A historical collection of impedance functions for 1

MM

## Abstract

urban planning as cities strive to become more sustainable. Accessibility analysis employs different methods such as gravity-based models, potential models, etc. An important component of these methods is the impedance function used to represent the responses of travelers to the friction of distance separating origins and destinations. The objective of this study is to investigate active travel behavior in Canada using time use data. Empirical estimates of impedance functions are calibrated to assess the time-willingness to reach different destinations such as work, school, grocery stores, restaurants, and sports places by walking and cycling. This research makes use of Canada’s General Social Survey Cycles 2, 7, 12, 19, 24, 29 thus giving a historical perspective on active mobility over the past 35 years. The focus of these surveys is on time use and the datasets contain information on travel time by active modes (cycling and walking) as well as the type of activity at the end of the trip which allows us to classify trips by purpose. Our focus is on Canadian Census Metropolitan Areas (CMAs) and the results indicate that the most common destinations for walking trips after work or school are grocery stores, other stores or malls are the most destinations for walking travels respectively. For trips by bicycle the most common destination after traveling to work or school, is sports centers, field or arena. Strong distance-decay effects are evident from the results. The impedance functions, in addition to providing information about the behavior of active travelers in Canada for the period of time under study, are a valuable resource for implementing active accessibility analysis in Canadian applications.

Keywords: Impedance function, Accessibility, Active travel mode

## Introduction

Urban and transportation planning has shown a growing interest in the idea that cities have the potential to shape travel behavior through intentional modifications. This notion stems from the recognition that the design and layout of urban environments can significantly influence how people choose to travel within the city. By creating environments that prioritize accessibility and offer diverse transportation options, cities can encourage individuals to opt for sustainable modes of transportation, such as walking, cycling, and the use of public transit. Indeed accessibility plays a crucial role in shaping travel behavior. It refers to the ease with which individuals can access desired destinations, services, and amenities within their city. By improving accessibility, cities aim to make it more convenient and attractive for people to choose sustainable transportation options over private vehicles. Factors such as increased population density, a mix of activities (e.g., residential, commercial, recreational), well-connected transportation infrastructure, and proximity to key destinations like schools, workplaces, and retail centers contribute to enhanced accessibility (Iacono, Krizek, and El-Geneidy 2008).

It is important to note that walking and cycling accessibility are closely intertwined. Both modes of active transportation contribute to the overall concept of “active accessibility” or “non-motorized accessibility.” While walking primarily involves travel on foot, cycling provides an additional mode that combines physical activity with efficient mobility. The integration of walking and cycling infrastructure, along with improved pedestrian and cyclist safety measures, further supports the goal of promoting sustainable travel choices within cities (Frank and Engelke 2001; Sallis et al. 2004; Wu et al. 2019).By considering and improving accessibility in urban and transportation planning, cities can create environments that facilitate and encourage active modes of transportation. This approach not only helps reduce dependence on private vehicles but also promotes healthier and more sustainable travel behaviors among residents.

A significant body of literature has contributed to the quantification of urban accessibility in recent decades. The assessment of accessibility levels for active modes of transportation, and specifically the calculation of accessibility using impedance functions, has emerged as a crucial research topic that has garnered substantial attention from scholars in the fields of transport planning, urban geography, and sustainable development (Nassir et al. 2016; Currie 2010; Frank et al. 2005; Iacono, Krizek, and El-Geneidy 2010; Krizek 2005). These studies generally agree on two primary components for measuring accessibility include: (1) the location and attractiveness of urban opportunities (benefit side), and (2) the impedance of travel from residential areas in the network to these locations (cost side). According to these definitions, areas with higher accessibility are those characterized by lower impedance when traveling to desirable destinations (Hansen 1959; Pirie 1979; Handy and Niemeier 1997; Geurs and Ritsema van Eck 2001; Bhat et al. 2002; Church and Marston 2003; Kwan et al. 2003; Geurs and Van Wee 2004; Levinson and Krizek 2005; Cascetta, Cartenı̀, and Montanino 2013).

