ARTICLE

Using Network Segments in the Visualization of Urban Isochrones

Jeff Allen
Department of Geography and Planning / University of Toronto / Toronto / ON / Canada

ABSTRACT

Since the early twentieth century, thematic mapping techniques such as isochrones have been used for visualizing the accessibility and mobility provided by urban transportation networks. These maps typically depict the area accessible from a point within a certain time or distance threshold. This article details a design alternative to conventional isochrones, which links travel times to network edges. Benefits of this technique include highlighting the network structure of transport networks and comparing travel times for different travel scenarios. This article details methods for producing these maps using free and open-source data and software and provides examples of visualizing different accessibility scenarios in Toronto, Canada.

Keywords: isochrones, accessibility, networks, urban transportation, Toronto

RÉSUMÉ

Depuis le début du XX^{e} siècle, les techniques de cartographie thématique comme les isochrones sont utilisées pour permettre la visualisation de l'accessibilité et de la mobilité assurées par les réseaux de transport urbain. Ces cartes dépeignent habituellement la région à laquelle il est possible d'accéder à partir d'un point dans un laps de temps donné ou à l'intérieur d'une distance donnée. L'auteur décrit en détail une solution de rechange conceptuelle aux isochrones traditionnels, qui relie les temps de déplacement aux extrémités du réseau. Les avantages de cette technique sont notamment la mise en évidence de la structure des réseaux de transport et la comparaison des temps de déplacement pour différents scénarios de parcours. Il décrit également les méthodes de production de ces cartes à l'aide de données et de logiciels d'accès libre et ouvert et propose des exemples de visualisation de différents scénarios d'accessibilité à Toronto, au Canada.

Mots clés : accessibilité, isochrones, réseaux, Toronto, transport urbain

Introduction

A primary function of transportation networks in cities is to enable people to travel to important destinations such as employment, school, shops, and social activities. The concept of accessibility, simply defined as the ease of reaching destinations, is often used to analyze the social outcomes of urban transport networks. Accessibility depends on where people live in relation to transportation networks (e.g., is there nearby transit service) and on land use patterns (e.g., are there nearby shops), as well as on socioeconomic factors (e.g., can someone afford a car) (Geurs and Van Wee 2004). It has long been noted that accessibility is a key component of good urban form, and urban planning strategies should strive to increase the levels of accessibility in a region (Hansen 1959; Lynch 1981). Because of the inherent complexity of urban transport networks, understanding and developing policy aimed at improving accessibility in cities is quite challenging. Multimodal transport networks in large urban areas are characterized by spatial intricacies and temporal variations such as congestion, transit schedules, and differing individual travel behaviour.

A common objective of cartography and information visualization is to distill the multivariate complexities of our world into two-dimensional graphics so that they can be better understood by researchers, policy makers, and the general public, often to provide a more holistic view of a subject matter. This is particularly important in urban transport policy, which is often politically divisive. Many people, from the general public to urban policy makers, often have a parochial perspective on transport networks, which can cause unequal allocation of infrastructure investments (Knight 2004). Using cartography to visualize variations in transport accessibility can increase understanding between conflicting viewpoints and aid more informative decision making.

  doi:10.3138/cart.53.4.2018-0013

Accessibility is commonly visualized using isochrones (Vasiliev 1997; O'Sullivan and others 2000). This thematic mapping technique uses isolines or concentric polygons to represent the area that is reachable from a specific point (iso = equal, chrone = time). In recent years, increased computation and improvements in algorithms have facilitated the rapid generation of isochrones (Gamper and others 2012; Bolzoni and others 2016) and speed of transport accessibility analysis (Owen and Levinson 2015; Farber and Fu 2017). Despite these increases in computational prowess, visualization strategies for isochrones have remained relatively unchanged over the past decades. But with the increase in computer memory, openly available transport network data, and efficient graph algorithms, there is an opportunity for the generation of more data-dense, comparative visualization techniques that have the ability to augment our understanding of urban transport networks.

Accordingly, the goal of this article is first to provide a background on how isochrones have been used to visualize accessibility in urban transport networks. It then details an alternative over these conventional mapping techniques using the edges of transport network graphs as the primary feature in the visual display of isochrones. These network-focused isochrones facilitate visual comparison of travel times and accessibility between travel scenarios or travel modes or by time of day. Moreover, these visualizations provide an opportunity for more data-dense graphics, highlighting the underlying network structure which determine travel times, and offer greater potential mapping in conjunction with other areal features. Examples of this visualization method are provided for the city of Toronto, Canada. All the data and tools used are open source, so the methods can be repeated with minimal cost.

