NATIONAL INSTITUTE FOR CONGESTION REDUCTION

FINAL REPORT
MARCH 2024

Measuring Access Using Crowdsourced Travel Behavior Data

The Easy Button to Real Access and Equity?

**Phil Lasley, Olivia Wang, Jack Kong
Jordan Gregory, Carly Venditti**

National Institute for Congestion Reduction
University of South Florida
Center for Urban Transportation Research | University of South Florida

NICR
NATIONAL INSTITUTE FOR CONGESTION REDUCTION

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

Measuring Access Using Crowdsourced Travel Behavior Data

The Easy Button to Real Access and Equity?

Prepared by

Phil Lasley, Olivia Wang, Jack Kong
Jordan Gregory, Carly Venditti
Texas A&M Transportation Institute

Prepared for

National Institute for Congestion Reduction
University of South Florida
Center for Urban Transportation Research

4202 E. Fowler Avenue, ENG030, Tampa, FL 33620-5375
nicr@usf.edu

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Measuring Access Using Crowdsourced Travel Behavior Data –The Easy Button to Real Access and Equity?		5. Report Date March 2024 6. Performing Organization Code
7. Author(s) Phil Lasley, Olivia Wang, Jack Kong, Jordan Gregory, and Carly Venditti		8. Performing Organization Report No.
9. Performing Organization Name and Address Texas A&M Transportation Institute 3135 TAMU College Station, TX 77843		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 69A3551947136, 79075-00 SUB B
12. Sponsoring Organization Name and Address U.S. Department of Transportation University Transportation Centers 1200 New Jersey Avenue, SE Washington, DC 20590 United States National Institute for Congestion Reduction 4202 E. Fowler Avenue Tampa, FL 33620-5375 United States		13. Type of Report and Period Covered Final Report September 1, 2021 – May 31, 2023 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Integrating accessibility into transportation planning seeks to improve policy and programming decisions that ensure congestion mitigation measures, encourage transportation equity, and improve urban livability. Traditional accessibility measures and methods have largely focused on modeling and/or estimation procedures, displaying a hypothetical universe of access—not where travel actually occurs. This research developed a suite of measures to assess accessibility, taking advantage of available crowdsourced origin-destination data to identify accessibility from real data rather than a modeled approach. The measures are calculated for all U.S. urban areas to inform congestion-mitigation decision-making based on actual travel behaviors. The results of this work will help transportation planners and policy makers understand where access is (or is not) adequately provided to identify appropriate and innovative solutions for shifting travel behavior to more equitable and sustainable approaches. The 2021 Urban Mobility Report and website will include the results of the research.

17. Key Words		18. Distribution Statement	
Accessibility, access, performance measure, mobility, equity, gravity model, space-time, theory, contour, travel time, trips, origin, destination, probe data, H3			
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 89	22. Price

Acknowledgments

The research team would like to acknowledge and thank the staff at INRIX for generously providing the national Trips Dataset for this research. The partnership between private entities and public research is critical to the betterment of global transportation. This research would not have been possible without this support.

Table of Contents

Figures

Tables

Equations

Executive Summary

With the passage of the Infrastructure Investment and Jobs Act (IIJA) and other legislation, transportation equity—and access to opportunities in general—has been pushed to the forefront of transportation theory, planning, policy, and project prioritization. The illumination of inequities stemming from transportation planning practices that unfairly and unjustly isolated large populations from opportunities like housing, employment, recreation, health, banking and financial services, food, and transportation options opens an opportunity to address and correct past planning consequences—whether unintended or deliberate. The pursuit of increasing motor vehicle speeds, reducing congestion, and over-reliance on (good but limited) performance measures weakened some neighborhoods' access to opportunities while supplying suburbs or other areas with transportation improvements.

The Rise of Accessibility Theory

For most of transportation planning's existence, practitioners have heavily relied upon the concepts of mobility theory. This theory and the measures developed to capture its goals provided practitioners with a framework by which they could make informed transportation planning decisions with extensive effort and, at the time, limited available data. Concepts such as speed, delay, reliability, and many others connect well with lay audience and policy makers—connecting lived commuting experiences with the theory of the ease of movement between two points.

During the same period that many mobility concepts were developed, a complementary theory, accessibility, was also being developed. While mobility focused attention on *the ease of movement between two points*, accessibility focused on *the broader ability to reach as many places as possible within a given time*. Accessibility promised to encompass several concepts more broadly because of its many benefits.

In theory, accessibility offers planners and practitioners a potential tool to begin to address equity and transportation concerns from a different perspective than traditional delay-based mobility measures usually provide. This is because accessibility incorporates many additional variables into the concept that provide significant benefits to the theory.

The Benefits to Accessibility

Accessibility as a concept offers several potential benefits to the transportation planning process.

- **Broader and More Inclusive Concept:** Accessibility encompasses several overarching principles in transportation and land use planning and is sensitive to changes in most subconcepts. The theory also provides more explanatory power to real-world events.
- **Land Use/Development Investment Inclusive:** Accessibility holds a direct connection to land use *and the economic decisions driving them*—independent of many traditional transportation concerns.
- **Mode-Neutral:** While many other concepts could be configured to be mode-neutral, accessibility inherently or easily considers modes and mode shifts. Even if data are part of a single mode, the results would highlight the need for modal inclusion.
- **Sensitive to Equity Concerns:** Accessibility purports to be sensitive to equity issues by building in the issues into many of its measures. Additionally, many measures that specifically target equity could be built into specific goals.

The Downside to Accessibility

While the concept of accessibility boasts many benefits, there are several issues with accessibility—and more importantly, its measures—that likely hinder the concept's uptake and use (Lasley et al., 2019).

- **Difficult to Explain:** Most accessibility measures are difficult to explain in concrete terms to lay audiences, policy makers, and even other transportation professionals. This quickly becomes problematic, as measures fail to easily relate to people's lived experiences and are hard to teach without the use of visuals and prior conceptual knowledge—inhibiting broad adoption.
- **Difficult to Calculate:** Many measures use complex formulas and require knowledge of advanced statistics, GIS, or modeling techniques to correctly calculate. Additionally, some measures are so involved they require an agency to hire full-time staff or an outside consultant to create.
- **Lack of or Difficulty Working with Data:** Many measures require the use of data that are rare, difficult to obtain, or simply do not yet exist. In many cases, expensive data purchases or travel surveys must be bought or performed to obtain a sample of data. If data are available, they often require intense manipulation, adding to the calculation difficulties.
- **Difficult to Operationalize, Create Policy, or Set Targets:** When measures are calculated, they fail to translate to policy goals and targets. Comparisons over time to measure changes or performance require additional calculation efforts, and values rarely connect directly to clearly defined accessibility goals. Agencies must also then integrate measures into project programming and selection processes.
- **Fundamentally Flawed—Based on the Hypothetical:** Finally, location and travel choices are far more complex than access alone. Existing measures describe a hypothetical universe of potential travel—not real travel decisions. An increase or decrease in accessibility does not account for actual decision making; it shows an increase or decrease in hypothetical destinations to which travelers *could* go.

What Makes a Good Measure?

To simultaneously capture the many benefits of accessibility and address the issues with its measures, it is helpful to understand what makes a good performance measure. The following can be used as targets for any new measure (accessibility or otherwise) (Prat and Lomax, 1996).

1. **Good Measures Are Easy to Calculate:** The best measures—even complex ones—are simple to calculate from readily available data and then teach to others. Complexity often stems from data, statistical, or other nuances that increase its difficulty, but the hallmark of a good measure is that these complicating factors can be stripped away and still reveal a simple construct. This allows agencies to easily pass on knowledge about calculation, use, and context quickly and efficiently to others.
2. **Good Measures Are Easy to Explain:** A good measure will be simple to explain in theory, outcome, and application to all audiences—regardless of their subject matter knowledge. While effective communication with other audiences is key, a good measure will lend itself to simplification without loss of impact or nuance. Additionally, explaining good measures should elicit lived experiences.
3. **Good Measures Are Easily Used to Create Policy, Targets, and Goals:** A critical attribute of good measures lies in their ability to be operationalized and used from a practical standpoint *within the correct context*. These practical applications include the ability to create policy based on measures and their outputs or outcomes; the ability to set reasonable, understandable, and realistic targets; and the ability to set goals based on those targets. Additionally, an ideal measure would provide the ability for comparison with peers—something many measures either do poorly or do not do at all.

4. **Good Measures Are Grounded in Real Behavior:** Finally, a good measure must be grounded in real and observed behavior. Any measure must reflect reality in some way to be effectively used for policy, planning, programming, or simply measuring the intended behavior.

Project Purpose

This project seeks to address the primary issues with accessibility and its current performance measures by examining existing measures, newly available crowdsourced data, and the issues listed above to create a new set of accessibility or accessibility-like measures that are grounded in actual and observed travel behavior that satisfy many—if not all—the hallmarks of good measures. These performance measures will then be integrated into the Texas A&M Transportation Institute's (TTI) Urban Mobility Report (UMR) as a new chapter on access and sustainability. The principal intent of this work lies in working toward two primary goals:

1. To better integrate the important concepts of accessibility into transportation planning and congestion mitigation at all levels of planning and governance—on par with the way mobility and delay-based measures are integrated into the planning process.
2. To promote the use of alternative mobility and congestion mitigation strategies, alternative modes, and development patterns to combat congestion, low levels of access and mobility, and improve overall transportation and social equity throughout the United States.

Both goals and project outcomes promote the use of innovative theory, mobility platforms, and data to battle congestion and simultaneously encourage equity sensitive or neutral transportation solutions. The use of innovative data and data-driven solutions will improve the quality of congestion monitoring and mitigation by allowing underused but valuable established theory to be more readily integrated into the planning process.

Assessment of Accessibility Concepts and Measures

While accessibility is a key concept in transportation planning, it has been defined and operationalized in different ways. Usually, accessibility refers to the extent to which the land use and transportation system allows people to reach activities, opportunities, and destinations by a certain transportation mode (cognizant of either ignoring or incorporating the impact economic and investor development decisions hold on land use and transportation systems). Generally, accessibility can be measured from two perspectives:

1. **The Perspective of Origins –** Based on a single origin or grouping of origins and the destinations accessible to them under a time constraint and illustrated by the number of grocery stores within a 30-minute travel time of one's house.
2. **The Perspective of Destinations –** Based on the number of origins or populations within a given distance or time from a single destination or group of destinations and illustrated by the number of low-income people within 0.5 miles of a light rail line.

Both perspectives have important implications for guiding and evaluating transportation and land use planning strategies: origin-based measures identify important social and economic opportunities while destination-based measures guide and optimize facility and opportunity locations.

Accessibility can also be viewed as person-based and location-based, depending upon the need. The nature of accessibility is impacted by several factors: the transportation system and its surrounding land use, transportation modes, time constraints, individual constraints, and individual capabilities.

Available Accessibility Measures and Their Prevalence of Use

Just as accessibility has been split into many components and perspectives, scholars (e.g., Geurs and van Eck, 2001; Geurs and van Wee, 2004; Halden et al., 2000; Kwan, 1998) have categorized accessibility measures into six distinct categories in practice.

1. **Infrastructure-Based Measures:** Primarily measure the transportation component of accessibility, exclusively focusing on performance, service level, and availability. These ignore the land use component and do not consider the characteristics of the destination locations, such as size, attractiveness, and quality. On the surface, these are similar to delay-based mobility measures.
2. **Distance-Based Measures:** Measure transportation connectivity between two points or places. These could be as simple as average straight-line distance or complex route-directness of transit.
3. **Contour Measures:** Count the number of destination activities or populations serviced within a given threshold of travel time or cost. These are usually displayed as contour maps that show a maximum distance from a single point accessible within the threshold.
4. **Gravity-Based Measures:** Measure the relative attractiveness of opportunities or the potential interaction of opportunities with a population under given constraints. These widely used but complex measures can incorporate many variables and are generally what are used to demonstrate access.
5. **Space-Time Measures:** Measure an individual's ability to move through space and time along a potential path area based on several constraints. These are similar to a combination of gravity and contour measures but focus on individuals rather than locations.
6. **Utility-Based Measures:** Measure an individual's perceived utility for choosing a specific set of transportation choices. Often considered the most complex, they generally provide mode choice.

Throughout the review of various accessibility measures, each measure was found to have advantages and limitations in measuring accessibility as a construct. Planners predominantly use location-based measures (infrastructure-, distance-, contour-, and gravity-based measures) in practice, as they hold important implications for informing transportation planning and land development policy. The location-based measures could be calculated from both the origin perspective to evaluate residents' access to destinations and the destination perspective to assess the number of residents served by a destination. These measures also could be calculated and compared for different travel modes and socioeconomic groups. However, location-based measures fail to reflect personal abilities and preferences. The person-based accessibility measures (space-time and utility-based measures) take individual characteristics into account but have intense and unrealistic data requirements, so are rarely used.

Emerging Data for Measuring Accessibility

The emergence of new data sources, such as mobile device probe data, location-based social media data, and public transit smart card data, provides a valuable opportunity for transportation researchers, planners, and practitioners to develop new location-based accessibility measures applicable to larger scales and reflective of actual travel behavior and individual or group preferences. Compared to traditional surveys and travel diaries, these datasets are more cost effective, offer valuable insight into human mobility for constructing accessibility measures at a large spatial-temporal scale, and provide opportunities for conducting dynamic analyses of accessibility with the consideration of temporal variation.

Application of Mobile Device Data in Measuring Accessibility

Although an increasing number of scholars have used mobile device data to study travel behavior, the application in constructing accessibility measures is relatively limited. Those studies predominantly focus on identifying travel and activity patterns (e.g., Wang et al., 2018) and measuring human mobility. Other applications of mobile device data include the calculation of dynamic accessibility based on real-time traffic conditions using historical traffic service data provided by INRIX (Sweet et al., 2015) and the construction of activity space measures to study the monthly variation in activity space over time.

Overall, the application of mobile device data in measuring accessibility is very limited. Most calculated measures are individual-level activity space measures to evaluate the disparities in activity space among different social economic groups. This application often requires strong data analytics and coding skills and experience assigning trips to each person—practically infeasible to be applied in daily planning practices.

However, mobile trip and trip trace data (data that contain origins and destinations or trip paths, respectively) could be used to easily develop and use location-level accessibility measures to reflect actual travel behavior. Based on the literature and accessibility measure assessment above, researchers found and illustrated that mobile device data may have many advantages in constructing future accessibility measures because the data record actual travel behavior, can convey real-time travel conditions, contain the necessary information to construct intensive origin-destination (OD) matrix information for each trip or all trips (used in modeling), and can usually distinguish between freight and personal-use vehicles.

Theory Development

Upon completion of the review of available accessibility measures and the application of now readily available mobile device data, researchers began developing an updated approach to measuring accessibility with these new data sources in mind. Researchers set several goals to guide the development process, based on the characteristics of good measures and shortcomings in previous measures, by which any new accessibility or “accessibility-like” measures should be judged. Ideally, all these goals would be met; however, researchers understood that some may not be possible to achieve.

Measure Analysis and Development

Knowing that the most suitable and readily available data to State departments of transportation (DOTs), metropolitan planning organizations (MPOs), or local agencies would be trip data (trip start and end points only with varying accompanying attributes) or trip trace data (trip start and end points with network-routable path data), researchers assessed each existing accessibility measure for translatable attributes that would be conducive to using these new datasets. Ultimately, researchers simplified the many concepts of accessibility—under the given data constraints and goals—to four primary concepts:

1. **Coverage –** How much of an area is reachable by an origin or can be reached by multiple origins.
2. **Density –** How many trips start or end in a specific area (usable as a weight).
3. **Reach –** How far are trips on average from different origins or destinations.
4. **Trip Attributes –** Basic attributes assignable to each trip (e.g., actual or average time, vehicle type, time of day).

Combined, these four components make up the bulk of accessibility measures and mimic features of gravity-based, space-time, contour, and distance-based measures. However, attributes of utility-based measures still appear to be mostly out-of-reach due to their intensive use of unavailable data. While these four concepts fail to capture several accessibility-specific attributes, like the specifics of land use, modal options, and individual characteristics, those attributes could theoretically be incorporated into or in addition to these concepts.

Researchers developed the following measures for the three primary concepts scalable at either a subregional zone level or at an urban-area level. Table i lists the measures.

Table i. Summary of Newly Developed Accessibility Measures.

Concept	Zone-Level Measure	Urban Area-Level Measure
Coverage	Area Coverage Ratio (Origin)	Total Real Urban Coverage (Origin)
Coverage	Area Coverage Ratio (Destination)	Total Real Urban Coverage (Destination)
Density	Zonal Trip Origin Density	Area Trip Origin Density
Density	Zonal Trip Destination Density	Area Trip Destination Density
Density	Total Number of Trips per Zone	N/A
Reach	Average Zonal Trip Distance (Origin)	Area Reach (Origin)
Reach	Average Zonal Trip Distance (Destination)	Area Reach (Destination)
Reach	N/A	Average/Median Urban Area Trip Length
Reach	Average/Median Trip Time	Average/Median Urban Area Trip Time

Coverage

The concept of coverage most closely mirrors conceptual aspects of space-time, contour, and gravity accessibility measures—cumulative opportunities and activity space. This measure concept most closely mimics the most common accessibility measure used today: access to destinations in a given time constraint.

At the sub-urban area or zonal level, the **area coverage ratio (ACR_O)** represents the estimated percentage of an urban area that origins from each zone reach in a given time restraint. At the same scale but from a destination perspective, destination coverage **(ACR_D)** represents the estimated percentage of an urban area that a destination is reached by any number of origins under a given time restraint. At the regional level, **total real urban coverage (TRUC)** aggregates all ACR values for an urban area into a single value that represents an area's overall coverage.