The impedance function, in its various forms, serves as a measure of the willingness to travel a certain distance to reach desired destinations and is a valuable tool for analyzing spatial patterns of travel behavior and can be used for any mode of transportation planning (Taylor 1975; Fotheringham 1981; Eldridge and Jones III 1991; Luoma, Mikkonen, and Palomäki 1993; Vale and Pereira 2017; Papa and Coppola 2012; Vale, Saraiva, and Pereira 2016). Generally, as the distance to a destination increases, the likelihood of walking or cycling decreases. Various distance decay functions have been utilized to describe the distribution of walking and cycling trips, both in general and for specific purposes (Iacono, Krizek, and El-Geneidy 2010; Larsen, El-Geneidy, and Yasmin 2010; Iacono, Krizek, and El-Geneidy 2008). When assessing accessibility using impedance functions, different cost decay functions have been employed, including threshold functions (e.g., step function) and smooth cost decay functions (e.g., inverse-potential, log-normal, logistic, exponential square-root, and half-life function) (De Vries, Nijkamp, and Rietveld 2009; Reggiani, Bucci, and Russo 2011; Östh, Lyhagen, and Reggiani 2016; ITF. 2017). Scholars place significant emphasis on the selection of an appropriate impedance function, leading to a diverse range of functions being employed. However, despite the numerous specifications of impedance functions used, there is limited available evidence to determine a priori which one might be superior. These various specifications primarily vary in their treatment of the influence of distance, consequently impacting the measurement of accessibility. Negative exponential distance-decay functions are commonly used in assessing non-motorized accessibility, capturing the willingness of individuals to walk or cycle to destinations (Handy and Niemeier 1997; Geurs and Ritsema van Eck 2001; Iacono, Krizek, and El-Geneidy 2010; Vega 2012; Millward, Spinney, and Scott 2013; Vale and Pereira 2017). The negative exponential form presents an advantageous characteristic of a more gradual decline when compared to the power function. This attribute renders it particularly effective in accurately estimating shorter trips, especially those associated with non-motorized modes of transportation (Kanafani 1983). In a recent study by Vale and Pereira (2017), the modified Gaussian and exponential functions were found to be the most robust for modeling walking accessibility when examining 20 pedestrian accessibility measures. Additionally, the study introduced a new cumulative Gaussian function that considers cumulative opportunities at close distances (200 or 400 m) and a modified Gaussian curve for longer distances (Vale and Pereira 2017). Prins et al. (2014) investigated bicycle and walking accessibility to grocery stores or markets for the elderly, estimating distance decay model parameters based on factors such as gender, age, and functional limitations (Prins et al. 2014). Iacono et al. (2010) calibrated the distance-decay model for five different trip purposes (work, shopping, school, restaurant, and recreation) and developed accessibility measures for both walking and cycling (Iacono, Krizek, and El-Geneidy 2008).

In addition to determining the form of the impedance function, the analyst must also specify the variable used to measure separation or impedance, which can be either time, cost, or a combination of both. Previous studies have employed both time and distance measures, and there are instances where the generalized cost concept has been applied as well. The choice between time and distance as the impedance variable has been found to be acceptable based on previous research. However, when it comes to non-motorized travel modes like bicycling and walking, extracting accurate travel times from existing network models can be challenging, which limits the options and makes distance a more practical choice (Handy and Niemeier 1997; Iacono, Krizek, and El-Geneidy 2010; Yang and Diez-Roux 2012; Arranz-López et al. 2019).

The objective of this study is to analyze historical data spanning from 1986 to 2015 in Canada to gain insights into people’s actual travel behavior, specifically focusing on active modes of transportation. The investigation encompasses various trip purposes, such as home, work or school, visiting others’ homes, outdoor activities, business-related trips, shopping, visits to libraries, museums or theaters, dining out, and attending places of worship. As non-work travel involves diverse trip purposes and distinct traveler behaviors, the impedance function assumes a pivotal role in examining non-work accessibility. Consequently, it becomes crucial to calculate separate impedance functions for each specific trip purpose (Grengs 2015). The study employs impedance functions as a method to understand individuals’ willingness to travel. While walking and cycling share similarities, they also exhibit notable differences (Tan and QL Xue 2014; DeMaio 2009). Both modes rely on human power but vary in terms of travel speed and distance coverage. Cycling allows for faster travel with a greater range, while walking offers adaptability without the need for special equipment. Previous research has often neglected the competitive nature between walking and cycling for short trips when both options are available. Consequently, individuals may opt for one mode over the other based on their preferences and costs. Hence, this article aims to separately calculate the impedance function for cycling and walking trips using data from the General Social Survey (GSS) dataset in Canada.

