modeling.

It is important to engage with the community in a way that allows modelers to identify specific nuances that matter in each context. People might prefer to spend extra time in a plaza along the way during a trip to "collect themselves". From a utilitarian model perspective, this is extra time that is "wasted". There is value to be captured by paying attention to other aspects of walking that are not just functional transportation.

Walkability Evaluation Metrics

A recurring theme from the workshop is that better metrics are needed to represent pedestrian experiences. The walking experience is rich and goes beyond travel time, distance minimization, or monetary value of time. To capture the value of walking in cities, we need easy but powerful metrics for not only walking benefits to communicate, but also to describe the suitability of city streets and infrastructure for walking-related activities.

During the rapid implementation of 'open-street initiatives' that resulted from the COVID-19 pandemic, attempts were made to broaden the focus of analysis to metrics that go beyond the "shortest" and the "quickest" benefits of walking. For instance, one could look at the impact of a street-based intervention on sales tax or consumer spending. This proved to be challenging to do in many places due to both data availability and due to the complex nature of controlled modeling to tease out such effects rigorously. Attempting to account for qualitative measures is likely to prove even more challenging.

When doing cost-benefit analysis, it is important to use the value of social and environmental benefits to justify decisions. It is also important for public opinion that these values are clearly communicated.

Borrowing an analogy from vehicular traffic planning, the value of travel time (VOT) is often used as a justification for infrastructure projects. If a newly planned highway cuts travel times for existing vehicular trips (albeit only temporarily due to the induced demand that vehicle infrastructure is known to produce), collective savings in travel time are often used to justify public funding for such projects. This presents a simple and powerful example of a metric that has guided vehicular infrastructure investments for decades now. We need analogous, yet specific metrics to capture benefits of walking infrastructure investments that are as easy to communicate.

Another popular metric from vehicular traffic planning is Level of Service (LOS) that captures the interplay between roadway capacity, use level and driving comfort. Ironically, roads with the highest LOS a are fast and empty roads, with no traffic, since they allow a driver to pass by rapidly with no congestion. Obviously LOS, as conceived for traffic, is ill-suited for the pedestrian realm. Analogous, but better metrics for Pedestrian Level of Service are needed to not only capture the ease of pedestrian movement on city streets, sidewalks, crossings and footpaths, but also the experiential benefits that such infrastructure offers to pedestrians–opportunities to see and engage with other people, opportunities to visit amenities, stores or institutions along the way, opportunities to sit or lie on grass, environmental comfort of these spaces (as perhaps captured by the Universal Thermal Climate Index or UTCI). Such pedestrian benefits have been rigorously described by pedestrian route choice studies, which quantify how specific environmental characteristics of streets affect pedestrian route choices and thereby illustrate which properties of spaces pedestrians are most attracted to, or repelled from.

Metrics are also needed to illustrate how urban environments suppress latent or unrealized walking trips from occurring. Such suppression can primarily result from two environmental deficiencies: lack of destinations within reasonable walking range, and poor pedestrian quality of routes leading to existing destinations. The provision of destinations is challenging to address directly through planning and design efforts–urban land uses and destinations follow an economic logic, whereby inequalities between neighborhoods are inherent (a key reason why the popular 15-minute city concept has been criticized). However, the poor pedestrian quality of routes leading to existing destinations is more readily addressable with planning, policy and design interventions.

The idea of latent demand for walking also suggests conceptual improvements for model architecture: the idea of trip generation, as popularized by Institute of Transportation Engineers (ITE) tables[4], is not necessarily equivalent to Travel Demand, which should be emphasized instead. Observed trip generation levels strongly depend on environmental characteristics of areas they were measured in–destination availability, street quality, demographic characteristics, climate, weather etc. Observed trip generation levels from one location may therefore not be appropriate as inputs at a different location. Even if both locations have similar densities and land use patterns, pedestrian trip generation depends not only on land use patterns, but also demographic, climatic and cultural factors.