Mapping Urban Accessibility with Isochrones

Accessibility, in the context of urban transportation, generally refers to the capability of a transport network to provide opportunity for interaction. The modern concept of accessibility can be dated back to Hansen (1959), who contextualized accessibility as the capability to reach destinations. This is related to, but not synonymous with, the concept of mobility, which describes the ability of people to travel over space (Cervero and others 1997). Travel times to destinations, what is reachable within certain times, varies both within and between cities. People living in some neighbourhoods are afforded better or worse access depending on available transport (e.g., is there nearby transit service), land use characteristics and available destinations (e.g., are there nearby shops), and individual characteristics (e.g., is someone healthy enough to walk to a transit stop) (Geurs and Van Wee 2004). Accessibility is also a function of time. Land use patterns, as well as transport networks, have daily rhythms; shops and services have opening hours, transit schedules change with time of day and day of week, and road congestion peaks at certain hours during the day. Over longer periods of time, transportation infrastructure changes: New roads or transit routes are added or altered, changing what is accessible within the urban context. As well, the access afforded to individuals is dependent on what mode(s) of travel are available to them. For example, if someone owns a vehicle, he or she is typically provided with the ability to travel to destinations further away than someone reliant on transit (Benenson and others 2011). Low accessibility can negatively impact urban economies and social outcomes. For example, it has been shown that low levels of access can discourage people from travelling to destinations such as shops and services, increase difficulty in finding employment opportunities, and result in social isolation (Preston and Rajé 2007; Lucas 2012). However, measuring and understanding the spatial and temporal aspects of accessibility and mobility in an urban context is complex, which often makes it difficult to design policy and urban planning strategies that are effective in increasing accessibility.

Cartography and information visualization are paramount in extracting spatial data from our dynamic world and presenting them to improve our understanding of complex phenomena (Robinson 1958; Tufte 1983). Cartography, in particular, has a long history of designing solutions to map temporal attributes (Vasiliev 1997). Measuring access by visualizing the space that is reachable within specific distance or time thresholds dates to when Galton (1881) generated a world map showing the travel times from London, England to anywhere in the world using concentric polygons, each representing a time range from London in days. This was the first popularized isochrone map. In the early twentieth century, the isochrone method was employed in urban areas for visualizing, evaluating, and planning new transport infrastructure. Since then, isochrones have been used by urban planners and researchers to depict accessibility to or from a point in space and to evaluate the accessibility and mobility provided by urban transport networks. Figure 1 shows an isochrone map of Toronto from 1945 (Toronto Transit Commission 1945). The colour bands indicate the area that is accessible from the centre for different travel time thresholds.

Urban isochrones are often generated using network graphs representing transportation networks. The basic procedure in generating an isochrone is first to compute all the nodes or edges in a network graph that can be reached from a starting point within a certain time or distance threshold. With modern routing software, this process often uses a shortest-path algorithm such as Djikstra or A*. Second, this set of points is used to estimate the area that is accessible from the starting point. This area can be generated by computing a convex hull from the set of accessible points or by generating buffers of specified radii around all accessible edges (Bolzoni and others 2016; van den Berg and others 2018). Differing methods can result in variations in estimates of the land area reachable from a point, as well as from any subsequent