Various studies have employed impedance values derived from locally-calibrated travel models. Nevertheless, it is crucial to recognize that these values can be influenced by the specific environment in which they were collected, particularly in the context of non-motorized transportation, where weather conditions can significantly impact travel behavior. Although the ideal approach would involve year-round data collection, covering all seasons, as suggested by Ortuzar and Willumsen (2001), practical constraints often lead to data collection over a limited period, reflecting prevailing weather conditions at the time of the survey(Iacono, Krizek, and El-Geneidy 2010; Dios Ortúzar and Willumsen 2011). This becomes especially important for non-motorized modes and regions with notable seasonal climate variations. For instance, if survey data are gathered during warmer and drier months, changes in travel behavior during colder or wetter months may be overlooked, potentially resulting in overestimating the number of pedestrians and bicyclists during colder weather. Additionally, changes in destination choices for discretionary trips can affect travel distances, consequently influencing the relevant impedance values. Therefore, accurate estimation of specialized impedance functions tailored to non-motorized modes requires access to appropriate travel survey data capable of capturing pedestrian and bicycling behavior. In this study, the impedance function was calculated using the GSS dataset, collected annually over a one-year period through telephone surveys.

#Background

The examination of distance decay functions concerning different transportation modes and destinations serves as a valuable foundation for comprehending the travel behavior attributed to each mode. The parameters of distance decay functions offer insights into the spatial coverage provided by each mode of transportation. By segmenting modal trips based on their purposes, it becomes possible to compare the distribution of trips between work-related and various non-work purposes for each transportation mode. Empirically derived distance decay functions offer valuable evidence that can be utilized to examine and substantiate various claims pertaining to travel behavior, thus supporting urban planning endeavors. For instance, the current interest in creating “livable” communities revolves around loosely held assumptions regarding individuals’ willingness to walk and cycling to different destinations. A common belief is that people are generally willing to walk up to a quarter of a mile to access most locations (Untermann 1984). However, there remains limited information regarding whether certain individuals are open to walking or cycling longer distances and, if so, how much farther they are willing to travel. Moreover, there is a dearth of evidence concerning the influence of trip characteristics, destination attractiveness, and the personal attributes of travelers in relation to the impact of distance on walking behaviors.

Conducting direct behavioral inquiries naturally leads to another significant application of distance decay functions – the calculation of accessibility measures. Accessibility measures for motorized modes are readily available due to the abundance of data on their usage and their relevance in various planning activities. In contrast, similar measures are seldom computed for walking and cycling trips, as they constitute a smaller proportion of overall urban travel and are less frequently observed. Nevertheless, with data on the spatial distribution of trips and basic indicators of attractiveness for different destinations, it is possible to derive accessibility measures for non-motorized modes. Such measures can prove valuable in illustrating the impacts of planning initiatives aimed at promoting non-motorized transportation or concentrating activities in proximity to specific locations.

Distance decay functions hold significant importance in transportation and land use planning activities, primarily due to their longstanding association with gravity models—a type of spatial interaction model commonly employed to predict trip distribution in transportation planning models. In essence, the unconstrained gravity model used to forecast interactions between zonal units (e.g., traffic analysis zones) in an urban region typically adopts the following form (Fotheringham and O’Kelly 1989):

In this context, the gravity model used for forecasting interactions between different zones in an urban region involves several key components. The variable T\_{ij} denotes the number of trips between zones i and j, while v\_{i} and w\_{j} represent factors indicating the attractiveness or intensity of the origin and destination zones, respectively. The function c\_{ij} plays a pivotal role as the distance decay function component of the gravity model, signifying the deterrence or impedance to travel or interaction between locations based on distance while holding all other interaction determinants constant (Fotheringham 1981). Of particular significance within the distance decay function is the parameter , which holds crucial information as it defines the level of deterrence or impedance resulting from distance. Alternatively, this parameter can be interpreted as the willingness of individuals to travel between locations, taking into account the conditions of the transportation network and activity distribution. The distance decay function is commonly presented as a power function in the aforementioned gravity model. Nevertheless, it can also be expressed as the inverse of distance or more frequently as a negative exponential function, exp(-bx), where x represents the distance variable. Irrespective of the mathematical form used, the primary objective of the distance decay function is to illustrate the decline in interaction strength as the distance between locations increases.

In trip distribution modeling, analysts sometimes adopt a simplified approach to the gravity model by assuming known origins and destinations, which is particularly applicable to habitual types of trips like commuting to work or school. This simplification streamlines the gravity model, focusing primarily on estimating its decay or deterrence function. Before reintroducing these functions into a forecasting model, separate estimates are often derived for different trip purposes (Bates 2007).