Modeling Complexity and Bias

Modeling walkability opens up the complexities of daily life, activities and travel in a way we haven't seen in motorized transportation models. This could be seen as a threat as models

[4] Institute of Transportation Engineers (ITE). (2016). *Trip Generation Handbook, 3rd Edition* (Third Edit). Institute of Transportation Engineers. https://ecommerce.ite.org/IMIS/ItemDetail?iProductCode=RP-028D-E

become more complicated and unable to match the complexities of the real world. It could also be seen as an opportunity for transportation researchers to pose questions that were not seriously explored in the past.

When it comes to modeling, the diversity of options, opinions and approaches can work as a safety net when compared to working with a single widely adopted standard model. The vehicle miles traveled (VMT) oriented traffic models common in the sixties led to disappointing results today. The prevalence of multiple models with various viewpoints and thought processes is arguably better than relying on a single modeling view point, or no modeling at all.

As we become more explicit about recognizing and acknowledging biases as modelers, it is important to acknowledge that modelers tend to advocate their own viewpoints and perspectives which guide their modeling approaches. When interacting with models and their results, it is vital to think about what aspects a model could be hiding or omitting? What viewpoints is the model overly emphasizing? How could the model be improved?

Appendix A. Workshop Schedule and Participants

Day 1 - Presentation Panels

Panel 1 - Pedestrian models in urban planning and design

This panel was designed to provide an opportunity to researchers with interest in modeling and simulation to present the current state of modeling frameworks developed by various research groups and institutions around the world. This panel included 15-minute presentations followed by time for questions and answers, with these presentation titles:

- Kelly Clifton, University of British Columbia. The Evolution of the Model of Pedestrian Demand (MoPeD).
- Alain Chiaradia, University of Hong Kong. Accessibility and Journey Level of Service in Volumetric Transport Interchange Hubs. sDNA model.
- Adrian Meister, Swiss Federal Institute of Technology (ETH). Integration of active mobility into the agent-based simulation framework MATSim.
- Lars Marcus, Chalmers University of Technology. The Issue of Representation in Modeling Pedestrian Mobility.

- Abdulaziz Alhassan / Andres Sevtsuk. Massachusetts Institute of Technology. Pedestrian modeling with Urban Network Analysis and automation with a new Python Library Madina.
- Rounaq Basu / Andres Sevtsuk. Massachusetts Institute of Technology. Pedestrian flow model calibration, and pedestrian impact assessment.
- Louis Merlin, Florida Atlantic University. Reconciling various theoretical models of pedestrian travel behavior.

Panel 2 - Pedestrian models in urban transport and policy.

This Panel was intended to shed light on practical issues facing policy makers and municipal officials around pedestrian activity, highlighting qualitative and behavioral aspects related to pedestrian mobility. Discussions revolved around bridging the gap between modeling theory and practical considerations. Presentations in this panel presented on the following titles:

- Geetam Tiwari, IIT Delhi. Pedestrian risk perception and actual risk in city streets in Delhi, Indi.
- Mark Seaman, Senior Economist, Office of the Commissioner New York City Department of Transportation. Stated Preference Valuation of Livable Street Improvements.
- Filipe Moura, University of Lisbon. On the importance of measuring walkability and exposure to changes of the pedestrian environment
- Kevin Manaugh, McGill University. Visualizing Active Living Potential at various spatial scales
- Mark Zuidgeest, University of Cape Town. Modeling pedestrian crossing behavior on Cape Town's freeways: Caught between a rock and a hard place?
- Winnie V. Mitullah Institute for Development Studies and UNESCO. Planning and Governance of Walking in African Cities.
- Juan Antonio Carrasco, Universidad de Concepción. Understanding the experience of traveling and walking: A mixed method perspective.
- Rosa Félix, University of Lisbon. Jittering: A method for generation pedestrian an bicycle realistic route networks from Origin-Destination data

Summary Discussion

In conclusion of the first day, moderated discussion was held to focus on the following themes

- What are the most important types of application areas for pedestrian models and how do we build global awareness about them?
- What are policy challenges preventing the use of pedestrian modeling in policy support?
- How do we achieve more applications of modeling and simulation in the Global South? More research collaborations? What critical data are needed?