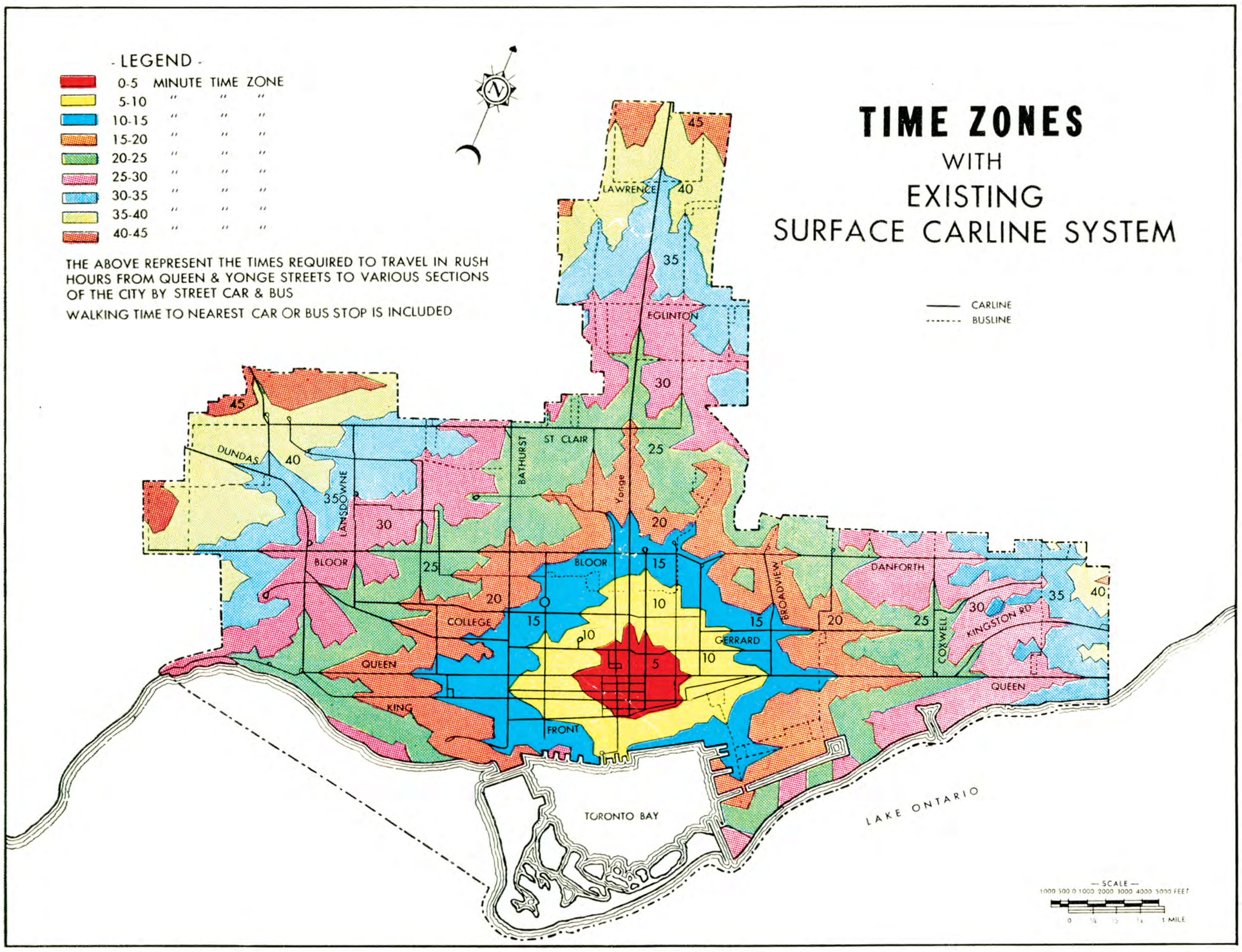

Figure 1. Isochrone map of the surface public transit system from downtown Toronto in 1945 (Toronto Transit Commission 1945)
Source: Courtesy of the University of Toronto Map & Data Library.

analysis of counts of population or number of destinations within these areas (Marciuska and Gamper 2010).

Areal isochrone generation has been incorporated into common desktop GIS software and various Web applications. ESRIs ArcGIS software produces isochrones, terming them "service areas" (ESRI 2017). Routing extensions of the popular spatial database management system PostGIS allow the output of reachable nodes, which can then be formed into polygons with additional convex hull queries (Graser 2011). The open source routing engine OpenTripPlanner (2017) can generate areal isochrones both in raster and vector data formats from network graphs which incorporate transit schedules (OpenTripPlanner 2017).

Applications in time geography have extended single-point isochrones to show the areas accessible between fixed origins and fixed destinations for trips with specified time budgets. These are often referred to as potential path areas (Miller 1991), and have had a number of applications in mapping whether a destination is accessible as an intermediate stop on a trip between two fixed points in space and time (for example, which shops can be reached between work and home, given a time window). This has also been extended to analyze the probability of travelling along certain paths (Downs and Horner 2012).

Recent studies have also used isochrones to examine the temporal variations of urban transport networks, often focused on varying transit schedules. O'Sullivan and others (2000) generated isochrones to examine temporal variations in accessibility due to transit schedules in Glasgow, Scotland. Lei and Church (2010) undertook a similar study examining variations in transit accessibility in southern California. Bauer and others (2008) developed a Java application to generate isochrones in multimodal schedule-based transport networks in Bolzano, Italy. Goliszek and Polom (2016) generated isochrones for different periods during a morning commute to visualize how temporal differences in transit schedules can affect the area accessible from certain locations. In another study, van den Berg and others (2018) created dynamic isochrone maps using spatiotemporal traffic data in the Netherlands.

Despite this recent research and computational developments, there has been little evolution in the methodology for visualizing isochrones. The convention is still to interpolate the area that is accessible from a point. There are several issues with this. First, this assumes that everything within these shaded regions is reachable. However, much of the land within this area may not be accessible (e.g., if it represents private or institutional land). This could potentially exaggerate accessibility from a point. This fault could be addressed with dasymetric mapping, but only if land use data are available, and this would certainly require additional steps. As well, isochrones are typically mapped overlaid with a reference street layer. This requires two data layers to convey the information regarding the land that is accessible and which routes people are likely to travel on. This increases the difficulty of providing comparisons with other polygonal data layers, whether these are other isochrones for differing travel scenarios (e.g., for comparing mobility differences between public transit and cars) or other areal data layers such as land use or demographics. The remainder of this article details the methodology and benefits of using network edges in the spatial representation of urban travel time isochrones in an attempt to overcome these limitations. Examples are provided for Toronto, Canada.

Network-Focused Isochrones

Network-focused isochrones visually classify the edges in a network graph with travel times from a point. If a street network graph is used, this is essentially a visualization of which streets are accessible from a given point in space and time, in contrast to the conventional visualization strategy, which maps the area that is accessible. Figure 2 is a simple schematic comparing the two visualization techniques.

The process of generating these network-focused isochrones involves the same initial steps as for conventional isochrones, but instead of the generation of shapes or the interpolation of a surface, the travel times are linked to street network segments. These segments can be the same edges as in the network graph used to generate the travel times. In a network graph, each edge has two associated nodes, a source and a target, which can be used to classify the travel time along each edge either by averaging or by computing a gradient. An alternative way to generate a similar result would be to generate midpoints of the lines, compute one-to-many travel times from a point to every midpoint, and then join these points back to the street network via a unique identifier. Once travel times are linked to network segments, they can easily be classified, reclassified, and visualized without additional computation. Conversely, areal isochrones typically require additional computation of geometry if the analyst wants to display different travel time thresholds.