The distance decay parameter is subject to dynamic changes over time, influenced by the development of transportation networks and alterations in urban spatial structure. For instance, Luoma, Mikkonen, and Palomaki (1993) offer evidence of a decline in the distance decay parameter as a consequence of increased travel speeds and more extensive network development. Subsequent research by Mikkonen and Luoma (1999) aimed to decompose the factors contributing to the observed variations in gravity model parameters over time (Luoma, Mikkonen, and Palomäki 1993; Mikkonen and Luoma 1999).

Moreover, the best-fit distance–decay function and associated parameters varies in accordance to the mode of travel (walking or cycling) and the trip purpose (Iacono et al., 2008, 2010; Larsen et al., 2010; Millward et al., 2013), reducing the usefulness of trying to generalize a unique distance–decay function, as different combinations of travel modes and purposes will require a different function. However, this is only the case when matching the impedance function with the observed walking behavior, Vale and Pereira 743 which might be different from the perceived behavior of the individual. Moreover, it should be noted that distance–decay is an aggregate concept based on travel frequency characteristics of a group of individuals according to distance. At the individual level, movements are much more complex, with significant variations among individuals (Golledge and Stimson, 1997), partly explaining the weak relationship between personal and place accessibility (Kwan, 1998).

The accessibility toolbox implements the five different impedance functions from Kwan (1998):

Inverse Power:

Negative Exponential:

Modified Gaussian:

$$ f(t\_{ij}) = e {{-t\_{ij}2}/2}

$${#eq-Modified\_Gaussian\_impedance-function}

Cumulative Opportunities Rectang:

Cumulative Opportunities Linear:

Gamma :

The inverse power, negative exponential, and modified Gaussian functions continuously discount the weight of opportunities as travel time increases using an impedance parameter β that accounts for the cost of travel. With a foundation in early gravity models of spatial interaction (Stewart 1948; Zipf 1949), the inverse power function produces a rapid decline in the weight of opportunities as travel time increases. While power functions draw analogs to Newtonian physics, their theoretical relevance to human travel behavior has been questioned (Sen and Smith 1995). The negative exponential function is more gradual and based on its strong theoretical foundations in entropy maximization (Wilson 1971) and choice behavior theory (Fotheringham and O’Kelly 1989), this function appears to have become somewhat of a de facto standard in applied accessibility analysis. The modified Gaussian function exhibits a much more gradual rate of decline around its origin and a slower rate of decline overall. While Ingram (Ingram 1971) argues that these properties make the function superior to its inverse power and negative exponential counterparts for explaining observed travel behavior, it appears to be rarely used in the applied literature.

The cumulative rectangular function is an isochronic measure that applies a constant weight to all opportunities reachable within some travel time window whose maximum is defined by ¯t. Although the application of a constant weight is contrary to the geographic principle of distance deterrence or decay that underpins travel behavior theory, such functions remain popular due to their ease of interpretation. Finally, the cumulative linear function is a hybrid of the continuous and cumulative approaches, linearly discounting opportunities within an isochrone. This set of impedance functions is by no means exhaustive. Numerous alternatives have been proposed, such as the exponential–normal, exponential–square root, and log–normal functions reviewed by Reggiani, Bucci, & Russo (Reggiani, Bucci, and Russo 2010) and the Box-Cox, Tanner, and Richards functions reviewed by Martínez & Viegas (Martínez and Viegas 2013). Although these functions could be implemented in future iterations of the tool, the present article’s focus on the functions specified in Kwan (1998) introduces some of the most widely used measures of impedance in applied accessibility analysis.

Kwan (1998) sets four impedance parameters for each continuous function designed to produce a weight of about 0.1 at travel times of 5, 10, 15, and 20 min respectively. Figure 1 recreates a figure from Kwan (1998) to visualize parameter values for the five functions: the inverse power function with β = 2 (POW2\_0), the negative exponential function with β = 0.15 (EXP0\_15), the modified Gaussian function with β = 180 (MGAUS180), and the cumulative rectangular (CUMR40) and linear (CUML40) functions with ¯t set to 40 minutes.

# Materials and Methods

# References

Arranz-López, Aldo, Julio A Soria-Lara, Frank Witlox, and Antonio Páez. 2019. “Measuring Relative Non-Motorized Accessibility to Retail Activities.” *International Journal of Sustainable Transportation* 13 (9): 639–51.

Bates, John. 2007. “History of Demand Modelling.” In *Handbook of Transport Modelling: 2nd Edition*, 11–34. Emerald Group Publishing Limited.