From a policy perspective, target ACRs could be individually or globally set to increase the percentage of an area covered. This most reflects many of the goals of current accessibility measures. Conversely, the measures are flexible enough to allow planners and policy makers to create zone-specific goals that shrink over time if a more compact urban form is desired. Since both ACR and TRUC measures are normalized by the number of zones in an area, they can easily be compared to each other or to other peer urban areas.

Density

The concept of density is not overtly measured in traditional accessibility measures, though the idea is inherent in many types. Researchers chose to break this specific concept into its own, because while the coverage concept shows how much of an area can be reached, it fails to show the weight of that coverage; a single trip or thousands of trips to different zones are treated the same.

Origin-based trip density summarizes the number of trips originating from each zone as a percentage of all trips within the urban area, while destination-based trip density summarizes the number of trips terminating in each zone as a percentage of all trips within the urban area. Both measures reflect the activity density of each zone. **Area trip density**, an urban area-wide density measure, provides value at different planning and policy scales and must be calculated as a holistic value in relation to the number of zones.

From a policy and planning perspective, these measures' values are neither inherently good nor bad; they provide context and a proxy for transportation density that can be difficult to calculate or assess. At the zonal level, goals and targets can be set for different areas, like a central business district (CBD), specific neighborhoods, or other activity centers. Should a goal be to increase the relative density of trips in a specific neighborhood, that zone could be watched for an increase compared to a relative decrease in other zones. Area values can also be used to compare urban areas against one another, which becomes especially important when examining freight or commute shed movements. Like other measures, the values themselves are inherently neutral and rely heavily on contextual targets, goals, and policies to provide relevancy.

Reach

The final concept—reach—includes a duality of accessibility attributes that have been lightly addressed by other measures developed thus far but from a different perspective. Reach, like coverage, incorporates space-time properties but more closely follows the results provided by contour measures.

As most data sources (trip or trip trace) give a path distance with each trip (actual distance; not as-the-crow-flies), reach measures calculate the average path length of trips either within a zone or in aggregate. This importantly differs from coverage measures that focus solely on the accessibility of one zone to another in a given time but fails to consider how trips are fulfilled between the origin and destination. Reach offers the ability to identify the potential for alternate routes, inefficient networks, or connectivity issues that most other measures would not be able to identify. Thus, the measure could indicate a level of connectivity and network development in addition to compactness and self-containment for each zone.

Reach at the zone level is measured by the **average zonal trip distance** based on the average trip distances of origins beginning from a zone **($AZTD_O$)** or based on the average trip distances of destinations ending in that zone **($AZTD_D$)**. The urban area version, **area reach**, represents the entire region's trip distance aggregated up to a normalized value. Both measures are conveyed in miles; the lower the value, the shorter the distance—and more direct a path—travelers are moving to reach their destinations. These values are neither good nor bad; those determinations depend upon the policies, goals, and targets created by planners and policy makers.

Higher values of either measure would indicate a relatively sprawling pattern of development, fewer alternate routes, and limited connectivity. Lower values may indicate more compact or self-contained development, higher connectivity, and numerous route options. Even though an urban area may have a low value, it does not mean accessibility in general is low; it could represent high levels of compact development with relatively high access. When used in conjunction with ACR or TRUC, reach measures provide valuable context on compactness, connectivity, and network development.

Computational Methodology and Processing

This project ultimately consisted of two main components: theory/measure development and data processing. Figure i displays how these two components interacted with one another through the life of the project.

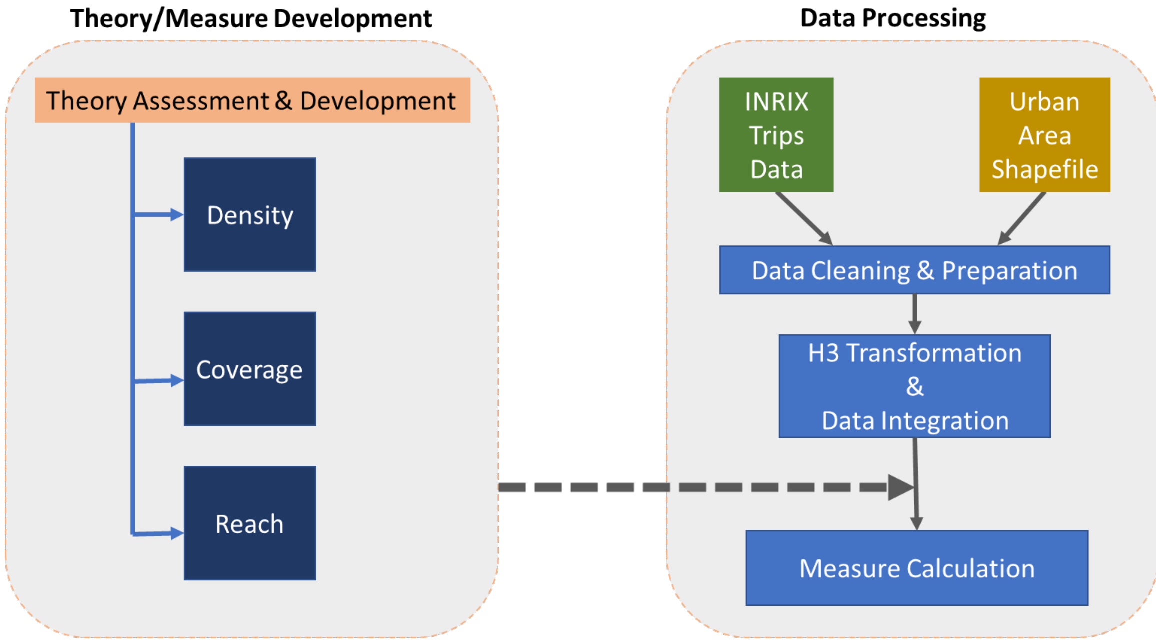

Figure i. Project process: theory and measure development in context with data processing.

Data Needs, Cleaning, and Preparation

As one of the goals of this research included reducing the data burden on users, researchers sought to minimize the amount of data required to calculate any measures produced. Ultimately, researchers determined the need to use only two data sources:

1. Origin-Destination trips data (provided by INRIX).
2. U.S. urban area spatial data (497 urban areas including 101 UMR urban areas).

Once researchers collected the data and inputted the data into an Azure cloud database, they then had to review and clean the data to minimize the number of potential issues when calculating the performance measures. Trips under 2 minutes and over 60 minutes were excluded from the data as the shorter trips were likely errors and the longer trips predominantly traveled outside of urban areas.

H3 Method

One of the major challenges in processing the billions of data points lies in the processing time and feasibility of using this data for accessibility calculations. Simply put, the trips dataset is so large that it hinders efficient calculation at a national scale.

Researchers also had to overcome the common zone conundrum: many accessibility measures (including the ones developed by this project) require the use of sub-city zones, like census tracts, block groups, or transportation analysis zones (TAZs) to measure intra-urban access between neighborhoods or districts. However, using these geographies is problematic: boundaries often change, they disallow the direct comparison with other urban areas, or they are too geographically large. Measures would work best with zones that are relatively stable, scalable, and universal across all U.S. urban areas.

To overcome this challenge, researchers chose to adopt Uber's Hexagonal Hierarchical Spatial Index (H3 method). H3 is a geospatial indexing system that divides the globe into hexagons at several resolutions that are geospatially pinned and do not change. After several tests, researchers chose a scale with hexagons 0.33 miles in length and an area of 0.28 square miles, which provided high resolution but fuzzied exact locations.

Data Integration and Measure Calculation

Researchers overlaid and clipped the H3 map to all U.S. urban areas and then assigned the trips data's start and end points to each hexagonal zone. From this point, researchers were able to easily program each performance measure's formula to generate values for each zone. Results were stratified by origin/destination orientations, time of day, trip length bins, and vehicle type. Researchers performed computational tests of each measure on the Austin, Texas, urban area to illustrate zone measures and then compiled values for all urban areas.

Zone Measure Results: Austin, Texas

Researchers chose to focus preliminary testing and assessment on the Austin, Texas, urban area as most of them live and work in the area and are familiar with its nuances and neighborhoods. While researchers assessed the results for logical cohesion to determine validity, since the measures reflect real behavior—barring any major data or computational flaws—the values are what they are. Researchers also performed a comparison with other accessibility maps of the region as available.

Since each measure has several user type and temporal variations, researchers chose to display the variations most relevant to likely audiences of the UMR and most alike to traditional accessibility maps. These include:

- **Accessibility Perspective:** Origins.
- **Time of Day:** All day.
- **Trip Length:** Trips less than 30 minutes.
- **Vehicle Type:** Consumer vehicles only.

Coverage

In Austin, the ACR_O reveals that the most accessible zones based on origins include the downtown area (also including the State capitol complex and the University of Texas campus [Figure ii[1]]). These zones provide access to approximately 65% of the urban area for trip origins and trips under 30 minutes. The zones with the highest access are concentrated in the north-northwest portions of the city known as the Domain and the Arboretum, which can reach approximately 74% and 70% of the urban area, respectively. These areas are known to be popular high-end residential, shopping, and employment centers (the Domain being a second CBD in Austin).

Another aspect of note with the ACR_O is the lack of access for many parts of the urban area. Many of the neighborhoods east of IH 35 cannot access much of the urban area compared to those well-built areas. These areas are historically segregated and low-income neighborhoods that were cut off from the city and its growth with the development of the interstate corridor. These areas of the city have ACR_O scores of 25% or less, indicating a significant transportation and access equity issue.

[1] Note that the black area in Figure ii represents geography outside the urban area and therefore outside the analysis zone. This could create a noticeable difference in the edge areas between Figure ii and Figure iii. However, this type of edge difference will occur regardless of geography used; urban areas have strict density rules that make this convenient as there generally is not much trip opportunity outside the boundary.

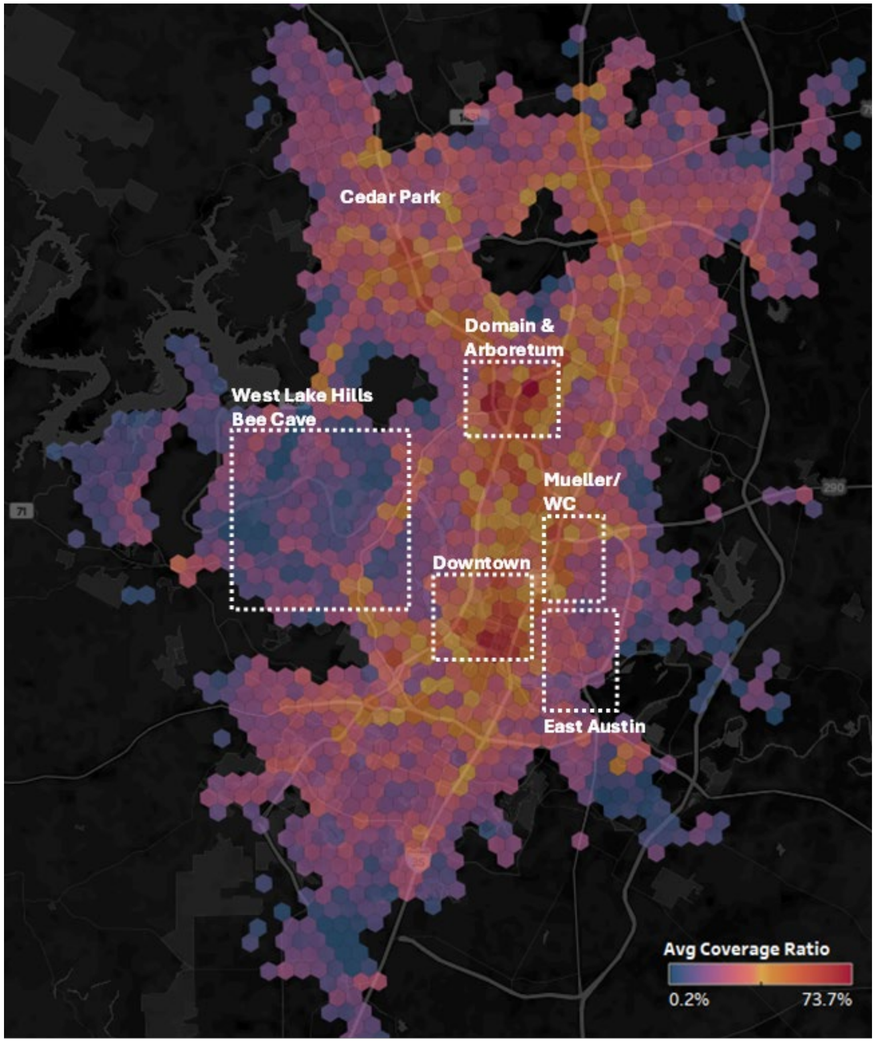

Figure ii. Area coverage ratio (origins) for trips under 30 minutes, Austin, Texas

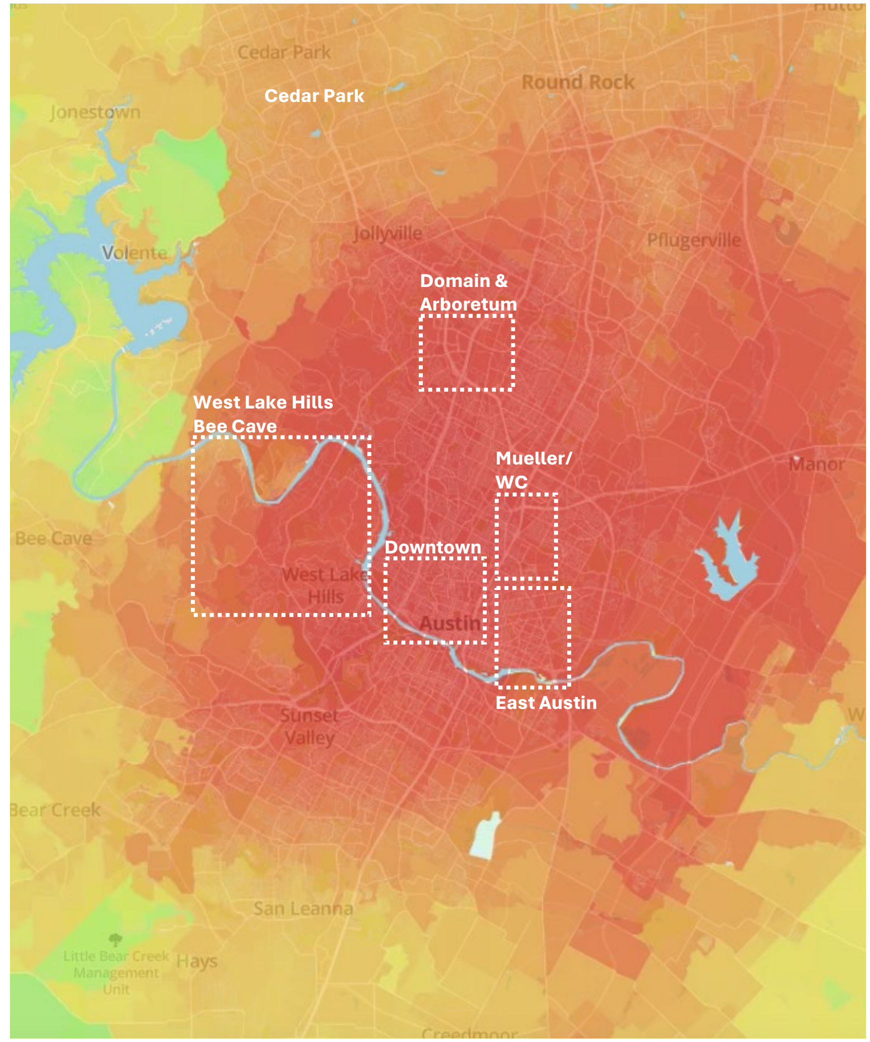

Figure iii. Auto accessibility to jobs within 30 minutes, Austin, Texas.

Comparison with a Traditional Measure

The ACR_O is most closely related to what is likely the most-used traditional accessibility measure: access to jobs within 30 minutes. Figure iii displays auto accessibility to jobs within 30 minutes in the Austin area during the same time period (2019) as the calcualted ACR_O measure (Owen & Murphy, 2021). One will quickly note that the two images differ significantly.

The traditional measure heavily inflates accessbility to Austin area employment from the access that actually occurred. This inlcudes neighborhoods isolated due to extreme topography and limited transportation network development. While spatially close to the Austin core, they are difficult to reach. These areas are also highly affluent areas where most residents have a significant amount of location choices. The traditional accessibility map also overstates accessibility to low-income and segregated neighborhoods. Referring again to areas east of IH 35, the map scores these areas with some of the highest accessbility ratings in the city. However, this access is unobserved in real behavior. This contradiction highlights a fundamental issue with traditional accessibility theory: it measures a hypothetical universe of access and fails to reflect actual access. In this case, transportation equity issues would be undiscoverable without extensive additional data.

Density

Meaures of density at the zone level show that the areas in and immediately around the University of Texas campus and downtown hold the highest density of trip origins, with values as high as 1.3% of all trips in the Austin area beginning at the university. Other hotspots were primarily limited to high-intensity retail and commercial office areas where multiple trips start and end throughout the day, though researchers believe further splits by time of day would separate these two from one another.

Notably, the only residential areas with any significant trip origin density were those located near commercial opportunities, such as along freeways and arterials, or that were located near high-activity centers. This would include downtown-adjacent neighborhoods; neighborhoods along South Congress Avenue, First Street, and Lamar Boulevard; areas with high-density apartment complexes; and areas near the commuter rail line.