Using the network as the visualization medium brings the geometric data structure of the street network that is used to generate travel times to the forefront of the map. As well, the roads can still be styled via other attributes. For example, while the colour of the line can pertain to travel time, the width of the line can pertain to road width or road class (local, highway, etc.). For example, the schematic in Figure 2 maintains the street hierarchy. Linking these data to network segments also frees space on the map for adding other areal attributes such as land use or population data (e.g., as choropleths). Using network segments also

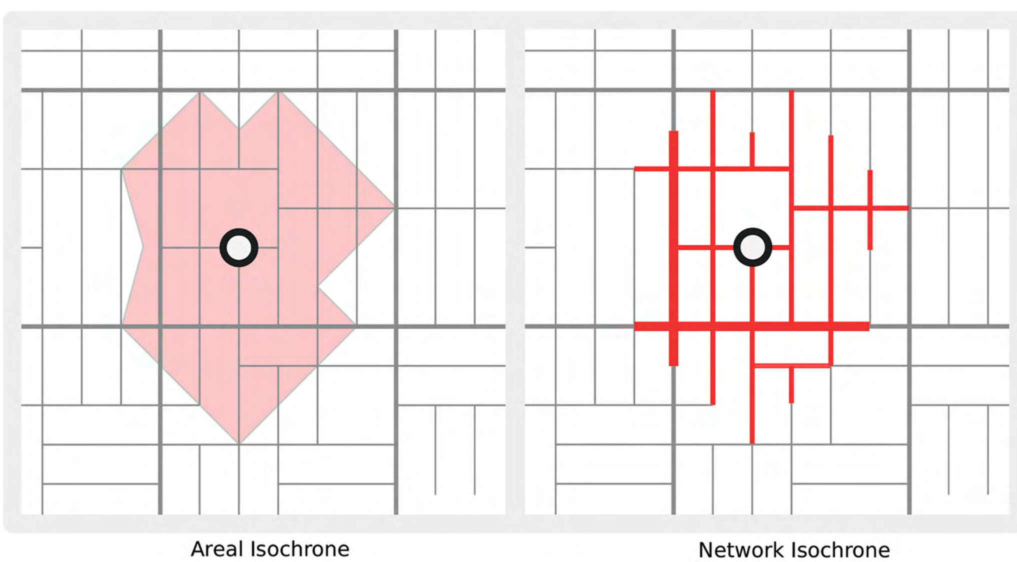

Figure 2. Schematic comparing areal and network-focused isochrones

provides the ability to amiably compare travel scenarios by visualizing differences in travel times. For example, if travel times from a point for two different travel modes are linked to the same network segments, then visualizing differences between these two scenarios simply involves a subtraction of tabular data.

The subsequent sections provide examples of network-focused isochrones that can be used for different types of comparative accessibility studies. These examples are for the city of Toronto and are aimed at showcasing how this visualization method can improve understanding of urban accessibility. The network graph used to generate these maps was built using the routing software OpenTripPlanner (2017), although the same type of visualizations could be generated with other routing software following similar steps (e.g., with PostGIS, ArcGIS Network Analyst, or OSRM). OpenTripPlanner is an open source routing and trip planning application written in Java. It has two main inputs. The first is the street network edges from OpenStreetMap. The second is GTFS (General Transit Feed Specification) data. GTFS is a standardized data format that encodes transit schedules and route information in a set of relational comma-separated value (csv) tables. For this study, GTFS data for the local transit agency, the Toronto Transit Commission, are used as the input. OpenTripPlanner has a map-based interface similar to Google Maps for estimating itineraries. It can also be scripted using Python for batch computations (e.g., for origin–destination matrices). Trip information can be requested for specific departure times, and travel time estimates include the time required for walking to and from transit stops, waiting for a transit vehicle, in-vehicle travel times, and any time transferring between vehicles, if necessary.

The subsequent visualizations were built by first generating travel time matrices from the origin point(s) displayed on the map to the set of nodes on the street network. Second, the values at nodes were assigned to network edges by averaging the values for the two nodes associated with each edge. The edges were then visualized in QGIS. For refined visualization, any edges longer than 100 m were bisected at their midpoints prior to computing travel times to limit generalization of travel times across longer segments. As well, the road network used for visualization is a subset of the OpenStreetMap network that only includes the City of Toronto and does not include any non-walkable segments (e.g., highways).

COMPARING BY TRAVEL MODE

Urban researchers are often concerned with analyzing the mobility and accessibility differences between different travel modes (Benenson and others 2011). Figure 3 is an example of mapping the differences in travel times between travel modes. This example compares travel times between bicycle and public transit from a central subway station in Toronto. A divergent colour scheme was used to highlight areas where each mode offers greater mobility. In simple terms, this map shows, if two people left the centre point at the same time, one by transit and the other by bike, which would get there first. The green streets are where a cyclist would arrive first, the