Bhat, Chandra, Susan Handy, Kara Kockelman, Hani Mahmassani, Anand Gopal, Issam Srour, and Lisa Weston. 2002. “Development of an Urban Accessibility Index: Formulations, Aggregation, and Application.” *Work* 4938 (4).

Cascetta, Ennio, Armando Cartenı̀, and Marcello Montanino. 2013. “A New Measure of Accessibility Based on Perceived Opportunities.” *Procedia-Social and Behavioral Sciences* 87: 117–32.

Church, Richard L, and James R Marston. 2003. “Measuring Accessibility for People with a Disability.” *Geographical Analysis* 35 (1): 83–96.

Currie, Graham. 2010. “Quantifying Spatial Gaps in Public Transport Supply Based on Social Needs.” *Journal of Transport Geography* 18 (1): 31–41.

De Vries, Jacob J, Peter Nijkamp, and Piet Rietveld. 2009. “Exponential or Power Distance-Decay for Commuting? An Alternative Specification.” *Environment and Planning A* 41 (2): 461–80.

DeMaio, Paul. 2009. “Bike-Sharing: History, Impacts, Models of Provision, and Future.” *Journal of Public Transportation* 12 (4): 41–56.

Dios Ortúzar, Juan de, and Luis G Willumsen. 2011. *Modelling Transport*. John wiley & sons.

Eldridge, J Douglas, and John Paul Jones III. 1991. “Warped Space: A Geography of Distance Decay.” *The Professional Geographer* 43 (4): 500–511.

Fotheringham, A Stewart. 1981. “Spatial Structure and Distance-Decay Parameters.” *Annals of the Association of American Geographers* 71 (3): 425–36.

Fotheringham, A Stewart, and Morton E O’Kelly. 1989. *Spatial Interaction Models: Formulations and Applications*. Vol. 1. Kluwer Academic Publishers Dordrecht.

Frank, Lawrence D, and Peter O Engelke. 2001. “The Built Environment and Human Activity Patterns: Exploring the Impacts of Urban Form on Public Health.” *Journal of Planning Literature* 16 (2): 202–18.

Frank, Lawrence D, Thomas L Schmid, James F Sallis, James Chapman, and Brian E Saelens. 2005. “Linking Objectively Measured Physical Activity with Objectively Measured Urban Form: Findings from SMARTRAQ.” *American Journal of Preventive Medicine* 28 (2): 117–25.

Geurs, Karst T, and Jan R Ritsema van Eck. 2001. “Accessibility Measures: Review and Applications. Evaluation of Accessibility Impacts of Land-Use Transportation Scenarios, and Related Social and Economic Impact.” *RIVM Rapport 408505006*.

Geurs, Karst T, and Bert Van Wee. 2004. “Accessibility Evaluation of Land-Use and Transport Strategies: Review and Research Directions.” *Journal of Transport Geography* 12 (2): 127–40.

Grengs, Joe. 2015. “Nonwork Accessibility as a Social Equity Indicator.” *International Journal of Sustainable Transportation* 9 (1): 1–14.

Handy, Susan L, and Debbie A Niemeier. 1997. “Measuring Accessibility: An Exploration of Issues and Alternatives.” *Environment and Planning A* 29 (7): 1175–94.

Hansen, Walter G. 1959. “How Accessibility Shapes Land Use.” *Journal of the American Institute of Planners* 25 (2): 73–76.

Iacono, Michael, Kevin J Krizek, and Ahmed El-Geneidy. 2010. “Measuring Non-Motorized Accessibility: Issues, Alternatives, and Execution.” *Journal of Transport Geography* 18 (1): 133–40.

Iacono, Michael, Kevin Krizek, and Ahmed M El-Geneidy. 2008. “Access to Destinations: How Close Is Close Enough? Estimating Accurate Distance Decay Functions for Multiple Modes and Different Purposes.”

ITF. 2017. *Linking People and Places: New Ways of Understanding Spatial Access in Cities*. OECD Publishing.

Kanafani, Adib. 1983. “Transportation Demand Analysis.”

Krizek, Kevin J. 2005. “Perspectives on Accessibility and Travel.” In *Access to Destinations*, 109–30. Emerald Group Publishing Limited.

Kwan, Mei-Po, Alan T Murray, Morton E O’Kelly, and Michael Tiefelsdorf. 2003. “Recent Advances in Accessibility Research: Representation, Methodology and Applications.” *Journal of Geographical Systems* 5: 129–38.