Reach

In Austin, the ATD_O reveals areas of relative self-containment (where most trips likely occur close to home). This can clearly be seen in the areas in and around the University of Texas campus. Again, this area experiences a high density of trips, but many of these trips are likely to nearby locations, with the lowest average trip distance of 1.9 miles. The highest average trip distances were in areas with generally low coverage because of topography (hills and the north bank of Lake Travis) and areas on the outskirts of the city. This makes sense as they have the lowest amount of access to key destinations. Also, low-income areas (mostly to the east of IH 35 and the far southeast) have some of the longest trip distances, again revealing a transportation equity issue.

National Results

The new accessibility concepts and measures are just as useful at a national level as they are within an urban area. Researchers calculated urban area scaled measures for all urban areas in the United States and ranked the 101 urban areas used in the UMR by each measure. Additionally, the 15 “Very Large” urban areas (as defined in the UMR) were also ranked, as those are most reported using mobility measures.

Coverage

Total real urban coverage (TRUC) describes coverage at larger scales and is similar to the ACR but reports the percentage of an urban area that can be reached in a single value for an entire region. Table ii displays the top 10 of the 101 UMR urban areas for coverage in 2019. The table can be read as: "In 2019, consumer vehicle trips that begin in Laredo, Texas, can reach 78.6% of the urban area within 30 minutes."

Table ii. Total Real Urban Coverage (Origins) for UMR 101 Urban Areas

Rank	Urban Area	*$TRUC_O$	Reach (Miles)
1	Laredo, TX	78.6%	4.0
2	Boulder, CO	72.6%	3.1
3	McKinney, TX	58.4%	3.8
4	Bakersfield, CA	57.6%	4.4
5	Salem, OR	53.2%	3.9
6	Fresno, CA	51.8%	4.8
7	Brownsville, TX	51.4%	4.4
8	Stockton, CA	50.3%	4.5
9	Boise City, ID	48.5%	4.2
10	Eugene, OR	48.0%	4.2

*Total Real Urban Coverage (See page 38 for further description of TRUC).

These results convey two distinct messages. First, some urban areas represent small to medium-sized cities with well-developed roadway networks and (likely) relatively low issues with mobility. These would include places like Laredo, Brownsville, Stockton, and Fresno. The higher reach values indicate travelers are traveling further to reach accessible destinations.

Second, some small to medium-sized urban areas represent more compactly developed areas that may benefit from their land development patterns. Boulder, Salem, McKinney, Boise, and Eugene all have relatively low reach values, but travelers can still access a high percentage of the urban area.

Density

Area trip density (ATD) describes the concept at the urban scale. In this case, ATD reports the average number of trips that begin per zone in an urban area. While similar to zonal trip density, ATD does not average zone densities on their own (i.e., an average of an average). Table iii displays the top 10 of the 101 UMR urban areas and their ATD values for 2019. The table can be read as: "Laredo, Texas, averaged 7,700 consumer vehicle 30-minute-or-less trip starts per zone in 2019."

Trip densities here can be viewed as a function of the urban area's population and development density and the likelihood of many smaller trips. The Los Angeles area is known for being one of the densest urban areas in the United States; it is no surprise it and others like San Jose, San Francisco, and New York saw high ATD scores.

Table iii. Area Origin Trip Density for UMR 101 Urban Areas

Rank	Urban Area	Trip Density
1	Laredo, TX	7,700
2	Los Angeles--Long Beach--Anaheim, CA	7,229
3	San Jose, CA	6,085
4	Las Vegas--Henderson, NV	5,605
5	San Francisco--Oakland, CA	4,748
6	New York--Newark, NY--NJ--CT	4,729
7	Miami, FL	4,628
8	Dallas--Fort Worth--Arlington, TX	4,604
9	San Diego, CA	4,578
10	McKinney, TX	4,298

Reach

Finally, area reach describes this concept at the urban scale. Area reach represents the average trip path length for the urban area and is expressed in miles. Table iv displays the top 10 of the 101 UMR urban areas for reach in 2019. The table can be read as: "In 2019, consumer vehicle trips of less than 30 minutes starting in Tulsa, Oklahoma, could travel an average of 5.8 miles."

Table iv. Area Origin Reach for UMR 101 Urban Areas

Rank	Urban Area	Reach
1	Tulsa, OK	5.8
2	Louisville/Jefferson County, KY--IN	5.8
3	Jacksonville, FL	5.7
4	Columbia, SC	5.6
5	St. Louis, MO--IL	5.6
6	Minneapolis--St. Paul, MN--WI	5.6
7	Little Rock, AR	5.6
8	Birmingham, AL	5.6
9	Jackson, MS	5.6
10	Memphis, TN--MS--AR	5.6

Like other measures, the top 10 follow a pattern: medium-sized and low-density urban areas with well-developed transportation networks and generally many freeway and interstate options.

These high-reach values indicate a level of motor vehicle accessibility likely due to decades of realized transportation priorities and freight movement. Several of these areas also have geographic constraints (rivers/bridges or protected areas) that may lengthen travel.

Next Steps

The development of this new theoretical framework and accompanying accessibility measures would be incomplete without the implementation and adoption of the theory and measures in real and practical applications. To do so, researchers plan to disseminate this research through several avenues:

1. Add a new chapter to TTI's Urban Mobility Report (UMR) with accompanying data visualization (https://mobility.tamu.edu/umr/congestion-data/).
2. Promote and publish in academic settings.
3. Speak at conferences, webinars, and other venues.

Furthermore, researchers plan to continue this research and expand the scale and scope of the theory and measures developed through the project. Additional research on this topic will amplify the reach of the implementable products exponentially over time.

Conclusion

While new developments in accessibility performance measurement could greatly impact how planners, policy makers, practitioners, and the public view transportation—especially considering how it interacts with land use—there is still no direct connection between access and equity, similar to mobility concepts' lack of connection. There have yet to be practical recommendations for using performance measures to truly impact transportation equity in a manner that is simple to implement and fits well within the entrenched transportation planning and programming framework.

This lack of connection stems from the issue that transportation equity, livability, and other similar concepts have yet to be adequately defined and operationalized in transportation terms. Multiple definitions, theories, and perspectives on transportation equity paralyze planners, practitioners, and policy makers into relative meaningful inaction. Both mobility and accessibility concepts could be operationalized in an equity-sensitive manner depending upon how equity is defined and how measures are used within specific contexts.

Researchers hope that progressing accessibility theory into one that reflects real behavior, is easy to measure, and simple from which to set policy, will ultimately push the discussion of transportation equity forward. Accessibility holds much promise—when used in context and appropriately with other concepts like mobility, reliability, and connectivity—to address many transportation equity concerns. Providing those responsible with the proper tools to make better transportation and land use decisions will set them up for success in the long term.

At the end of the day, planners and other transportation professionals need to make complex programming and investment decisions and therefore will rely on those performance measures that aid in the decision-making process.

Chapter 1. Introduction: The Push for Equitable Access

With the passage of the Infrastructure Investment and Jobs Act (IIJA) and other legislation, transportation equity—and access to opportunities in general—has been pushed to the forefront of transportation theory, planning, policy, and project prioritization. The identification and recognition of both historic and present transportation inequities have illuminated issues with transportation planning practices that unfairly and unjustly isolated large populations from opportunities: housing, employment, recreation, health, banking and financial services, food, and transportation options. This reduction in access to opportunities (accessibility) has hindered the equitable growth of various communities, causing instabilities that ripple throughout the U.S. economy and social fabric. All of this opens an opportunity to address and correct access and equity issues.

While deliberate action or willing ignorance caused a great deal of this inequitable growth, unintended side effects from and the ill-informed use of auto-centric transportation performance measures, transportation policy targets, and simply the way we have often "done planning" greatly worsened social and transportation equity and access to opportunities. The pursuit of congestion reduction, the impulse to increase motor vehicle speeds, and the appeal of the American Dream through suburban living, along with several other factors, pushed transportation planners to develop and adopt mobility theories and performance measures that, when used in isolation and lacking context, prioritized transportation projects that favored urban sprawl, weakened neighborhood bonds, and ultimately made travel for many populations much more difficult.

The Rise of Accessibility Theory

For most of transportation planning's existence, practitioners have heavily relied upon the concepts of mobility theory. This theory and the measures developed to capture its goals provided practitioners with a framework by which they could make informed transportation planning decisions with extensive effort and, at the time, limited available data. Concepts such as speed, delay, reliability, and many others connect well with lay audience and policy makers—connecting lived commuting experiences with the theory of the ease of movement between two points. Additionally, planners could more easily estimate missing data with greater confidence for mobility measures than with other theories' measures.

During the same period that transportation researchers developed many mobility concepts, a complementary transportation theory was also being developed. While mobility focused the attention on *the ease of movement between two points*, accessibility focused on *the broader ability to reach as many places as possible within a given time*. Simply put, accessibility refers to a traveler's overall ability to reach desired destinations or activities (often summarized to how many desired destinations one can reach in a given period of time). But this theory, while more encompassing and showing great promise to the transportation community, has gained little traction with practitioners.

The Benefits of Accessibility

Before discussing why accessibility concepts failed to take off like mobility concepts, one should understand why accessibility offers many benefits to transportation planning.

Broader and More Inclusive Concept

Researchers and planners generally view accessibility as a broader, overarching concept of true transportation and land use planning than other concepts like mobility, reliability, or connectivity. Accessibility by its nature includes all those concepts within itself to some extent—especially mobility—and can be sensitive to changes in any of those subcategories that might not be picked up in the subcategory itself (Handy, 2002). For example, policies, projects, or processes meant to increase mobility or connectivity will also generally increase accessibility within that area by making more destinations reachable, but it is also possible to have neutral or negative impacts to mobility or reliability and still have good access. A good example of this could be seen in a congested neighborhood where there is convenient access to a variety of important destinations such as grocery stores, schools, and parks.

Additionally, accessibility concepts impact or are impacted by a broader set of variables, making the concept more flexible to measurement, explanatory power of real-world happenings, and use cases in addressing both transportation and land use issues. But with this broader set of variables comes more complexity that may help explain, in part, why accessibility has not been more actively pursued by planners and other transportation decision-makers.

Land Use/Development Investment Inclusive

Likely one of accessibility's greatest benefits is the concept's direct connection to land use. Changes in land use *and the economic decisions driving them*—independent of any traditional transportation concerns—directly impact the accessibility of travelers. For example, the construction of a new grocery store in a food desert (generally not considered to have much to do with transportation and would not be recognized as a transportation issue) would have a dramatic impact on the accessibility of a neighborhood's residents to groceries. This would then trickle down to the traditional transportation planning sphere by showing shorter trip times, potential mode shifts, and either an increase or decrease in speed and delay. Impacts to system reliability and operations may also be seen as fewer trips are made over longer distances, easing pressure on other network facilities or systems.

Mode-Neutral

While mobility, reliability, and other transportation concepts can all be technically classified as "mode-neutral," only accessibility directly accounts for shifts in mode share as an integral part of the concept. For example, a neighborhood with many nearby destinations may have poor mobility and high congestion when viewed solely through the lens of motor vehicles, but nearly all mobility measures would be capable or sensitive to trips made via other modes due to their relative location to the origin. While a person's trip may last 20 minutes regardless of mode, it may be more advantageous or desirable to walk or bike instead of drive—especially when examining door-to-door travel times.

While efforts to develop mode-sensitive or mode-neutral performance measures have introduced some success, traditional mobility performance measures still rely heavily on motor vehicle traffic. Planners, researchers, and practitioners rightfully argue that motor vehicles dominate the overall mode share and most trip types (FHWA, 2017), alternate mode use may be dramatically more prevalent in meso- or micro-scale applications, such as large urban centers, central business districts or specialty planning districts, historic neighborhoods, pre-war commercial and neighborhood centers, and newer transit-oriented development projects. A failure of mobility measures lies in accounting for these areas and treating them either as unique oddities or islands to be lumped into a single mass origin.

Sensitive to Equity Concerns

While all the previous benefits place accessibility in a unique position to greatly improve transportation planning, none of them compare to accessibility's *proposed potential* to address social and transportation equity concerns over other transportation concepts. Access to affordable housing and that housing's ability to access food, banking, employment, and a host of other community resources has become a top priority for equity and social justice within the urban planning and transportation discussion. Accessibility purports to be sensitive to these issues and crafting existing accessibility measures to specific equity goals or outcomes may be possible. More research will be needed to make adequate connections between accessibility and transportation and social equity, but the future looks promising.

The Downside to Accessibility

While the *concept* of accessibility boasts many benefits, planners and practitioners have been unable to properly operationalize accessibility planning into the transportation planning processes, policies, and general thinking of the practicing profession. But why? The theory has been around nearly as long as others and holds immense potential; however, there are several issues with accessibility—*and more importantly, its measures*—that likely hinder the concept's uptake and broader use (Lasley et al., 2019).

Difficult to Explain

While the broad definition and explanation of accessibility is relatively straightforward and easily understood, deeper concepts and its measures are not. Accessibility measures, such as gravity models, utility measures, constraint-based measures, and others, are extremely difficult to describe in concrete terms to lay audiences. At times, it can even be difficult to explain or discuss concepts of these measures to other professionals. This quickly becomes problematic, as measures fail to easily relate to people's lived experiences. This is a legitimate issue that needs to be addressed if accessibility is to become a commonly used concept.

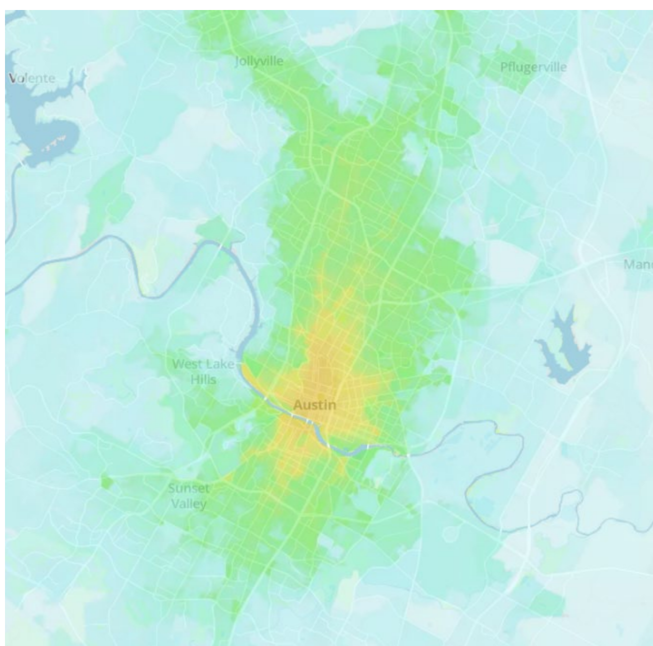

Figure 1. Jobs accessible within 30 minutes in Austin, Texas, 2019.

Additionally, many measures require the use of a map—either a heat map or contour lines—or some sort of complex model to convey meaning. While maps and diagrams provide visual interest, they fail to succinctly convey meaning to the viewer. For example, a heat map (Figure 1) showing the transit accessibility of an area might intuitively make sense at some level: deeper red colors indicate higher access to employment opportunities via transit while green colors indicate lower access to employment via transit (Owen & Murphy, 2020). However, if one were to ask for a more detailed explanation of how the map was created and what the various colors mean, it becomes exponentially more difficult to explain without requiring prior advanced knowledge in accessibility, transportation theory, and math.

This difficulty to explain measures and their meanings extends in many directions. First, the inability to rapidly explain measures to policy makers reduces their impact in explaining the transportation-land use interactions and their ability to be implemented (discussed later). Policy makers generally have little knowledge of accessibility theory—let alone the nuances of its measures or the measures' meanings—so any difficulties in comprehension usually mean it won't be useful to broader discussions. Second, their lack of meaningfulness to a lay person's lived experience (compared to other mobility measures like delay, the travel time index [TTI], or the planning time index [PTI]) will generally keep them from being adopted as a means of describing transportation concepts. Note that the "desert" concept describing the absence of a service within a reasonable distance does exist in common vocabulary, but directly tying this concept to a specific measure (like delay and traffic congestion) does not exist. Third, the difficulty in explaining measures to other professionals ultimately hinders their broader adoption by cities, metropolitan planning organizations (MPOs), or State departments of transportation (DOTs). These entities often have high turnover in staff who calculate and use performance measures for planning, programming, and project selection. A broad gap exists between longstanding institutional knowledge of concepts and how to properly use those concepts (i.e., it isn't enough to know what a measure is or means unless one also knows how to interpret and use the measure in the broader planning, programming, and project selection process). Therefore, measures must be simple enough to quickly understand and relate to the policy goals and targets used by transportation decision-makers.

Difficult to Calculate

Even if accessibility measures are well explained and generally understood by practitioners, most are prohibitively difficult to calculate in a meaningful way. Most accessibility measures require the use of advanced planning models, geographic information systems (GIS), statistics, or advanced math in addition to comprehensive academic understanding of the concept to calculate each measure correctly. This usually requires the use of specialized and expensive outside consultants or at least one FTE (full-time equivalent) employee with specialized understanding of the measures and how to use them. Many cities and MPOs lack the resources and human capital to dedicate to accessibility measure production.

Only the largest urban areas or State DOTs with dedicated modeling and forecasting departments are generally able to calculate accessibility. This on its own creates an inequitable situation in that many smaller urban areas or departments lacking the proper size and resources are unable to use measures that may better address transportation equity. In essence, equity in the transportation planning process is relegated to the "Haves" in yet another way.