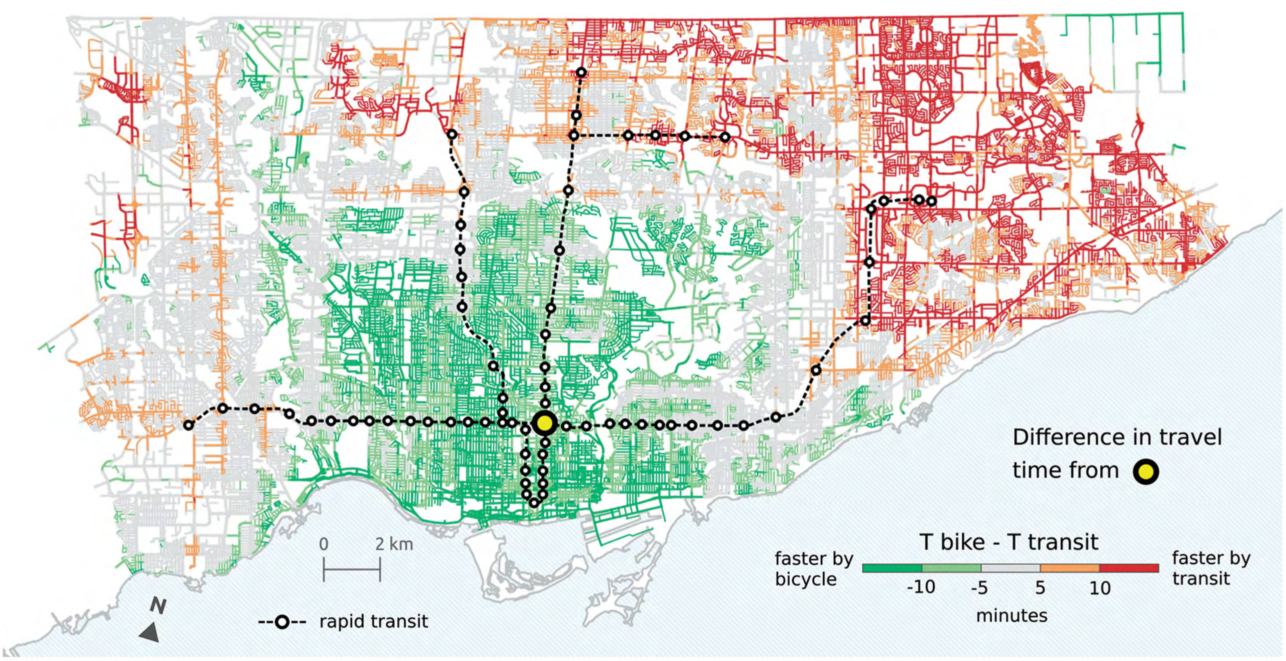

Figure 3. Using network segments to compare travel times between bicycle and public transit

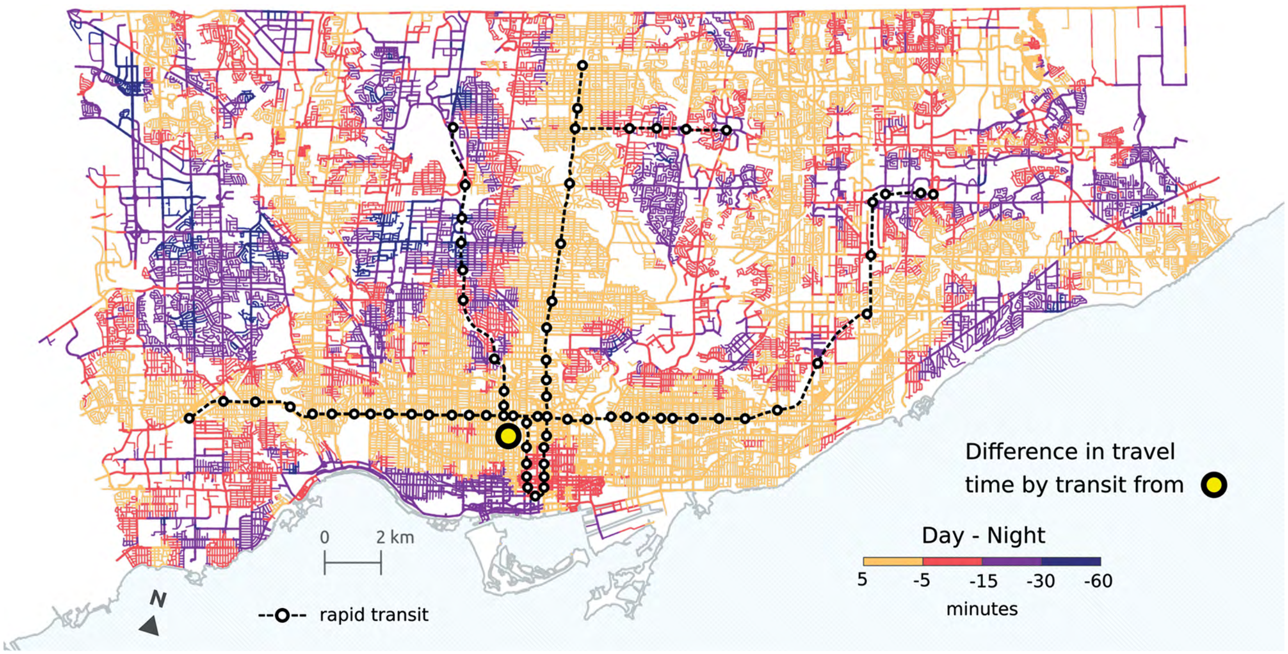

Figure 4. Using network segments to compare travel times by transit during the day and at night