Larsen, Jacob, Ahmed El-Geneidy, and Farhana Yasmin. 2010. “Beyond the Quarter Mile: Re-Examining Travel Distances by Active Transportation.” *Canadian Journal of Urban Research* 19 (1): 70–88.

Levinson, David M, and Kevin J Krizek. 2005. *Access to Destinations*. Elsevier Publishers.

Luoma, Martti, Kauko Mikkonen, and Mauri Palomäki. 1993. “The Threshold Gravity Model and Transport Geography: How Transport Development Influences the Distance-Decay Parameter of the Gravity Model.” *Journal of Transport Geography* 1 (4): 240–47.

Mikkonen, Kauko, and Martti Luoma. 1999. “The Parameters of the Gravity Model Are Changing–How and Why?” *Journal of Transport Geography* 7 (4): 277–83.

Millward, Hugh, Jamie Spinney, and Darren Scott. 2013. “Active-Transport Walking Behavior: Destinations, Durations, Distances.” *Journal of Transport Geography* 28: 101–10.

Nassir, Neema, Mark Hickman, Ali Malekzadeh, and Elnaz Irannezhad. 2016. “A Utility-Based Travel Impedance Measure for Public Transit Network Accessibility.” *Transportation Research Part A: Policy and Practice* 88: 26–39.

Östh, John, Johan Lyhagen, and Aura Reggiani. 2016. “A New Way of Determining Distance Decay Parameters in Spatial Interaction Models with Application to Job Accessibility Analysis in Sweden.” *European Journal of Transport and Infrastructure Research* 16 (2).

Papa, Enrica, and Pierluigi Coppola. 2012. “Gravity-Based Accessibility Measures for Integrated Transport-Land Use Planning (GraBAM).” *Accessibility Instruments for Planning Practice* 117: 124.

Pirie, Gordon H. 1979. “Measuring Accessibility: A Review and Proposal.” *Environment and Planning A* 11 (3): 299–312.

Prins, Richard G, Frank Pierik, Astrid Etman, Reinier P Sterkenburg, Carlijn BM Kamphuis, and FJ Van Lenthe. 2014. “How Many Walking and Cycling Trips Made by Elderly Are Beyond Commonly Used Buffer Sizes: Results from a GPS Study.” *Health & Place* 27: 127–33.

Reggiani, Aura, Pietro Bucci, and Giovanni Russo. 2011. “Accessibility and Impedance Forms: Empirical Applications to the German Commuting Network.” *International Regional Science Review* 34 (2): 230–52.

Sallis, James F, Lawrence D Frank, Brian E Saelens, and M Katherine Kraft. 2004. “Active Transportation and Physical Activity: Opportunities for Collaboration on Transportation and Public Health Research.” *Transportation Research Part A: Policy and Practice* 38 (4): 249–68.

Tan, Zheng, and Charlie QL Xue. 2014. “Walking as a Planned Activity: Elevated Pedestrian Network and Urban Design Regulation in Hong Kong.” *Journal of Urban Design* 19 (5): 722–44.

Taylor, Peter. 1975. “Distance Decay Models in Spatial Interactions.” *(No Title)*.

Untermann, Richard K. 1984. “Accommodating the Pedestrian: Adapting Towns and Neighbourhoods for Walking and Bicycling.”

Vale, David S, and Mauro Pereira. 2017. “The Influence of the Impedance Function on Gravity-Based Pedestrian Accessibility Measures: A Comparative Analysis.” *Environment and Planning B: Urban Analytics and City Science* 44 (4): 740–63.

Vale, David S, Miguel Saraiva, and Mauro Pereira. 2016. “Active Accessibility: A Review of Operational Measures of Walking and Cycling Accessibility.” *Journal of Transport and Land Use* 9 (1): 209–35.

Vega, Amaya. 2012. “Using Place Rank to Measure Sustainable Accessibility.” *Journal of Transport Geography* 24: 411–18.

Wu, Xueying, Yi Lu, Yaoyu Lin, and Yiyang Yang. 2019. “Measuring the Destination Accessibility of Cycling Transfer Trips in Metro Station Areas: A Big Data Approach.” *International Journal of Environmental Research and Public Health* 16 (15): 2641.

Yang, Yong, and Ana V Diez-Roux. 2012. “Walking Distance by Trip Purpose and Population Subgroups.” *American Journal of Preventive Medicine* 43 (1): 11–19.