Lack of or Difficulty Working with Data

Accessibility measures suffer a similar fate as all other transportation measures when it comes to data—or lack thereof. Likely one of the most relevant reasons mobility and delay-based measures were broadly adopted over the last several decades is that data could be relatively easily estimated, even though the ideal data did not yet exist to calculate the measures properly and precisely. The data required to properly or even roughly calculate the simplest accessibility measures remain difficult to acquire or still do not exist. Datasets with high geospatial granularity, data that describe multiple travel modes, and data that provide high-resolution land use or specific services (e.g., banks, grocery stores, childcare facilities, etc.) may still not exist.

Data that do exist are often highly aggregated or only exist at micro-geographic scales based on surveys or small samples. Issues such as cost, privacy concerns, and difficulties in collecting and updating all contribute to the lack of suitable datasets. This relegates many accessibility measures to the modeling and forecasting realm of transportation planning where many of these issues are resolved through planning models for an urban area. This leaves a substantial gap for state and regional planners who would appreciate statewide or regionwide measures at meso- or micro-scales. Where comprehensive data do exist, they usually lie behind the paywall of a private data aggregator. While State DOTs and MPOs are recognizing the need to buy large datasets from private entities, their limited budgets prioritize data that can be used in multiple other ways—something not easily accommodated by many accessibility measures' data needs.

Difficult to Operationalize, Create Policy, or Set Targets

In rare cases when accessibility measures are regularly produced, they often go unused or underutilized by planners and policy makers due to their difficulty to be operationalized. Closely related to the issue of being difficult to explain (recall Figure 1), planners and policy makers may receive accessibility measures but find difficulties in their interpretation and application. Like any other measure, it is one thing to have the measure and it is a different thing to know what it means or what to do with it.

Additionally, the nature of many accessibility measures' values makes the process of selecting targets and crafting policy incredibly difficult. For example, is it better to invest in a highly populated area where there is already high accessibility, or would it be more advantageous to invest in a sparsely populated area with low accessibility? A policy maker can surely say they want accessibility to increase, but what values would they point toward with certain confidence to make that a reality? To what values can targets be set? Again, in the delay-based mobility measurement realm, policy makers can easily set policy and target values of TTI and PTI measures based on a common understanding of the measure and a *relative agreement* of what constitutes an acceptable level of congestion or delay. Additionally, progress toward those goals can easily be determined over time. While some accessibility measures do offer this ability, many do not.

Fundamentally Flawed—Based on the Hypothetical

Finally, accessibility measures operate under a fundamental conceptual flaw: at this point, all accessibility measures only measure a hypothetical universe of potential travel—not real travel decisions. This is critical in evaluating accessibility because even if all other issues with accessibility measures are addressed, the outputs of those measures would still only be measuring an increase or decrease in hypothetical destinations to which travelers *could* go. They fail to measure actual decision-making. This is a serious issue, because while travelers may have numerous destinations accessible to them, they only will functionally travel to a few places—some of which may be outside the zone of what is accessible.

This conceptual flaw rests on two fallacies often seen in transportation theory:

1. **People Make Rational and Transportation-Based Choices.**
   Transportation researchers, planners, and practitioners often fall into the trap of thinking that people solely make housing location choices and travel choices based on transportation factors. These could include current congestion, estimated travel time, travel costs, need or desire to make the trip, access to transportation facilities, or even access to destinations; however, while these do play a role in the decision-making process, research has shown they play a mid-level role at best. People often make

seemingly irrational choices when viewed through a transportation lens although the decision may be incredibly rational. For example, a transportation planner may view a housing location decision through a lens of being close to one's job or access to transit. However, the individual may consider aspects such as home price and affordability, being a two-income household, availability of nearby family for childcare, elements of the home that are appealing, neighborhood aesthetic and reputation, safety, proximity to friends, or local school quality (Lasley, 2017).

2. **People will Naturally "Self-Contain" their Behavior.**
   This second fallacy stems from the largely failed concept of jobs-housing balancing—the idea that if a community balances the amount of housing with a similar amount or mix of employment opportunities, people will live close to work and shorten their trip length. This theory can be seen in the wild as "Live, Work, Play" developments. The issue stems from the belief of self-containment—people will naturally select to live close to where they work in a "self-contained" manner. However, much like the first fallacy, people's choices are complex and priorities change over time. While some longer trips may be replaced with shorter trips, people's jobs or life situations may change over time, requiring once-ideal self-containment to vanish (Blumenberg & King, 2021).

The impact of these two fallacies on accessibility reveals that while increasing the hypothetical universe of accessible destinations to a population may provide some benefit, understanding real behavior—or the trip origins and destinations of travelers—will likely provide a more accurate window into a populations universe of realized destinations and choices. In turn, this will impact and progress equity efforts in a more meaningful way. However, all this must be congruent with all planning decisions having both positive and negative impacts on society. People want different housing, transportation, and amenity options: a decision to focus on one may create "winners'' but will also create "losers" regardless of intention.

Better Measures in Transportation Planning

While the discussion of both accessibility and mobility measures to this point may paint a relatively bleak picture, these attributes should be used to shed light on solutions and steps forward. Many good performance measures do exist and when used appropriately, can be powerful tools in shaping the built environment towards an equitable future. Therefore, it would behoove a planner and practitioner to understand and recognize what makes a "good" performance measure—of any theoretical background.

What Makes a Good Measure?

There are several markers of a good performance measure that should be recognizable regardless of what it is measuring theoretically. Consider the following and critically examine a simplified non-transportation measure as the following are discussed (Prat and Lomax, 1996).

1. **Good Measures Are Easy to Calculate.**
   While the best measures may seem complex on the surface, the theory and concepts driving them will usually be easily understood and explained. Complexity often comes from nuances driven by data, statistical issues, or other outside forces that increase the difficulty. However, the hallmark of a good measure is that these complicating factors can be stripped away and still reveal a simple construct.

   Another factor is that good measures require that data exist and are accessible to the user. If data cannot be easily acquired, proxy data or estimates that are easily obtained or calculated must be available. If neither of these are true, then the measure cannot be calculated and it must reside in the realm of potential until data do exist.

Finally, a good measure will be easy to teach others and will require little accessory knowledge for calculation. From a practical perspective, a good measure should require little specialized training in theory or concepts, allowing for a novice to follow a well-annotated formula. This will allow agencies to pass on knowledge about calculation, use, and context quickly and efficiently to others who may step into a role and reduce the need for outside consultancy.

2. **Good Measures Are Easy to Explain.**
   A good measure will be simple to explain in theory, outcome, and application to all audiences—regardless of their subject matter knowledge. While much of this relies upon the explainer's ability to effectively communicate with other audiences, a good measure will lend itself to simplification without loss of impact or nuance. This simplification must also include a flexibility to use terms understood by different audiences, such as policy makers (who must understand the concept quickly, a measure's practical use, and the implications of its use), lay person or the public (who likely have no transportation knowledge and must connect concepts with lived experiences), or practitioners with varying technical vocabularies (like engineers or transportation-adjacent professionals who may be able to handle more nuance and complexity but in terms they understand).

   Additionally, a good measure should be able to be explained in a manner that elicits lived experiences, regardless of audience or knowledge level (e.g., delay measures and their direct connection to congestion or access to [specific types of services] and their connection to an actual thought of those destinations near where someone lives).

3. **Good Measures Are Easily Used to Create Policy, Targets, and Goals.**
   A critical attribute of good measures lies in their ability to be operationalized and used from a practical standpoint *within the correct context*. These practical applications include the ability to create policy based on measures and their outputs or outcomes; the ability to set reasonable, understandable, and realistic targets; and the ability to set goals based on those targets. All these require that measures can be tracked over time in a consistent manner and be used in contextually relevant cases.

   Additionally, an ideal measure would provide the ability for comparison with peers—something many measures either do poorly or do not do at all. While there's wisdom in the adage "The only one you should compare yourself to is yourself," many policy makers and planners still and will always attempt to compare their community with other peer communities—even when directly told not to make the comparison.

4. **Good Measures Are Grounded in Real Behavior.**
   Finally—and most importantly—a good measure must be grounded in real and observed behavior. Any measure must reflect reality in some way to be effectively used for policy, planning, programming, or simply measuring the intended behavior. Measures that reside in conveying a hypothetical universe of options fail to capture travel choices that also include non-transportation variables that would not normally be accounted by aspects of the measure (and planners nearly never perform a comprehensive regression analysis to identify variables that are left out that may be impacting factors).

While there are few—if any—measures that adequately meet all these criteria, some meet more than others and those that currently measure accessibility meet none or nearly none.

One final thought on good measures—or more their use—is that a good measure is one that is used in context with other measures to help tell a complex story. There are no silver bullets or a single measure that adequately or accurately describes any aspect of the transportation system; using one as such would create severe consequences. Critics of mobility theory and delay-based measures will readily point this out with the historical overuse and misuse of those measures. All too often, policy makers set policy goals and targets based on the simplest and easiest concepts and measures. This creates an overreliance on the concepts those measure and will inevitably miss entire concepts or aspects of the transportation and land use systems. Any users of new accessibility measures should take heed of this lesson and use the valuable aspects of all measures in a cohesive transportation policy.

Project Purpose

This project seeks to address the primary issues with accessibility and its current performance measures by examining existing measures, newly available crowdsourced data, and the issues listed above to create a new set of accessibility or accessibility-like measures that are grounded in actual and observed travel behavior that satisfy many—if not all—the hallmarks of good measures. These performance measures will then be integrated into the Texas A&M Transportation Institute's (TTI) Urban Mobility Report (UMR) as a new chapter on access and sustainability. This will begin to address prominent critiques of the heavily used report and move the delay-based measures therein toward a more balanced systems view. This will allow report readers to better use a diverse set of precalculated transportation performance measures in national, state, and regional planning.

The principal intent of this work lies in working toward two primary goals:

1. To better integrate the important concepts of accessibility into transportation planning and congestion mitigation at all levels of planning and governance—on par to the way mobility and delay-based measures are integrated into the planning process.
2. To promote the use of alternative mobility and congestion mitigation strategies, alternative modes, and development patterns to combat congestion, low levels of access and mobility, and improve overall transportation and social equity throughout the United States.

Both goals and project outcomes promote the use of innovative theory, mobility platforms, and data to battle congestion and simultaneously encourage equity sensitive or neutral transportation solutions. The use of innovative data and data-driven solutions will improve the quality of congestion monitoring and mitigation by allowing underused but valuable established theory to be more readily integrated into the planning process.

Project Approach

To complete this project, researchers must be proficient in the understanding and application of accessibility theory and performance measures in transportation planning. Understanding the current theory and measures will allow researchers to also understand the pitfalls and nuances before improving upon that theory. Additionally, researchers must manipulate the large datasets provided and understand the nuances of those. Once this is accomplished, researchers will be able to develop new performance measures that meet the criteria listed previously. To complete this project, researchers will complete the following:

1. Develop an understanding of accessibility theory and the components that encapsulate the theory.
2. Understand the currently available accessibility measures, their formulas, required data, and prevalence.

3. Investigate the use of emerging datasets, such as mobile probe data, in accessibility measure calculation.
4. Critically examine and assimilate the information and develop new accessibility concepts and measures based on parallels from existing measures.
5. Calculate the new measures for a small test case, assess, and iteratively refine the methodology.
6. Calculate all measures for all urban areas nationally.

Upon completion of the calculations, researchers will then publish the results in the upcoming edition of TTI's UMR for public assessment and use. In past development processes, researchers at TTI have relied upon local planners and policy makers to provide important feedback and assessment of the measures developed and published in the UMR.

Chapter 2. Assessment of Accessibility Concepts and Measures

While accessibility is a key concept in transportation planning, it has been defined and operationalized in different ways. It could measure the ease of reaching one or more locations using a particular transportation system, the potential opportunities that could be reachable, the freedom of people to participate in different activities, or the benefits provided by a transportation and land use system. Usually, accessibility refers to the extent to which the land use and transportation system allows people to reach activities, opportunities, and destinations by a certain transportation mode *(cognizant of either ignoring or incorporating the impact economic and investor development decisions hold on land use and transportation systems)*.

Generally, accessibility could be measured from two perspectives:

1. **The Perspective of Origins –** An accessibility orientation based on a single origin or grouping of origins and the destinations accessible to them under a time constraint. The number of grocery stores within a 30-minute travel time of one's house illustrates this origin-based perspective.
2. **The Perspective of Destinations –** An accessibility orientation based on the number of origins or populations within a given distance or time from a single destination or group of destinations. This perspective is illustrated by the number of low-income people within 0.5 miles of a light rail line.

Both perspectives have important implications for guiding and evaluating transportation and land use planning strategies. For example, accessibility measures from the origin perspective are important social indicators as these measures evaluate the availability of social and economic opportunities for people. Accessibility measures from the destination perspective could be used to guide and optimize location choices of different activity opportunities and public facilities.

The nature of accessibility, based on its operationalized definition, is impacted by several factors: the transportation system and its surrounding land use, transportation modes, individual constraints, and individual capabilities. Geurs and van Wee (2004) identified and summarized four components of accessibility that capture these factors and others: a transportation component, a land-use component, a temporal component, and an individual component.

- **Transportation Component –** Includes the supply of transportation infrastructures in space and characteristics, and the travel demand from passenger and freight movement. It also reflects the disutility (costs) that people experience from their origin to destination, often measured as travel time, monetary and other costs, and efforts. The disutility varies by travel mode.
- **Land Use Component –** Reflects the distribution of the supply and demand of opportunities in space. It refers to the spatial distribution of the supply of opportunities, including destinations and their characteristics, and the spatial distribution of demand for destination activities and their characteristics, including the distribution of populations and socioeconomic groups. The land use component also could measure the confrontation and competition of supply and demand for spatial activities and opportunities.
- **Temporal Component –** Reflects the availability of destination activities at different times and the time individuals are available to conduct trips and participate in activities. The temporal component of accessibility originates from the space time prism proposed by Hagerstrand (1970), in which the potential reachable area for individuals is constrained by the time people have.

- **Individual Component –** Reflects the needs and capabilities people have. The socioeconomic characteristics of people could partially reflect their travel needs. For example, families with kids may have higher travel needs for schools. Capabilities refers to individuals' capabilities to access a mode such as affordability to own a car, their disability status, financial abilities, travel time budgets to travel, and so on. The individual component requires extensive data to adequately measure. Thus, in practice, accessibility measurements are often categorized into individual-based measures and location-based measures based on whether the measurements consider individual components.

Available Accessibility Measures and Their Prevalence of Use

Just as accessibility has been split into many components and perspectives, scholars (e.g., Geurs and van Eck, 2001; Geurs and van Wee, 2004; Halden et al., 2000; Kwan, 1998) have grouped accessibility measures into several different categories in practice. As stated earlier, measures can be viewed from an origin or destination perspective and could be person-based and location-based.

Accessibility measures could also be categorized based on the core components being addressed and how these components are incorporated into the measures. Geurs and van Wee (2004) and Paez et al. (2012) provide in-depth reviews of known accessibility measures from a theorical basis and include discussions on interpretability and communicability. These have been grouped into six broad categories:

1. Infrastructure-Based Measures
2. Distance-Based Measures
3. Contour Measures
4. Gravity-Based Measures
5. Space-Time Measures
6. Utility-Based Measures

Infrastructure-Based Measures

Infrastructure-based measures mainly consider the transportation component of accessibility measurements, measuring exclusively the performance and service levels of transportation infrastructure. The measures may vary with the time of day, infrastructure types, transportation modes, and locations of transportation infrastructure. However, these measures neither reflect the distribution of land use nor consider the characteristics of the destination locations, such as size, attractiveness, and quality, among other aspects. Infrastructure-based accessibility measures are similar to mobility measures, such as average travel speed (including free-flow speed and congested speed), congestion level measures, and average peak period travel time. Generally, the higher the infrastructure measure, the higher the level of mobility.

Distance-Based Measures

Distance-based measures assess transportation connectivity between two points or two places, either from origins to destinations or from zones to other zones. Distance-based accessibility measures could gauge simple straight-line distances between two points or average travel time or distance between two locations. Although relatively simple, distance-based measures are practically feasible considering both the land use and transportation components.

Two examples of distance-based accessibility measures include distance to nearest location and route directness. The **distance to nearest location** is often used as a standard for the maximum travel distance to a location or transportation infrastructure (Geurs and van Wee, 2004). For example, residents should have a grocery store within 30 minutes of travel from their home. **Route directness** is often used to measure a public transportation system's level of service for people to access destinations: the higher the index, the poorer the levels of service (not related to more common level of service measures).

Contour Measures

Contour measures count the number of destination activities or number of populations serviced within a given threshold of travel time or cost (Equation 1).

Equation 1. Contour Measures

$$A_i = \sum_j O_j f(T_{ij})$$

A_i is the accessibility for location *i*, which could be an origin home or destination activity location such as a residential home or a transit stop. O_j is the number of opportunities in location *j*, when measuring origin-based accessibility; O_j is the number of populations in location *j*, when measuring destination-based accessibility. T_{ij} is the travel cost (time or distance) between *i* and *j*. $f(T_{ij})$ is the weight function. The contour measures take a binary weighting function that applies time or distance thresholds to calculate accessibility. Opportunities located within a specific travel time or distance would be counted while opportunities located out of a specific travel time or distance would not be counted as accessible opportunities.

Contour measures usually are operationalized in a few main ways:

1. Fixed Cost – The number of opportunities reachable with a given time or cost.
2. Fixed Opportunity – Travel time cost to reach a given number of opportunities.
3. Fixed Population – Average number of opportunities within a given travel time or cost.

These three measures are built from the origin perspective; however, some of these and others can be transformed into a destination orientation. An example would include the measure called *population serviced*. This measure equals the number of populations serviced by a facility within a travel time threshold.