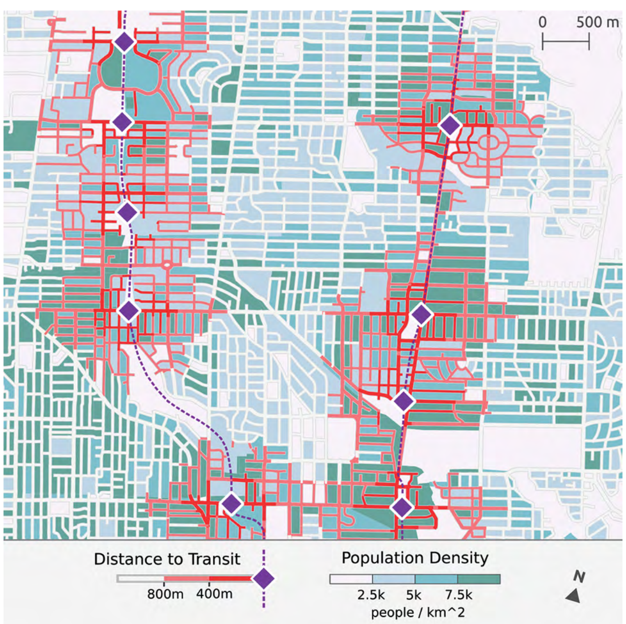

Figure 5. Example of mapping distance to transit stops in conjunction with population density

red streets are where a transit rider would arrive first, and grey streets represent nearly equal travel times. The transit travel times are based on the afternoon peak travel period (averaged from 4:00 to 6:00 p.m.) Such a map has the potential to encourage residents to cycle, particularly if they live in the dark green area, and reduce crowding on public transit.

COMPARING BY TIME OF DAY

Figure 4 displays a similar application, but instead of comparing travel modes, it compares travel times on public transit by time of day. Specifically, it compares scheduled midday service (averaged from 1:00 to 3:00 p.m.) with scheduled night service (averaged from 2:00 to 4:00 a.m.) from a university campus in Toronto. University students often study at late hours and need to rely on the less frequent night transit service to return to their homes. If transit service is insufficient, students can be dissuaded from travelling to and from campus (Allen and Farber 2018). The light orange areas on the map are where, on the average, travel times to these locations are approximately equivalent, while the purple areas are where travel times are much quicker during the day than at night. This type of comparison could also be used to compare transit schedules between days of the week, or for comparing between times of day by driving, for example between congested (i.e., rush hour) and freeflow road networks.

MAPPING WITH AREAL DATA

For this example, we present how network-focused isochrones are useful in mapping in conjunction with areal data. Figure 5 uses network segments to visualize walking distance to major transit stops in north Toronto in relation to population density displayed as a choropleth. Mapping and analyzing populations proximate to transit stations is a common approach to examining transit provision (Schlossberg and Brown 2004). Figure 5, in particular, shows a higher concentration of population near transit stations than further away, but there are still several high-density blocks without nearby rapid transit.

POTENTIAL PATH AREAS

Beyond looking at travel time to or from a single point, the same methodology can be used to visualize the streets accessible on a trip between two points. This type of analysis is common in time-geographic measures of accessibility (Hägerstraand 1970; Miller 1991). The potential path area (PPA) is a map of any intermediary locations that can be reached on a trip between two anchor points. Figure 6 shows a theoretical diagram of a potential path area (right) and how it can be visualized using network-focused isochrones for travel times by transit (left). For example, if you live at the yellow dot and need to be at the green dot within 90 minutes, the dark purple streets are those where you could have at least 30 minutes to make an intermediary stop (for a drink, grocery shopping, etc.). In Figure 6, TB represents the overall time budget for an individual (e.g., TB equals 90 minutes if it is currently 5:30 p.m. .and you have to be at the destination by 7:00 p.m.), TA is the time required to participate in an activity (e.g., at least 30 minutes to shop for groceries), and TT is the total travel time to get to any intermediary location plus the travel time from the intermediary location to home (e.g., the combined time to travel from work to a grocery store and then from the grocery store to home).

Conclusions

In this article, we provided a brief background on how isochrones have been used to visualize accessibility on urban transport networks. We then detailed an alternative to conventional isochrones that classifies the edges of transport network graphs by their travel times from a point rather than estimating an accessible area. These network-focused isochrones facilitate visual comparison of travel times and accessibility between travel scenarios or travel modes or by time of day, and are thus useful for urban planners and researchers who aim to understand and improve urban accessibility. This is not to say that the above methods