A synthesis of this discussion is provided in section Workshop Summary and Future Directions

Day 2 - Modeling Discussion Workshops

The second day was dedicated to a workshop designed to elicit feedback on the current pedestrian modeling frameworks. Participants included researchers interested in modeling, as well as researchers and practitioners interested in practical policy relevance. Participants were divided into four groups, each group was assigned a modeling framework to critique and present. Each group had one or more subject matter experts in the modeling framework assigned to the group. The Workshop included Four sessions of breakout group discussion followed by a communal across group summarizing discussion. Each session was centered around a single prompt given to all teams. The day concluded with an open discussion around challenges and opportunities for pedestrian modeling frameworks.

Breakout Session 1: Pedestrian Trip Generation.

Prompts: With respect to your assigned modeling framework, describe:

- How is trip generation handled in models?
- What data is needed to calibrate the models?
- Is accessibility conceptualized in models, and if so how?
- What are the shortcomings of how the generation of pedestrian trips is represented and how could they be improved?
- Is the conceptualization of trip generation useful for policy and planning, if so how?

Breakout Session 2: Pedestrian Trip Distribution.

Prompts: With respect to your assigned modeling framework, describe:

- How is trip distribution handled in models?
- How are pedestrian destinations represented, at what resolution?
- Are activity schedules handled in models, and if so how?
- What data is needed to calibrate the models?
- What are limitations of how the distribution of pedestrian trips is modeled? How could they be improved?
- Is the conceptualization of trip distribution useful for policy and planning, if so how?

Breakout Session 3: Pedestrian Mode Choice.

Prompts: With respect to your assigned modeling framework, describe:

- Is mode choice handled in the models? If so, how?
- If not, how could it be included?
- What data is needed to calibrate the models?
- What are limitations of handling pedestrian mode choice? How could they be improved?
- Is the conceptualization of mode choice useful for policy and planning, if so how?

Breakout Session 4: Pedestrian Route Assignment

Prompts: With respect to your assigned modeling framework, describe:

- How is pedestrian route assignment handled in models?
- What route characteristics can be accounted for as part of travel costs? What data is needed to calibrate the models?
- What are limitations of handling pedestrian route assignment? How could they be improved?
- Is the conceptualization of route assignment useful for policy and planning, if so how?

Open Discussion - Challenges and opportunities of pedestrian models

The discussion was focused around the following themes:

- How to account for socio-demographic differences in modeling walking trips?
- Is it important to use activity schedules in models? What are the tradeoffs?
- How to better integrate mode-choice into pedestrian models?
- Upcoming grant applications and potential for collaborative work.