The contour measures are also widely used in practice to measure accessibility at a zone level and inform local transportation and land use planning and policy. These measures are generally easier to calculate with available data and consider both land use and transportation components. Additionally, they can be used to compare different travel modes and socioeconomic areas of interest. However, the measures do not reflect travel behavior; those given threshold values of travel cost fall into a false homogeneity of behavior. People have different capabilities and choices of traveling. Given the same time threshold, the number of opportunities that could be reached would vary for different socioeconomic groups.

These measures are generally displayed as travel time or isochronal contour maps, as shown in Figure 2 (TTI, 2022). While these maps can only consider a single point at a time, they are usually the easiest accessibility measures to explain to lay audiences and policy makers.

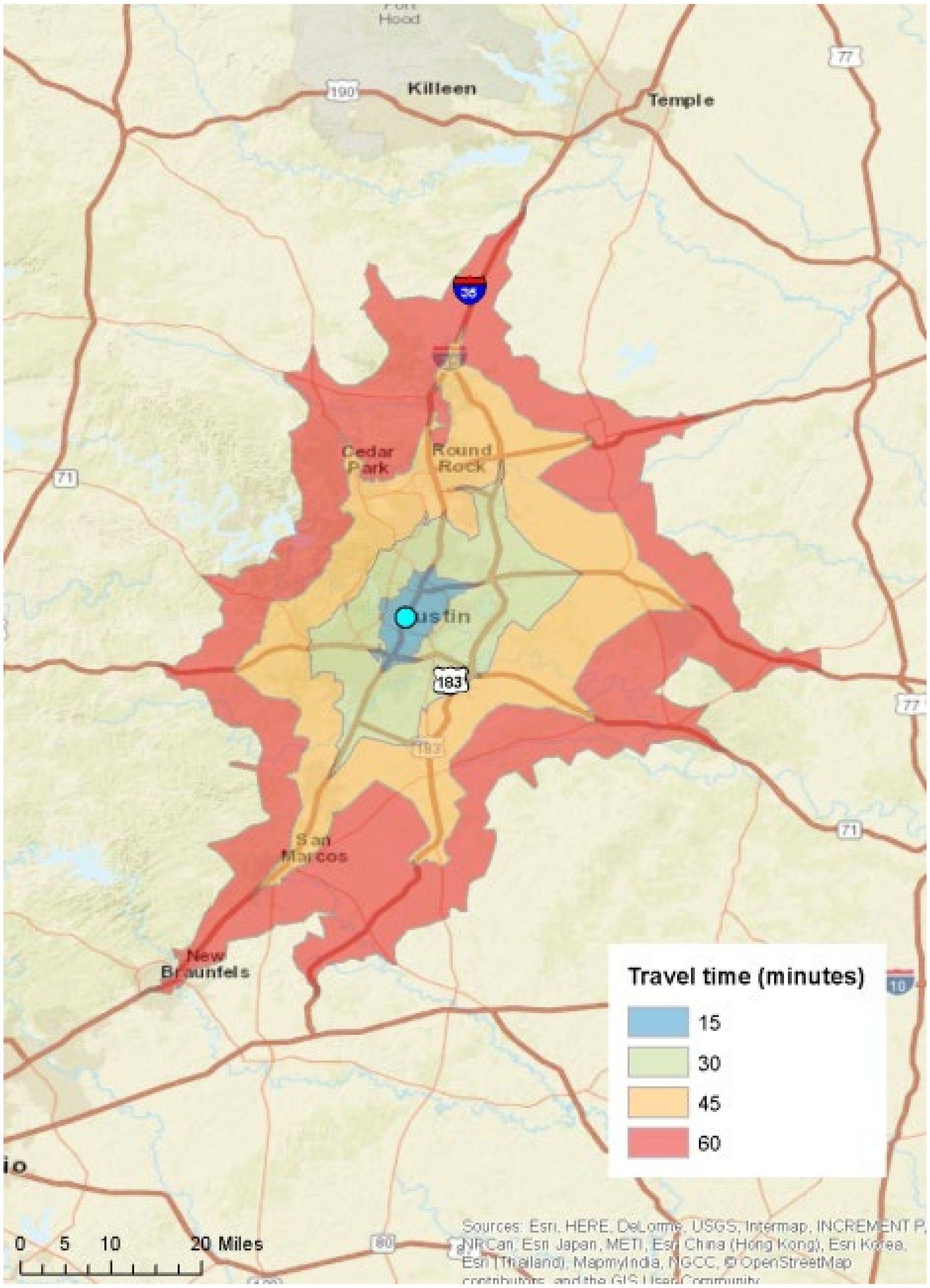

Figure 2. Weekday 5:00 p.m. travel time contours from downtown Austin, Texas.

Gravity-Based Measures

Gravity-based measures are another widely used accessibility measurement in transportation modeling, forecasting, and planning and geography studies. Gravity-based measures refer to the potential opportunities for interaction and are normally calculated at a zone level due to their complexity. Gravity-based measures could be created from both origin and destination perspectives. An origin perspective would provide the number of potential opportunities reachable given a travel cost decay function that is used to weight the number of opportunities based on travel time and cost. A destination perspective would provide the number of potential populations reachable given a travel cost decay function.

Compared to contour measures, gravity-based measures apply travel cost decay weighting functions, which suggest that opportunities far away from origins are less accessible. The travel cost decay functions vary in practice, including negative exponential functions (Handy & Niemeier, 1997) and Gaussian functions (Ingram, 1971).

Like contour measures, gravity-based measures could be calculated for different transportation modes and socioeconomic areas. These measures could also be weighted by the number of populations in the origin zone to consider demand for opportunities. However, gravity-based measures also suffer from the limitations all location-based accessibility measures have. The measurement does not account for the capabilities and needs of individuals and the temporal constraints of opportunities and individuals. Moreover, the selection of the travel cost decay functions plays an important role in influencing the gravity-based accessibility measure. Scholars usually use travel diary survey data to calibrate travel cost decay functions to consider travel behavior. However, the travel cost decay functions may vary with the socioeconomic characteristics of populations and in different locations.

Space-Time Measures

The pioneering work of Hagerstrand (1970) proposed the space-time prism to depict the allocation of activities, social interaction, and time in time and space (Figure 3). The accessibility measurement is the number of opportunities within the **potential path areas** (PPA in Figure 3) reachable given the constraints. PPA is the important concept of the space-time prism. The space-time prism takes the following constraints into account when measuring accessibility: individuals' capabilities to travel; coupling constraints of when, how, where, and how long to travel with others; and authority constraints of the availability of some destinations.

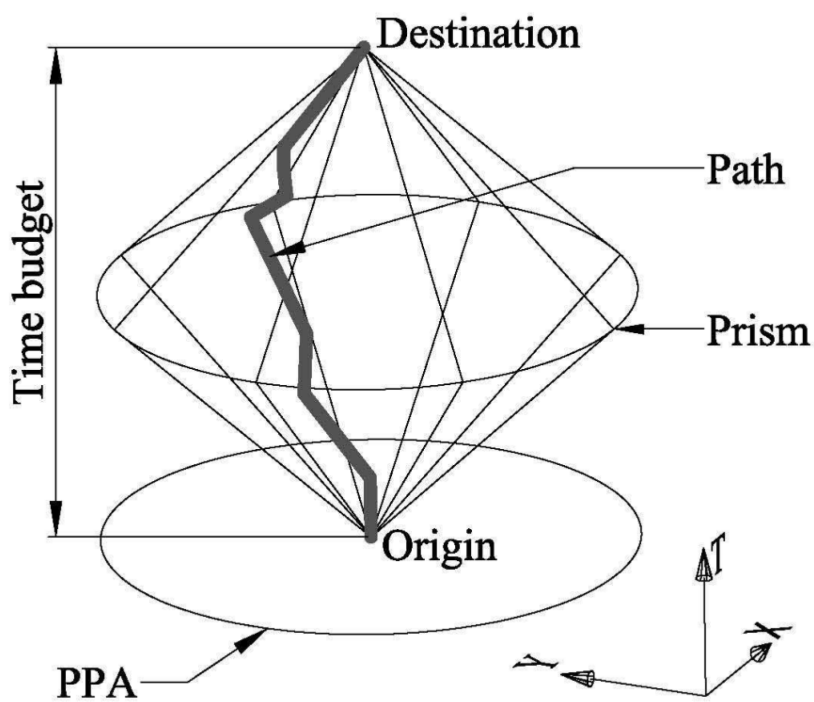

Figure 3. Space-time prism (Miller, 1998).

Space-time accessibility measures take all four core accessibility components into account: distribution of land use, transportation infrastructure, temporal constraints, and individual constraints. Since the measurement is at the individual level, the calculation of space-time measures requires a large amount of high-resolution data. Thus, in practice, the space-time accessibility measurement is often only calculated for a small sample of people.

Another similar concept to PPA is activity space. **Activity space** refers to locations or areas with which individuals have direct interaction as a result of day-to-day activities. Opportunities or destinations located within the spatial and temporal bounds of individuals' routine activity space can be considered more accessible than those located outside the activity space. An opportunity "inside the activity space" is interpreted as one a person could potentially obtain with relative ease, while opportunities "outside the activity space" are interpreted as requiring the person to deviate from normal routine or expend extra resources to access.

In practice, scholars proposed various approaches to measure active space (Patterson & Farber, 2015), including ellipses and circles, network-based approaches, kernel density approaches, minimum convex-hull polygons (MCP), and others. The size and shape of activity space could be a measure of accessibility; a small activity space usually represents limited accessibility. The number of varying destination opportunities within the activity space could be further calculated as measures of accessibility. The measurement of activity space and the accessibility based on activity space are also calculated at the individual level and usually require detailed travel diary data. Thus, like the PPA model, this measurement is often only calculated for a small sample of people.

Utility-Based Measures

Utility-based accessibility measures treat accessibility as the outcome of a set of transport choices. Individuals who are faced with multiple alternatives choose the one associated with the maximum utility. Individuals' utilities of these alternatives are influenced by the individuals' characteristics and use and transportation characteristics. U_{ij} is the utility of person *i* for an opportunity of *j* (Equation 2). C_{ij} is the cost of travel for people *i* to opportunity *j*.

Equation 2. Perceived Utility

$$U_{ij} = V_{ij} - \beta C_{ij} + \varepsilon_{ij}$$

The utility-based accessibility measures are built on the utility function above. Each individual has multiple destination alternatives for a specific type of destination and assigns a utility to each destination choice. Individuals select the alternative maximizing their utilities. Usually, a multinomial logit model is adopted to model the impacts of individuals' characteristics, destination characteristics, and transportation characteristics on the probability of choosing the alternative associated with max utilities. The log sum of the denominator is a summary measure of utility of the full choice set, and thus provides a measure of accessibility.

Table 1. Accessibility Measures, Descriptions, and Applications

Measures	Description	Zone Level	Person Level	Origin or Destination Based	Applications
Infrastructure-Based Measures					
Roadway Length	Total length of roadway.	Yes	No	Origin	DETR (2000)
Travel Speed	Travel speed on roadways.	Yes	No	Origin	AVV (2000)
Distance-Based Measures					
Distance to the Nearest Locations	How far away the origin is from the nearest destination. $$A^{ip} = \frac{MIN}{J\epsilon Lp}\left(d_{ij}\right)$$	Yes	No	Origin	Scott & Horner (2008)
Route Directness	An index measuring the directness of identified routes between points. It is usually measured by dividing the route length by distance between travel road network or direct distance between two points.	Yes	No	Origin	Randall & Baetz (2001)
Contour Measures					
Cumulative Opportunities (Fixed Cost)	Typically calculated from the origin perspective as the number of destinations or opportunities that can be reached within an acceptable amount of time.	Yes	No	Origin	Gutiérrez & Urbano (1996)
Fixed Opportunities	The (average or total) time or cost required to access a fixed number of opportunities.	Yes	No	Origin	Breheny (1978)
Diversity of Activity Index	The fraction of different services available in the area reached within a certain time threshold.	Yes	No	Origin	Albacete et al. (2017)
Fixed Population	The average (over the population) of the number of opportunities available within various fixed travel costs.	Yes	No	Origin	Breheny (1978)
Relative Supply	The number of opportunities within a time threshold normalized by population.	Yes	No	Origin	Apparicio et al. (2007)
Access to at Least One Facility	The presence of at least one facility within a distance or time threshold. Equaling to 1 if there is at one facility within a travel distance or time threshold.	Yes	No	Origin	Horner & Mascarenhas (2007)
Population Serviced	The number of populations within travel time of a destination opportunity.	Yes	No	Destination	Cervigni et al. (2008)
Gravity Measures					
Opportunity Accessibility	The potential of opportunities for interaction; it could use inverse cost travel cost decay function, negative exponential function, etc.	Yes	No	Origin	Gutiérrez & Gómez (1999)
Mean Accessibility	The number of opportunities at zone of origin to residents of the area.	Yes	No	Origin	Cervigni et al. (2008)

Measures	Description	Zone Level	Person Level	Origin or Destination Based	Applications
Space-Time Measures					
PPA	The characteristics of PPA, including area, shape, size, and location.	No	Yes	Origin	Lee & Miller (2019)
Average Space-Time Prism (ASTP)	The ASTP is the representative space-time prism for a group of individual STPs with respect to area, shape, size, and location.	No	Yes	Origin	Lee & Miller (2019)
Number of Opportunities in PPA	The count of various opportunities within PPA.	No	Yes	Origin	Lee & Miller (2019)
Area-Weighted Sum in PPA	An area-weighted sum of various opportunities in PPA.	No	Yes	Origin	
Length of Road Segment in PPA	The sum of all network or road segments in PPA.	No	Yes	Origin	Kwan M. (1998)
Standard Deviational Ellipse	The spatial distribution of activity sites visited outside the household, expressed as a bivariate normal distribution at one standard deviation. An ellipse whose major and minor axes correspond respectively to the maximum and minimum directional standard deviations.	No	Yes	Origin	Buliung & Kanaroglou (2006)
Network-Based Approach	The areas with which people are familiar are related to their actual travel through space and constrained by transport networks. Activity space is measured as buffer areas around the shortest path connecting a sequence of activity locations.	No	Yes	Origin	Schonfelder & Axhausen (2003)
Kernel Density Estimation	Kernel density is used to interpolate point data to a continuous face based on the frequency of and distance to nearby activities.	No	Yes	Origin	Kwan (1991)
MCP	MCP is the minimum-sized polygon encompassing a collection of activity locations over a period of time.	No	Yes	Origin	Casas (2007)
Activity Locations	The number of activities locations or unique destinations as measures of activity space size.	No	Yes	Origin	Kamruzzaman et al. (2012)
Utility-Based Measures					
Log Sum Accessibility Measures	The log sum summarizes the utilities of the full choice set.	No	Yes	Origin	Levine (1998)

Measure Analysis Summary

Throughout the review of various accessibility measures, each measure was found to have advantages and limitations in evaluating accessibility as a construct. The infrastructure-based, distance-based, contour, and gravity-based measures are all location-based; space-time measures and utility-based measures are both person-based. The location-based measures could be calculated from both the origin perspective to evaluate residents' access to destinations and the destination perspective to assess the number of residents served by a destination. These measures also could be calculated and compared for different travel modes and socioeconomic groups.

Thus, planners predominantly use these measures in practice, which hold important implications for informing transportation planning and land use development policy. However, these measures could not reflect the actual accessibility of individuals in locations without considering actual travel behavior and preferences. A population's capability to travel, public transportation availability and level of service, and socioeconomic characteristics would influence abilities and preferences to reach opportunities.

The person-based accessibility measures, including the space-time and utility-based measures, take individual characteristics into account. Space-time measures allow the consideration of people's constraints and ability to travel while utility-based measures take abilities, constraints, perceptions, and preferences into consideration. However, the calculation of these two measures requires extensive data and can be applied only in a small areas and populations. Thus, planners rarely use these in practice.

The emergence of new data sources, such as mobile device data, provides a valuable opportunity for transportation researchers, planners, and practitioners to develop new location-based accessibility measures that could be applied in a larger scale and reflect actual travel behavior and individual or group preferences. However, other issues such as calculation complexity, ease of explanation, and relevance to broader policy activities still need to be overcome.

Chapter 3. Emerging Data for Measuring Accessibility

With the development of information and communication technologies (e.g., smartphones and built-in vehicle GPS devices), there is a growing body of research applying data generated by these new technologies to quantitively measure accessibility and examine how accessibility varies among different urban environments and socioeconomic groups. Compared to traditional surveys and travel diaries, these datasets provide a valuable resource for understanding human mobility and constructing accessibility measures at a large spatial-temporal scale. The datasets usually contain a larger amount of individual-level data (though lacking some important details), have more fine-grained trip origin-destination information, offer real-time transportation network conditions, and cover a longer period compared to traditional survey data (Chen et al., 2016). They also are cost-effective compared to traditional survey data and provide opportunities for conducting dynamic analyses of accessibility with the consideration of temporal variation.

There are various types of big data in transportation research including mobile device data, location-based social media data, and public transit smart card data. Mobile device data include cell phone call detailed records (CDRs) (Gonzalez et al., 2008; Wang et al., 2018), mobile signaling data (MSD) (Xu et al., 2016), and GPS data. Mobile data—especially signal and GPS data—are the most widely used data source.