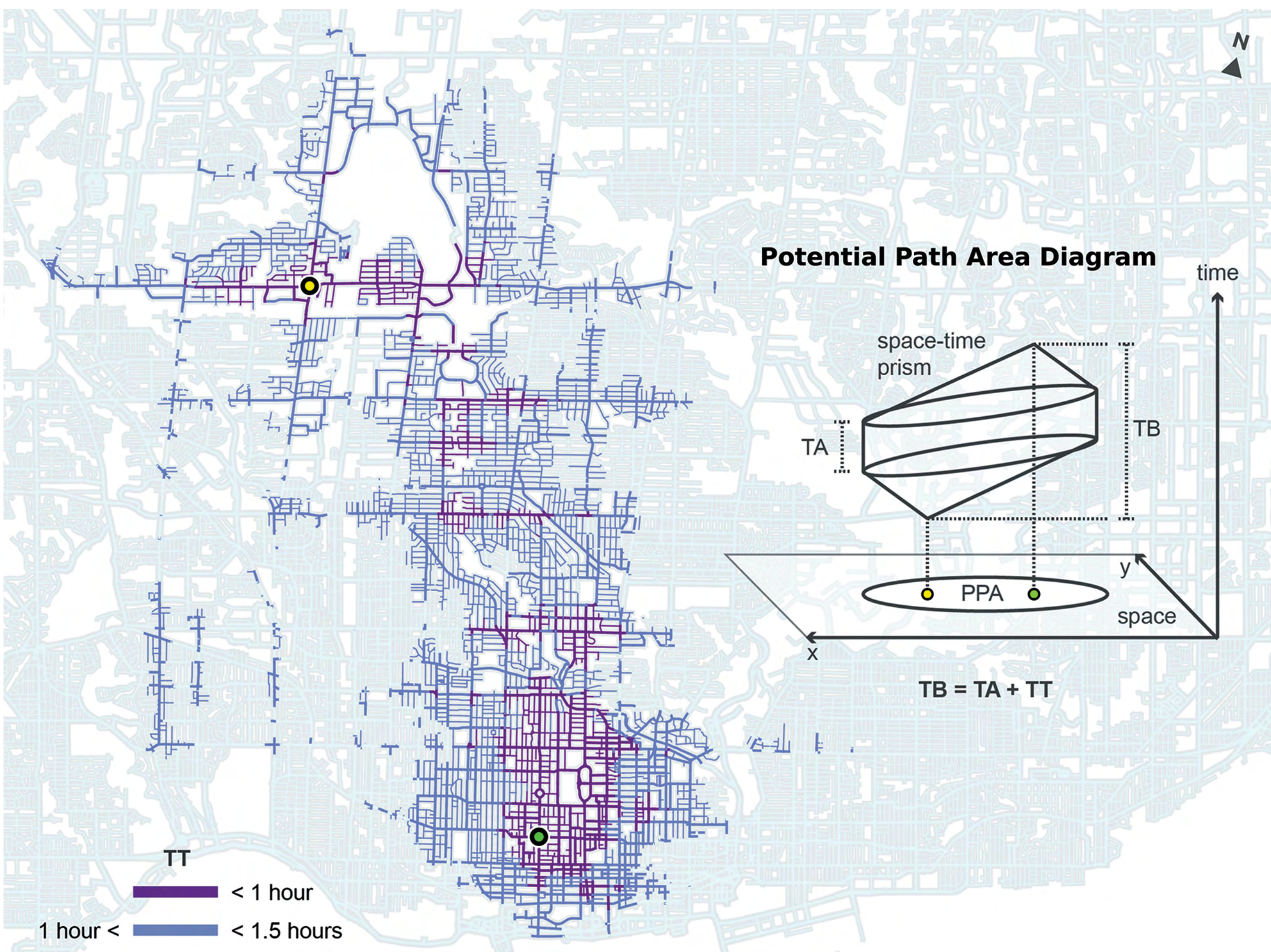

Figure 6. Example of the potential path area between two points by public transit

should always be used over conventional areal isochrones, but in some cases, as in the examples provided in the previous section, they can provide benefits for conveying the complexities of urban accessibility. These benefits include more options for mapping in conjunction with areal data, comparing multiple travel time scenarios within a single graphic, and bringing the network structure to the forefront of the map. Directions for improvement could include faster computation and porting this technique to Web-based interactive applications to allow users to select and generate network-focused isochrones without having to run specialized software.

Author Information

Jeff Allen is a PhD student in geography and spatial information systems at the University of Toronto. His research interests include spatial analysis and cartography, typically applied to analyzing and visualizing urban systems. Some of his maps and research can be found online at http://jamaps.github.io/. E-mail: jeff.allen@mail.utoronto.ca.

References

Allen, Jeff, and Steven Farber. 2018. "How Time-Use and Transportation Barriers Limit On-Campus Participation of University Students." *Travel Behaviour and Society* 13: 174–182. https://doi.org/10.1016/j.tbs.2018.08.003.

Bauer, Veronika, Johann Gamper, Roberto Loperfido, Sylvia Profanter, Stefan Putzer, and Igor Timko. 2008. "Computing Isochrones in Multi-modal, Schedule-Based Transport Networks." In *Proceedings of the 16th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*, 78. New York: ACM.

Benenson, Itzhak, Karel Martens, Yodan Rofé, and Ariela Kwartler. 2011. "Public Transport versus Private Car GIS-Based Estimation of Accessibility Applied to the Tel Aviv Metropolitan Area." *Annals of Regional Science* 47(3): 499–515. https://doi.org/10.1007/s00168-010-0392-6.

Bolzoni, Paolo, Sven Helmer, and Oded Lachish. 2016. "Fast Computation of Continental-Sized Isochrones." *International Conference on GIScience Short Paper Proceedings* 1(1): 21–24. https://doi.org/10.21433/B31171h533kp.

Cervero, Robert. 1997. "Paradigm Shift: From Automobility to Accessibility Planning." In *Urban Futures (Canberra)* (22): 9–20.

Downs, Joni A., and Mark W. Horner. 2012. "Probabilistic Potential Path Trees for Visualizing and Analyzing Vehicle Tracking Data." *Journal of Transport Geography* 23: 72–80. https://doi.org/10.1016/j.jtrangeo.2012.03.017.

ESRI. 2017. ArcGIS Network Analyst. Available at https://www.esri.com/software/arcgis/extensions/networkanalyst.