References

1. US DOT Federal Highway Administration. (1999). Guidebook on Methods to Estimate Non-Motorized Travel: Overview of Methods. Retrieved from https://safety.fhwa.dot.gov/ped_bike/docs/guidebook1.pdf
2. Matlick, J. M. (1996). If We Build It, Will They Come? (Forecasting Ped Use and Flows) Forecasting the Future . Bicycle Federation of America / Pedestrian Federation of America.
3. Berghauser Pont, M., Stavroulaki, G., & Marcus, L. (2019). Development of urban types based on network centrality, built density and their impact on pedestrian movement. Environment and Planning B: Urban Analytics and City Science. 46(8), 1549–1564. https://doi.org/10.1177/2399808319852632
4. Bolin, D., Verendel, V., Berghauser Pont, M., Stavroulaki, I., Ivarsson, O., & Håkansson, E. (2021). Functional ANOVA modeling of pedestrian counts on streets in three uropean cities. Journal of the Royal Statistical Society: Series A (Statistics in Society), 184(4), 1176–1198. https://doi.org/10.1111/rssa.12646
5. Batty, M. (2003). Agent-based pedestrian modelling. In The CASA Book of GIS (p. pp 81-108). New York: ESRI.
6. PTV. (2008). Pedestrians' Big Debut in Traffic Simulation: from Bit Player to Main Character. PTV Compass, Vol 1, 4–8. Retrieved from https://www.yumpu.com/en/document/view/4277652/pedestrians-big-debut-in-traffic-simulation-ptv-america
7. Puusepp, R., Lõoke, T., Cerrone, D., & Männigo, K. (2017). Simulating Pedestrian Movement. In Humanizing Digital Reality (p. pp 547-557).
8. Zhang, Q., Moeckel, R., & Clifton, K. (2022). Assessing pedestrian impacts of future land use and transportation scenarios. Journal of Transport and Land Use, 15 (1), 547–566. https://doi.org/10.5198/jtlu.2022.2117
9. Allen, W. G., Clifton, K., Davies, G., & Radford, N. (2004). Pedestrian Flow Modeling for Prototypical Maryland Cities. https://drum.lib.umd.edu/handle/1903/21516
10. Clifton, K. J., Singleton, P. A., Muhs, C. D., & Schneider, R. J. (2016). Representing pedestrian activity in travel demand models: Framework and application. Journal of Transport Geography, 52, 11–122. https://doi.org/https://doi.org/10.1016/j.jtrangeo.2016.03.009
11. Cooper, C. H. V, & Chiaradia, A. J. F. (2020). sDNA: 3-d spatial network analysis for GIS, CAD, Command Line & Python. SoftwareX,12, 100525.
12. Crucitti, P., Latora, V., & Porta, S. (2006). Centrality in Networks of Urban Streets. Chaos,16(1).
13. Dogan,T., Samaranayake, S., & Saraf, N. (2018). Urbano-A New Tool to Promote Mobility-Aware Urban Design, Active Transportation Modeling and Access Analysis for Amenities and Public Transport. Proceedings of SimAUD 2018.0.

14. Porta, S., Crucitti, P., & Latora, V. (2005). The network analysis of urban streets: a primal approach. Environment and Planning B, 35(5), 705–725.
15. Sevtsuk, A. (2018). Urban Network Analysis. Tools for Modeling Pedestrian and Bicycle Trips in Cities. Harvard Graduate School of Design. http://cityform.mit.edu/projects/una-rhino-toolbox
16. Sevtsuk, A. (2021). Estimating pedestrian flows on street networks: revisiting the betweenness index. Journal of the American Planning Association,87(4), 512–526. https://doi.org/10.1080/01944363.2020.1864758
17. Sevtsuk, A., Basu, R., & Chancey, B. (2021). We shape our buildings, but do they then shapeus? A longitudinal analysis of pedestrian flows and development activity in Melbourne. PLOS ONE. https://doi.org/10.1371/journal.pone.0257534
18. Turner, A. (2001). Depthmap: A Program to Perform Visibility Graph Analysis. 3rd International Symposium on Space Syntax. Georgia Institute of Technology, 7-11 May 2001.
19. Kazerani, A., & Winter, S. (2009). Can Betweenness Centrality Explain Traffic Flow? 12th AGILE International Conference on Geographic Information Science, Leibniz Universität Hannover, Germany., 1–9
20. Sevtsuk, A., & Mekonnen, M. (2012). Urban Network Analysis Toolbox .International Journal of Geomatics and Spatial Analysis, 22(2), 287–305.
21. Ye, P., Wu, B., & Fan, W. (2016). Modified Betweenness-Based Measure for Prediction o fTraffic Flow on Urban Roads. Transportation Research Record, 2563(1), 144–150.