Application of Mobile Device Data in Measuring Accessibility

Although an increasing number of scholars have used mobile device data to study travel behavior, the application in constructing accessibility measures is relatively limited. Those studies predominantly focus on identifying travel and activity patterns (e.g., Wang et al., 2018) and measuring human mobility. The human mobility measures used include daily trip frequency (Pas and Koppelman, 1987; Pas and Sundar, 1995), daily travel time (Pas and Sundar, 1995), daily trip distance (Calabrease et al., 2013) a combination of distance and travel time (Axhausen et al., 2002), activity space (Susilo and Kitamura, 2005), activity participation (Kang and Scott, 2010), and "unique" trip sequences (Moiseeva et al., 2014). Some of those human mobility and travel behavior measures were derived from the emerging data such as daily trip length; daily trip time could be treated as a distance-based accessibility measure. For example, Calabrease et al. (2013) used mobile phone trace data to develop two measures for human mobility: average individual trip length and individual total daily trip length.

A wide application of mobile device data into accessibility is through the dynamic accessibility calculation considering dynamic traffic conditions. For example, Sweet et al. (2015) studied the impact of congestion on accessibility using historical traffic service data provided by INRIX. Moya-Gómez and García-Palomares (2015, 2017) used TomTom's Speed Profiles data to create dynamic maps, revealing the impact of congestion on daily accessibility.

Another application of mobile device data into accessibility measurement is the construction of activity space measures since the data collects high-dimensional travel information at the individual level. For example, Jarv et al. (2014) used mobile device CDR data to study the monthly variation in activity space over 12 months. Silm and Ahas (2014) used mobile device data to study and compare the activity spaces of out-of-home nonemployment activities over a one-year period in Estonia and abroad and revealed no differences.

Overall, the application of mobile device data in measuring accessibility is limited. Most calculated measures are individual-level activity space measures to evaluate the disparities in activity space among different social economic groups. This application often requires strong data analytics as well as coding skills and experience assigning trips to each person—practically infeasible to be applied in daily planning practices. However, mobile trip and trip trace data (data that contain origins and destinations or trip paths, respectively) could be used to easily develop and use location-level accessibility measures to both reflect actual travel behavior.

Based on the literature and accessibility measure assessment above, researchers found and illustrated that mobile device data may have many advantages in constructing future accessibility measures.

- The data record actual travel behavior.
- The data have the potential to convey real-time travel conditions.
- The data contain the necessary information to construct intensive OD matrix information for each trip or all trips (used in modeling).
- The data can usually distinguish between freight and personal-use vehicles.

Chapter 4. Theory Development

Upon completion of the review of available accessibility measures and the application of now readily available mobile device data, researchers began the task of developing an updated approach to measuring accessibility with these new data sources in mind.

Researchers set several goals by which any new accessibility or "accessibility-like" measures should be judged to determine the success of the development process.

1. Each measure should be simple to understand and communicate to others.
2. Each measure should be simple to calculate.
3. Each measure should be conducive to the setting of policy, goals, and targets and be able to be tracked year over year.
4. Each measure should be flexible to a variety of policy types (e.g., urban growth, increasing density, etc.).
5. Each measure should use real observed travel behavior data.
6. Each measure should be scalable to different geographic levels.
7. Each measure should allow comparisons between different areas or geographies (e.g., ability to compare one urban area against another).

Each goal relates back to different attributes of good performance measures and the shortcomings of traditional accessibility measures. Ideally, all these goals would be met; however, researchers understood that some may not be possible to achieve.

Measure Analysis and Development

Knowing that the most likely suitable data that is most readily available to State DOTs, MPOs, or local agencies would be motor vehicle trip data (trip start and end points only with varying accompanying attributes) or trip trace data (trip start and end points with network-routable path data), researchers began to assess each existing accessibility measure (Table 1) for translatable attributes that would be conducive to using these new datasets, initially for motor vehicle trips but in a manner scalable to other modes.

Researchers examined the goals of the different major categories of accessibility measures (i.e., Distance, Gravity, Contour, etc.) and found those to be more helpful in developing a simplified theory transferable to real observed behavior versus a direct translation of measures. While some concepts translated easily, others were far more difficult and caused researchers to fall in a common accessibility trap.

As researchers began the first conceptual construction of new measures, they attempted to include multiple attributes, modes, and features into a single measure. The goal was to capture accessibility as a concept in one holistic manner, much like the concept of delay captures much of the essence of mobility as a concept. Researchers developed at least five promising yet fatally flawed attempts at new measures but ultimately scrapped them due to their ever-increasing complexity, required data needs, and difficulty in explanation. Anecdotally, researchers found incredible difficulty in describing most concepts to other colleagues in hour-long meetings, which was the first clue that ultimately made them realize these attempts were flawed.

Researchers decided to start afresh from a different angle: what common attributes are most accessibility measures trying to measure from an extremely basic level independent of mode or other specific factors? They performed a second assessment of existing accessibility measures and discovered that many measures incorporate four basic components:

1. **Coverage –** How much of an area is reachable by an origin or can be reached by multiple origins?
2. **Density –** How many trips start or end in a specific area (usable as a weight)?
3. **Reach –** How far are trips on average from different origins or destinations?
4. **Trip Attributes –** Basic measures and attributes assignable to each trip (e.g., actual or average time, vehicle type, time of day, etc.).

Combined, these four components make up the bulk of accessibility measures and mimic features of gravity-based measures, space-time measures, contour measures, and distance-based measures. However, attributes of utility-based measures still appear to be mostly out-of-reach due to their intensive use of data that are still largely unavailable in bulk form. Researchers also anecdotally found that explaining these concepts to others—including those not in transportation-related fields—became much simpler and usually took less than 30 seconds.

While these four concepts fail to capture several accessibility-specific attributes, like the specifics of land use, modal options, and individual characteristics, those attributes could be theoretically incorporated into or in addition to the concepts. For example, destination type (such as access to grocery or banking options) could be easily interwoven into coverage, density, and reach. Additionally, all concepts are mode-neutral in that they could be easily applied with the same meaning to any mode or all modes equally.

Satisfied with these preliminary concepts, researchers began to determine if measures could be developed that achieve the seven measure development goals with trip or trip trace data sources. They quickly discovered that these concepts could not only be used to create simplified measures, but those measures would also accomplish most—if not all—of the goals.

Researchers developed the following measures for the three primary concepts scalable to any or all modes and at either a sub-regional zone level or at an urban-area level. Table 2 lists the measures.

Table 2. Summary of Newly Developed Accessibility Measures

Concept	Zone-Level Measure	Urban Area-Level Measure
Coverage	Area Coverage Ratio (Origin)	Total Real Urban Coverage (Origin)
Coverage	Area Coverage Ratio (Destination)	Total Real Urban Coverage (Destination)
Density	Zonal Trip Origin Density	Area Trip Origin Density
Density	Zonal Trip Destination Density	Area Trip Destination Density
Density	Total Number of Trips per Zone	N/A
Reach	Average Zonal Trip Distance (Origin)	Area Reach (Origin)
Reach	Average Zonal Trip Distance (Destination)	Area Reach (Destination)
Reach	N/A	Average/Median Urban Area Trip Length
Reach	Average/Median Trip Time	Average/Median Urban Area Trip Time

Coverage

The concept of coverage most closely mirrors the conceptual aspects of space-time, contour, and gravity accessibility measures—cumulative opportunities and activity space. At the sub-urban area or zonal level, origin coverage represents the estimated percentage of an urban area that origins from each zone reach. At the same scale but from a destination perspective, destination coverage represents the estimated percentage of an urban area that a destination is reached by any number of origins.

In traditional measures, cumulative opportunities from the origin perspective calculate the number of destinations or opportunities that can be reached within an acceptable amount of time. In practice, the acceptable travel time is often estimated based on the transportation network instead of the real travel time. For example, the Accessibility Observatory at the University of Minnesota calculated the cumulative opportunities for different modes of use based on the travel time of different mode networks. However, coverage measures use the real travel time for each zone to estimate the reachable area.

Activity space refers to locations or areas with which individuals have direct interaction as the result of day-to-day activities. Activity space is usually calculated at the individual level. Coverage measures are zone-level activity space measures, reflecting the areas with which individuals in each zone could have direct interaction as their daily trips. Opportunities or destinations located within coverage areas can be considered more accessible than those located outside coverage areas.

Area Coverage Ratio (Origin or Destination)

At a sub-urban area or zonal scale, the area coverage ratio (origin), or ACR_O, represents the number of zones that trips originating from a single zone can reach within a given time constraint. This is expressed as a percentage of the entire area and is expressed as Equation 3 and illustrated in Figure 4.

Equation 3. Area Coverage Ratio (Origin)

$$Area\ Coverage\ Ratio\ (ACR_O) = \frac{Number\ of\ \boldsymbol{zones}\ reached\ by\ trips\ originating\ from\ \boldsymbol{zone\ k}.}{Total\ number\ of\ \boldsymbol{zones}\ in\ the\ urban\ area.}$$

**Note: The origin zone can also be counted as a destination zone.*

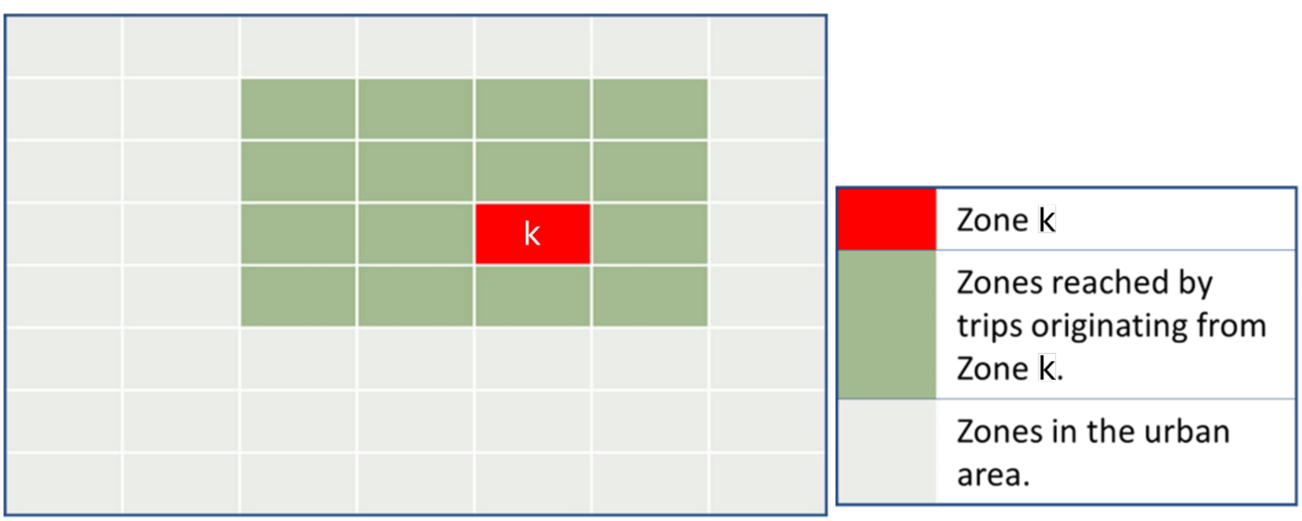

Figure 4. Area coverage ratio (origin) illustrated.

Much like many other accessibility measures, the area coverage can also be calculated from a destination perspective. Area coverage ratio (destination), or ACR_D, represents the number of trips beginning in various zones reaching a single zone. For destinations, it represents how many zones could be attracted to a certain zone within a certain travel time constraint. This concept is opposite that of ACR_O in that while ACR_O focuses on how many zones can be reached by a single origin, ACR_D focuses on how many origins can reach a destination. This is expressed as a percentage of the entire area and is expressed as Equation 4 and illustrated in Figure 5.

Equation 4. Area Coverage Ratio (Destination)

$$Area\ Coverage\ Ratio\ (ACR_D) = \frac{Number\ of\ distinct\ \boldsymbol{zones}\ with\ trips\ that\ can\ reach\ \boldsymbol{zone\ k}.}{Total\ number\ of\ \boldsymbol{zones}\ in\ the\ urban\ area.}$$

**Note: The destination zone can also be counted as an origin zone.*

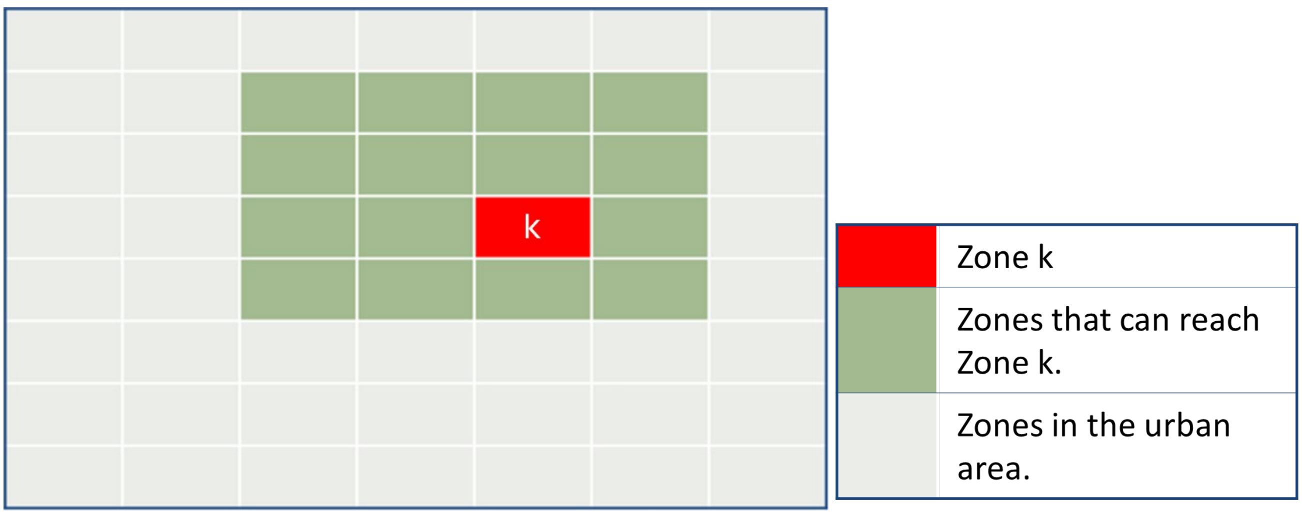

Figure 5. Area coverage ratio (destination) illustrated.

From a policy perspective, ACRs throughout an area could be assessed and targets could be individually or globally set to increase the percentage of an area covered. This most reflects many of the goals of current accessibility measures in that the general aim is to increase access across an urban area. Conversely, the measures are flexible enough to allow planners and policy makers to create zone-specific goals that shrink over time if a more compact urban form is desired. Since both ACR measures are normalized by the number of zones in an area, they can easily be compared to each other.

Modal options can also be accounted for in that some modes may have smaller footprints than others. Under this perspective, the actual map of zones reached or with originating trips could be created to provide useful contextual information.

Total Real Urban Coverage (Origin or Destination)

While both ACR_O and ACR_D provide interesting accessibility information at relatively small geographic scales, they do not provide a good picture of the overall coverage an urban area experiences in a single value. For this reason, researchers developed an aggregate measure, total real urban coverage (TRUC), that can be calculated from either the origin or destination perspective. This measure averages all ACR scores for an urban area into a single value between one and zero; one being a perfectly accessible city within a given amount of time and zero being a perfectly inaccessible city within a given amount of time. The larger the value, the more travelers can reach various destinations from various origins (and the opposite for the destination-based value). TRUC is expressed by Equation 5 and illustrated in Figure 6.

Equation 5. Total Real Urban Coverage

$$Total\ Real\ Urban\ Coverage\ (TRUC) = \frac{\sum_{Urban\ Area}[ACR_O\ or\ ACR_D]}{Total\ number\ of\ \boldsymbol{zones}\ in\ the\ urban\ area.}$$

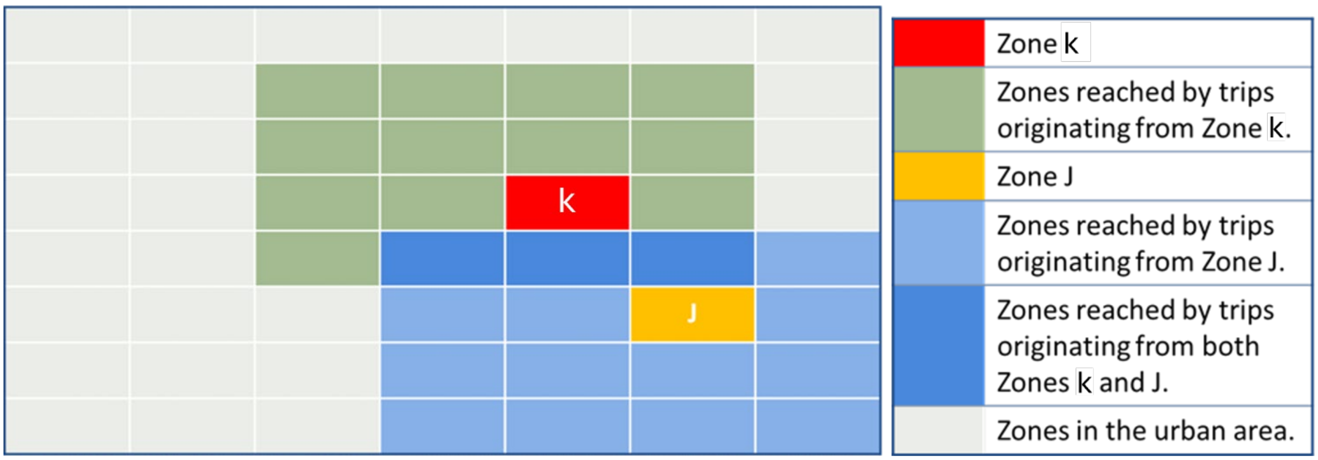

Figure 6. Total real urban coverage illustrated.