Farber, Steven, and Liwei Fu. 2017. "Dynamic Public Transit Accessibility Using Travel Time Cubes: Comparing the Effects of Infrastructure (Dis)investments over Time." *Computers, Environment and Urban Systems* 62: 30–40. https://doi.org/10.1016/j.compenvurbsys.2016.10.005.

Galton, Francis. 1881. "On the Construction of Isochronic Passage-Charts." *Proceedings of the Royal Geographical Society and Monthly Record of Geography* 3: 657–58.

Gamper, Johann, Michael Böhlen, and Markus Innerebner. 2012. "Scalable Computation of Isochrones with Network Expiration." In *Scientific and Statistical Database Management*, Lecture Notes in Computer Science, Vol. 7338, Anastasia Ailamaki and Shawn Bowers, eds., 526–43. Berlin: Springer.

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. https://doi.org/10.1016/j.jtrangeo.2003.10.005.

Goliszek, Slawomir, and Marcin Polom. 2016. *The Use of General Transit Feed Specification (GTFS) Application to Identify Deviations in the Operation of Public Transport at Morning Peak Hours on the Example of Szczecin*, Europa XXI 30. Warsaw: IGIPZ PAN. https://doi.org/10.7163/eu21.2016.31.4.

Graser, Anita. 2011. Drive Time Isochrones – An Example Using Finnish Airports. Available at https://anitagraser.com/2011/02/12/drive-time-isochrones/.

Hägerstraand, Torsten. 1970. "What about People in Regional Science?" *Papers in Regional Science* 24(1): 7–24. https://doi.org/10.1111/j.1435-5597.1970.tb01464.x.

Hansen, Walter G. 1959. "How Accessibility Shapes Land Use." *Journal of the American Institute of Planners* 25(2): 73–76. https://doi.org/10.1080/01944365908978307.

Knight, Brian. 2004. "Parochial Interests and the Centralized Provision of Local Public Goods: Evidence from Congressional Voting on Transportation Projects." *Journal of Public Economics* 88(3–4): 845–866. https://doi.org/10.1016/s0047-2727(03)00064-1.

Lei, Ting L., and Richard L. Church. 2010. "Mapping Transit-Based Access: Integrating GIS, Routes and Schedules." *International Journal of Geographical Information Science* 24(2): 283–304. https://doi.org/10.1080/13658810902835404.

Lucas, Karen. 2012. "Transport and Social Exclusion: Where Are We Now?" *Transport Policy* 20: 105–113. https://doi.org/10.1016/j.tranpol.2012.01.013.

Lynch, Kevin. 1981. *A Theory of Good City Form*. Cambridge, MA: MIT Press.

Marciuska, Sarunas, and Johann Gamper. 2010. "Determining Objects within Isochrones in Spatial Network Databases." In Fourteenth East European Conference on Advances in Databases and Information Systems, Barbara Catania, Mirjana Ivanovíc, and Bernhard Thalheim, eds., 392–405. Berlin: Springer.

Miller, Harvey J. 1991. "Modelling Accessibility Using Space-Time Prism Concepts within Geographical Information Systems." *International Journal of Geographical Information Systems* 5(3): 287–301. https://doi.org/10.1080/02693799108927856.

OpenTripPlanner. 2017. OpenTripPlanner Analyst Documentation. Available at http://docs.opentripplanner.org/en/latest/.

O'Sullivan, David, Alastair Morrison, and John Shearer. 2000. "Using Desktop GIS for the Investigation of Accessibility by Public Transport: An Isochrone Approach." *International Journal of Geographical Information Science* 14(1): 85–104. https://doi.org/10.1080/136588100240976.

Owen, Andrew, and David M. Levinson. 2015. "Modeling the Commute Mode Share of Transit Using Continuous Accessibility to Jobs." *Transportation Research Part A: Policy and Practice* 74: 110–122. https://doi.org/10.1016/j.tra.2015.02.002.

Preston, John, and Fiona Rajé. 2007. "Accessibility, Mobility and Transport-Related Social Exclusion." *Journal of Transport Geography* 15(3): 151–160. https://doi.org/10.1016/j.jtrangeo.2006.05.002.

Robinson, Arthur H. 1958. *Elements of Cartography*. New York: Wiley.

Schlossberg, Marc, and Nathaniel Brown. 2004. "Comparing Transit-Oriented Development Sites by Walkability Indicators." *Transportation Research Record: Journal of the Transportation Research Board* 1887(1): 34–42. https://doi.org/10.3141/1887-05.

Toronto Transit Commission. 1945. Rapid Transit for Toronto.

Tufte, Edward. 1983. *The Visual Display of Quantitative Information*. Cheshire, CT: Graphics Press.

van den Berg, Joris, Barend Köbben, Sander van der Drift, and Luc Wismans. 2018. "Towards a Dynamic Isochrone Map: Adding Spatiotemporal Traffic and Population Data." LBS 2018: 14th International Conference on Location Based Services, Peter Kiefer, Haosheng Huang, Nico Van de Weghe, and Martin Raubal, eds., 195–209. Cham, Switzerland: Springer.

Vasiliev, Irina. 1997. "Mapping Time." *Cartographica* 34(2): 1–51. https://doi.org/10.3138/d357-234g-2m62-4373.