This measure is useful at higher-level and -geographical policy and planning perspectives. It provides a single value summarizing an urban area's coverage. This is useful for target setting: goals can be set to increase an area's TRUC value over time based on projects or policies throughout the area or in specific zones. Additionally, since TRUC values are normalized based on the total number of zones in an urban area, they can be compared to peer cities in an appropriate manner. Statewide planning could use these to assess the relative coverage access between cities within a state to determine the impacts of statewide accessibility policies and practices.

Density

The concept of density is not overtly measured in traditional accessibility measures, though the idea is inherent in many types. Researchers chose to break this specific concept into its own, because while the coverage concept shows how much of an area can be reached, it fails to show the weight of that coverage; a single trip or thousands of trips to different zones are treated the same.

Zonal Trip (Origin or Destination) Density

Origin-based trip density summarizes the number of trips originating from each zone as a percentage of all trips within the urban area, while destination-based trip density summarizes the number of trips terminating in each zone as a percentage of all trips within the urban area. Both measures reflect the activity density of each zone and are expressed by Equation 6 and Equation 7 and illustrated in Figure 7.

Equation 6. Zonal Trip Density (Origin)

$$Zonal\ Trip\ Density\ (TD_O) = \frac{Number\ of\ \boldsymbol{trips}\ originating\ from\ \boldsymbol{zone\ k}.}{Total\ number\ of\ \boldsymbol{trips}\ in\ the\ urban\ area.}$$

**Note: The origin zone can also be counted as a destination zone.*

Equation 7. Zonal Trip Density (Destination)

$$Zonal\ Trip\ Density\ (TD_D) = \frac{Number\ of\ \boldsymbol{trips}\ ending\ in\ \boldsymbol{zone\ k}.}{Total\ number\ of\ \boldsymbol{trips}\ in\ the\ urban\ area.}$$

**Note: The destination zone can also be counted as an origin zone.*

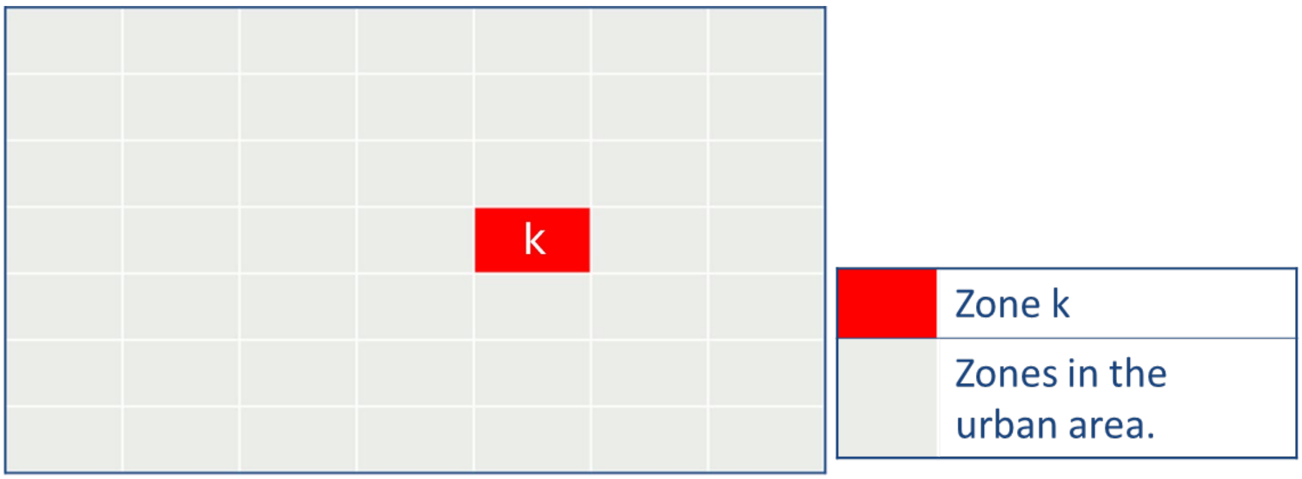

Figure 7. Zonal trip density (origin or destination) illustrated.

Again, measures are scored between zero and one: zero being that no trips originate or are destined to that particular zone, and one meaning all trips in an urban area originate or are destined to that particular zone. While neither of these scores are possible or meaningful, the percentage does provide a "geographic histogram" of sorts, spatially illustrating where trips occur as a percentage of the total.

In both cases, only a single zone is considered regardless of trip origination or trip destination. This measure provides flexibility at the zonal level to understand the magnitude of trips and trip origin or destination distribution throughout the urban area. Additionally, the measures can be used as weights for other applications.

From a policy and planning perspective, the value of these measures is neither inherently good nor bad; they provide context and a proxy for transportation density that can be difficult to calculate or assess. At the zonal level, goals and targets can be set for different areas, like a central business district (CBD), specific neighborhoods, or other activity centers. Should a goal be to increase the relative density of trips in a specific neighborhood, that zone could be watched for an increase compared to a relative decrease in other zones. Alternately, neighborhoods targeted to maintain or decrease density (for several purposes, including historic preservation) could watch for a constant or decreasing value. Note that these and other density measures are highly relative to other zones. Additionally, the targets or goals should always accompany the values as they lose value without context.

Total Number of Trips per Zone

Like zonal trip density, the total number of trips per zone is an unweighted and raw value that can be calculated merely for contextual purposes. This value represents only the number of origins or destinations in each zone on their own; there is no dividend value.

Since most trip and trip trace datasets are only a sample set of values, this measure does not adequately create a representative portrayal of all trips taken unless the data specifically hold the entirety of all trips taken by a population. However, understanding this value does offer useful context for planning.

For planners, the total number of trips per zone represents a value of magnitude that the previous measures might not adequately convey. Additionally, these values could be useful as weights in other use cases and in other measures—especially for alternate mode calculations.

Area Trip (Origin or Destination) Density

Similar to the coverage concept, an urban area-wide density measure provides value at different planning and policy scales. However, unlike the summation of ACRs into a single average value, area-wide density—area trip density—must be calculated as a holistic value in relation to the number of zones. Like the others, area trip density can be calculated from an origin or destination perspective.

This measure requires a methodological change from all other measures up to this point. Where all other measures have been calculated using only trips that both started and ended within the urban area, this measure requires the inclusion of trips that ended both inside and outside the urban area (for the origin perspective) and the inclusion of trips that began both inside and outside the urban area (for the destination perspective). These values are then divided by the number of zones in an urban area to normalize the values and allow them to be on par with other urban areas. These measures can be seen in Equation 8 and Equation 9.

Equation 8. Area Trip Origin Density

$$Area\ Trip\ Origin\ Density = \frac{Number\ of\ \boldsymbol{trips\ originating}\ inside\ the\ urban\ area.}{Total\ number\ of\ \boldsymbol{zone}\ in\ the\ urban\ area.}$$

**Note: Trips ending outside the urban area can also be included but exclude through trips.*

Equation 9. Area Trip Destination Density

$$Area\ Trip\ Destination\ Density = \frac{Number\ of\ \boldsymbol{trips\ ending}\ inside\ the\ urban\ area.}{Total\ number\ of\ \boldsymbol{zones}\ in\ the\ urban\ area.}$$

**Note: Trips beginning outside the urban area can also be included but exclude through trips.*

Values created represent the average number of trips any zone within an urban area might be expected to contain (though this could be skewed depending on the spatial distributions of trips throughout the area). For example, a relatively high area trip origin density value would indicate that significantly more trips are begun within that urban area, which could be an indication of urban density and form. From a destination perspective, a relatively high value would indicate a regional attraction greater than the urban area's self-contained reach.

These values can also be used to compare urban areas against one another, which becomes especially important when examining freight or commute shed movements. Like other measures, the values themselves are inherently neutral and rely heavily on contextual targets, goals, and policies to provide relevancy.

Reach

The final concept—reach—includes a duality of accessibility attributes that have been lightly addressed by other measures developed thus far but from a different perspective. Reach, like coverage, heavily incorporates properties of space-time accessibility measures and measures characteristics of ACR, but more closely follows the results provided by contour measures.

As most data sources (trip or trip trace) offer a path distance with each trip (actual distance, not as-the-crow-flies), reach measures calculate the average path length of trips either within a zone or in aggregate. This importantly differs from coverage measures that focus solely on the accessibility of one zone to another in a given time but fail to consider how trips are fulfilled between the origin and destination. For example, consider two trips that start in zone A and end in zone C. One trip takes a direct but congested route and arrives in 30 minutes. The second trip takes an alternate and longer route and arrives in the same 30-minute travel time. In almost all measures (including many mobility measures), these two trips would be nearly indistinguishable. However, these trips would have different reach scores noting that an alternate route had occurred.

Alternately, two zones may have the same ACR_O, indicating residents in each could reach the same amount of an urban area. However, for one zone, more trips within the ACR terminate in adjacent zones with shorter trip distances because of adjacent compact development that experiences higher levels of self-containment. In the other zone, more trips terminate in zones at the boundary of the ACR. These two zones would have different measures of reach and communicate different policy perspectives that coverage alone could not convey.

The two zones with the same ACR may also have different reach measures, resulting from different transportation network systems; the zone with a well-connected street network tends to have a lower measure of reach. Thus, the measure could indicate a level of connectivity and network development in addition to compactness and self-containment for each zone.

Average Zonal Trip Distance (Origin or Destination)

Reach at the zone level is measured by the average zonal trip distance (AZTD) based on the average trip distances of origins beginning from a zone ($AZTD_O$) or based on the average trip distances of destinations ending in that zone ($AZTD_D$). Like other measures created up to this point at the zonal scale, they are normalized by the total number of trips within that zone to allow them comparability with other zones. Equation 10 and Figure 8 display the concept for origin-based trips.

Equation 10. Average Origin Zonal Trip Distance

$$Average\ Origin\ Zonal\ Trip\ Distance\ (AZTD_O) = \frac{\sum \boldsymbol{Trip\ lengths\ originating}\ in\ zone\ k.}{Total\ number\ of\ \boldsymbol{trips\ originating}\ in\ zone\ k.}$$

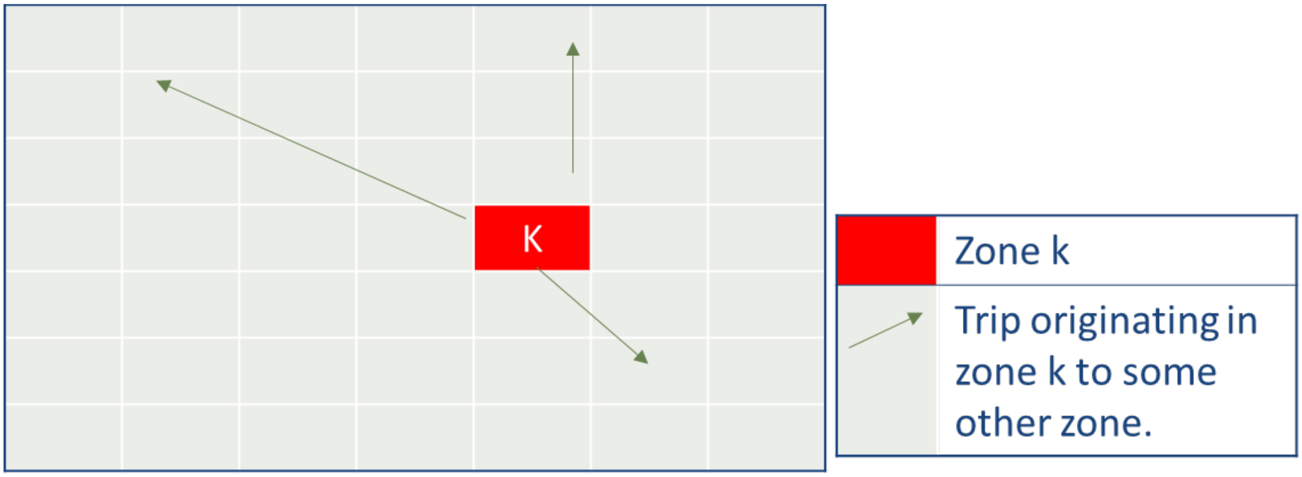

Figure 8. Average origin zonal trip distance illustrated.

Conversely, $AZTD_D$ conveys the average trip distance of trips that start outside of the zone in question but end in that zone. These trip lengths are not straight-line distances, but rather the length of the actual route taken by the traveler. Equation 11 and Figure 9 display the concept for destination-based trips.

Equation 11. Average Destination Zonal Trip Distance

$$Average\ Destination\ Zonal\ Trip\ Distance\ (AZTD_O) = \frac{\sum \boldsymbol{Trip\ lengths\ ending}\ in\ zone\ k.}{Total\ number\ of\ \boldsymbol{trips\ ending}\ zone\ k.}$$

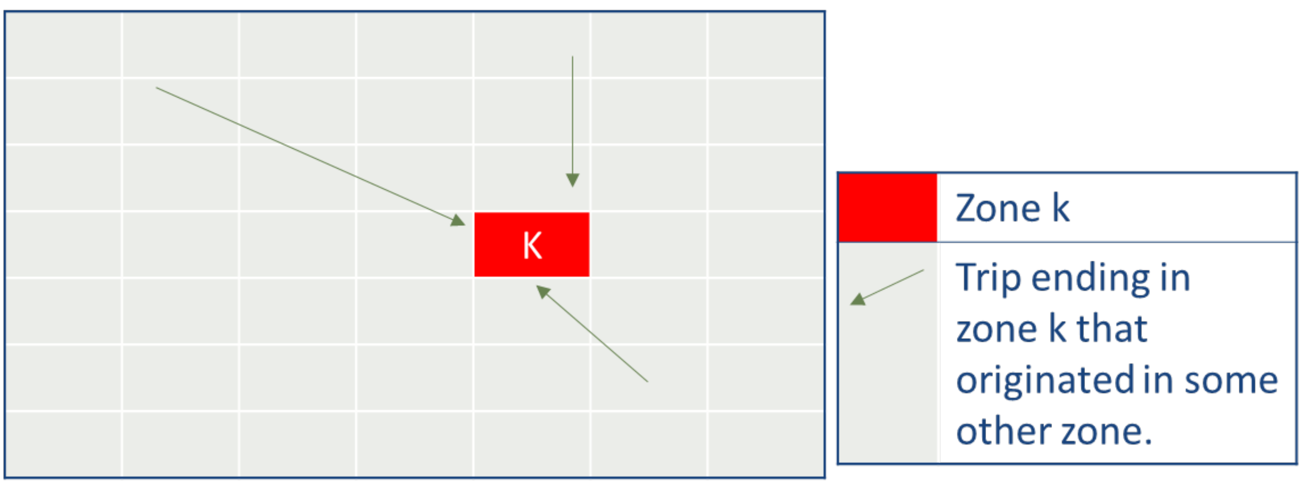

Figure 9. Average destination zonal trip distance illustrated.

Both measures are conveyed in miles (or any distance measure desired); the lower the value, the shorter the distance—and more direct a path—travelers are moving to reach their destinations. These values offer no inherently good or bad nature but are solely contingent upon the policies, goals, and targets created by planners and policy makers.

Researchers plan further investigation into this method to determine if using a form of the median trip difference might be better suited to instances where the distribution is skewed to the right. Such a skew would make a median more representative and stable over time. However, the inclusion of trips with trip lengths over one hour would likely need to be included to provide an accurate value.

When used in conjunction with ACR and density measures, this method would enable planners to measure relative compactness and connectivity of a zone or the prevalence of alternative routes and the magnitude of those trips. These play important roles for planners and policy makers to guide area-wide transportation system improvements, operations improvements, and land use development and street network improvements.

Area Reach (Origin or Destination)

Similar to the other two concepts, reach also has a single urban area-wide measure that can be used to compare various regions against one other or to summarize this concept for an entire region in a single value. The measure, area reach, can also be calculated based on origins or destinations. As with area trip density, this measure can be used with trips originating or ending outside the urban area (though for this analysis, the measure was calculated using trips internal to the urban area for simplicity). Equation 12 and Figure 10 describe the area reach concept from an origin perspective.

Equation 12. Area Reach (Origin)

$$Area\ Reach\ (Origin) = \frac{\sum Average\ origin\ zonal\ trip\ distances.}{Total\ number\ of\ \boldsymbol{zones}\ in\ the\ urban\ area.}$$

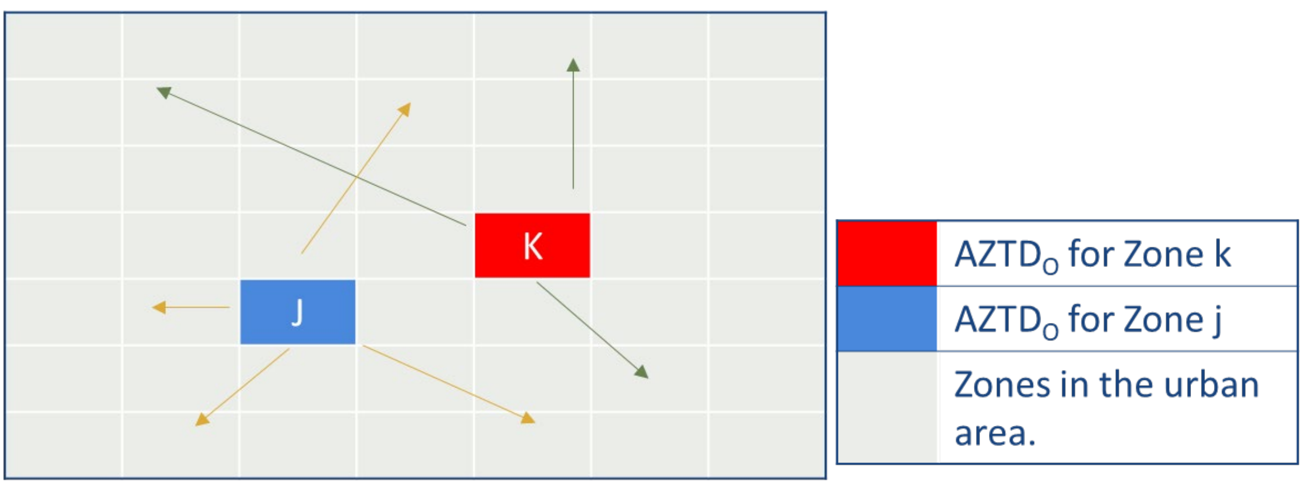

Figure 10. Area reach (origin) illustrated.

Conversely, the same measure can be created from a destination perspective, as seen in Equation 13 and Figure 11.

Equation 13. Area Reach (Destination)

$$Area\ Reach\ (Destination) = \frac{\sum Average\ destination\ zonal\ trip\ distances.}{Total\ number\ of\ \boldsymbol{zones}\ in\ the\ urban\ area.}$$

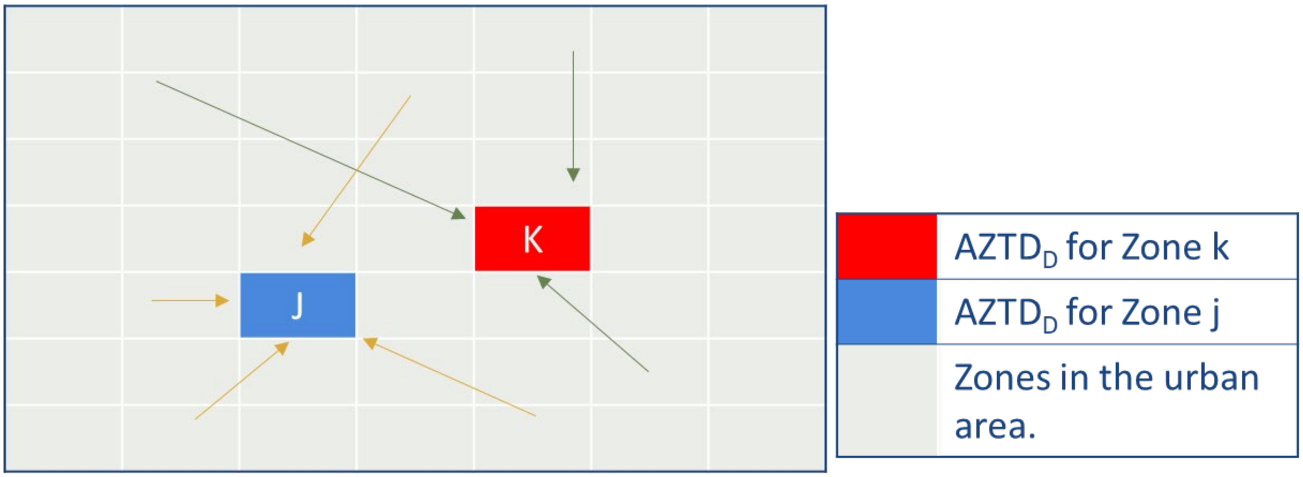

Figure 11. Area reach (destination) illustrated.

Both measures create a single average trip length value for both origination and destination trips. Higher values of either measure would indicate a relatively sprawling pattern of development, fewer alternate routes, and limited connectivity. Lower values may indicate more compact or self-contained development, higher connectivity, and numerous route options. It is important to note that an urban area with a low value does not necessarily mean accessibility in general is low; it could represent high levels of compact development with relatively high access.

For analysis using only trips beginning and ending within the urban area, one might think the origin- and destination-based measures would produce the same value; however, that is not the case. The average of the zones will provide different values. Each of these values should be interpreted separately, even if they are similar. In extreme cases, one might show a directional imbalance in the urban area's connectivity or compactness.

As seen with the other regional measures, area reach provides a single normalized value by which policy makers and planners can assess a region's general path or compare it with other regions. As in other measures, the context of a region's goals and targets play an integral role in interpretation.

Average/Median Trip Length/Time

Average or median trip lengths can also be calculated at the area level by bypassing the zonal average equation. However, this represents a raw value with no normalizing dividend that cannot be compared to other urban areas and nuance about each zone's impact to the region will be lost.

Likewise, average/median trip time can be calculated at both the zone and urban area scales. These values should follow the formulas for average zonal trip distance and area reach to provide a useful value. However, since all measures are crosscut by different travel times, these may not offer a completely accurate picture of travel times in a zone or urban area. To do so, one must perform the calculation agnostic to any travel time bins that may have been used in the other measures thus far.

Chapter 5. Computational Methodology and Processing

Both concurrent to and after the measure development stage, researchers began planning for how the new measures would be calculated and cleaning the available data. This project ultimately consisted of two main components: theory/measure development and data processing. Figure 12 displays how these two components interacted with one another through the life of the project.

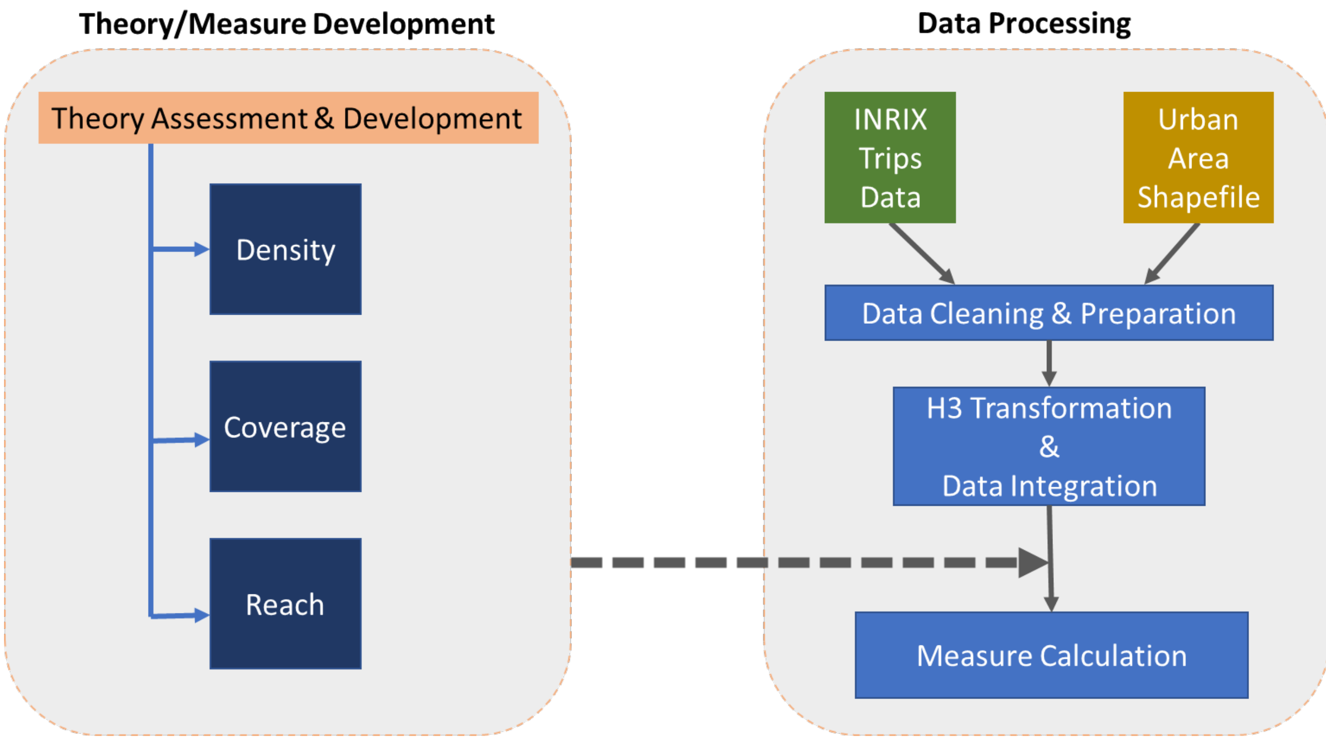

Figure 12. Project process: theory and measure development in context with data processing.

Data Needs

As one of the goals of this research included reducing the data burden on users, researchers sought to minimize the amount of data required to calculate any measures produced. Ultimately, researchers determined the need to use only two required data sources:

1. **Origin-Destination Trips Data –** Provided by INRIX, the Trips dataset offered stripped-down national origin-destination data. *Note that for simplicity and proof of concept, only motor vehicle data were used. Alternative mode data could also be used if available, such as bicycle trip data, detailed travel survey data, etc.*
2. **U.S. Urban Area Shapes –** Provided by the U.S. Census Bureau, this .shp spatial file outlines the boundaries of all urban areas and clusters in the United States.

Researchers found that other data sources could be easily included to add depth and dimension to many of the measures (integrating aspects of utility-based accessibility measures in the process), but they chose to use as little data as possible for replicability and ease of calculation.

INRIX Origin-Destination Data

INRIX provides fine-grained, probe-based, speed level data that cover most of the roadway network, including freeways and surface roads, at high spatial and temporal resolutions.[2] INRIX data can be obtained in various formats, including raw waypoints, trips (origin-destination), or higher-level aggregated products such as Probe Data Analytics and the National Performance Management Research Data Set (NPMRDS).

Basic origin-destination data, like INRIX's Trips dataset, were once difficult to acquire simply because few reliable sources existed or were costly to create through surveys or other methods. However, many states and urban areas have purchased this type of data, as data have become more prevalent from various companies.

This research used national trips data for July and October 2019 (representative months where school is both in and out of session). The trips data include essential information about the trip, such as vehicle type (commercial or consumer), start and end timestamps, longitude and latitude, trip length, total travel time, and other relevant data points. Figure 13 provides an example of all trips that started in Texas in July 2019.

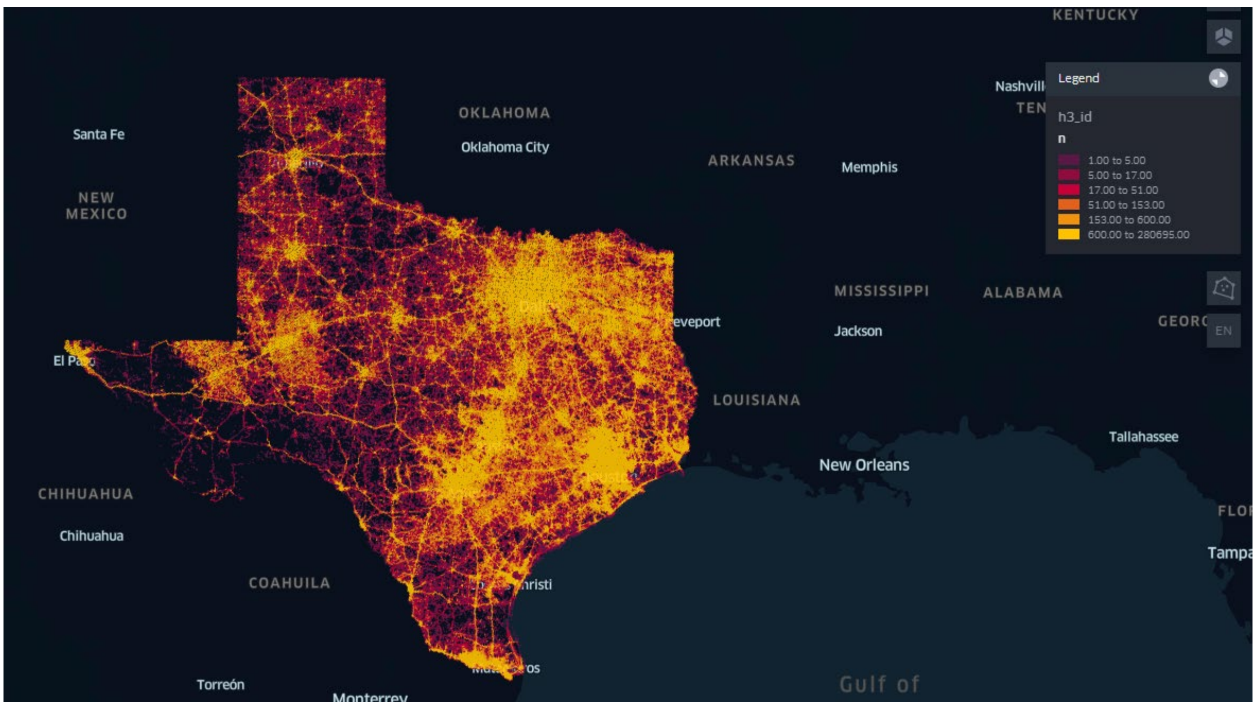

Figure 13. Trip origins in Texas during July 2019.

Upon receiving data from INRIX, researchers examined the data and created a summary of the included information, listed in Table 3. Researchers discussed data stability over time with INRIX, as this could be an issue for future measure calculations. The received data include fleet, connected vehicle, and mobile device data from multiple providers but specifically did not include data that might later become unavailable to users. This alleviates some concerns of data skewing toward freight or newer vehicles, though more research is needed.

[2] Note that trip data obtained from INRIX or other data providers are usually "fuzzied" in some form to protect privacy concerns—often by truncating latitude and longitude to four or three decimals. Data obtained for this research were not fuzzied, though the methods used to categorize trips into zones amply achieved this outcome.

Table 3. INRIX Trips Data Summary Information

Data Collection Period	Total Trips	Consumer Vehicles	Fleet Vehicles
July 2019	1,581,077,663	1,425,664,145	155,413,518
Oct 2019	1,755,765,041	1,595,493,523	160,271,518
Total	**3,336,842,704**	**3,021,157,668**	**315,685,036**

U.S. Census Urban Area Data

The U.S. Census Bureau defines urban areas based on the results of the decennial census, which identifies densely populated areas that include residential, commercial, and other non-residential land uses. These areas are characterized by high population density and urban land use and represent the "urban footprint" of a metropolitan region. Urban areas are ideal for transportation planning purposes because they provide an accurate footprint for development and travel behavior that reasonably occurs. Any larger geography would give empty land too large a weight; any smaller geography would exclude important suburban and exurban commute sheds.

Urban areas are divided into two distinct types: urbanized areas (UAs) with populations of 50,000 or more and urban clusters (UCs) with populations of at least 2,500 but less than 50,000 (excluding urban clusters in the U.S. Virgin Islands and Guam, which may have populations over 50,000). Each urban area is assigned a unique five-digit census code, which may include leading zeroes, for identification purposes. Figure 14 displays a sample of urban areas distributed across the United States as an example—not all urban areas are included in this figure for visualization purposes. There are a total of 3,601 urban areas across the United States (U.S. Census Bureau, 2022).

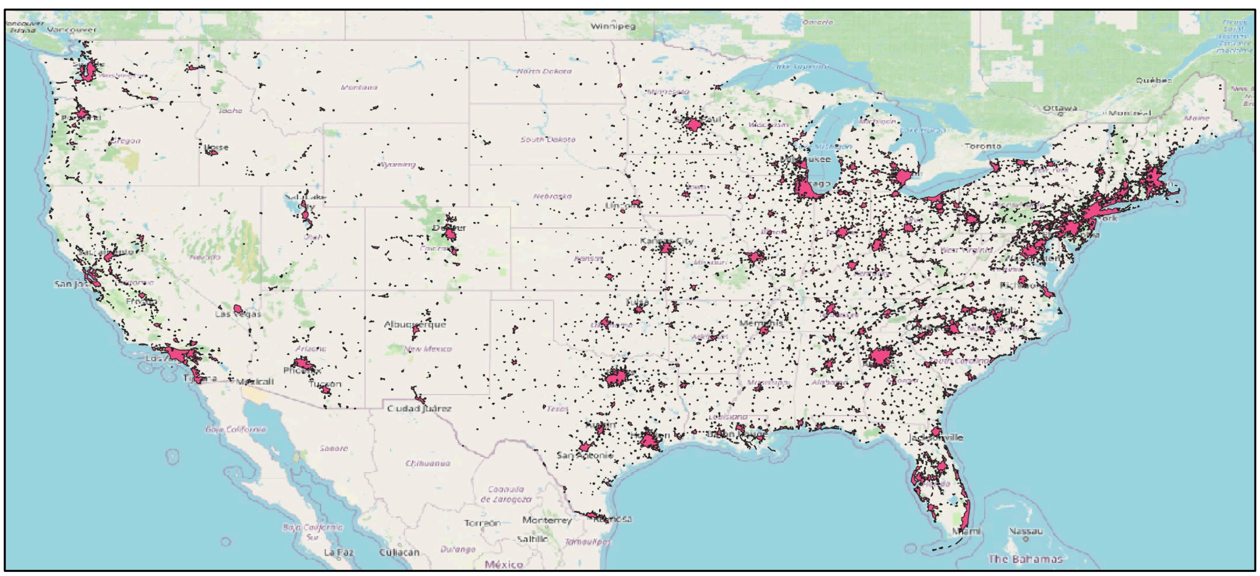

Figure 14. Sample of the urban areas in the United States.

This research focused on the 497 large, urbanized areas as identified in the 2010 U.S. Decennial Census (urban areas with the "U" designation in the shapefiles) and further identified the 101 urban areas used in the Texas A&M Transportation Institute's (TTI) Urban Mobility Report (Schrank et al., 2021). Researchers performed computational tests of each measure on the Austin, Texas, urban area.

Data Cleaning and Preparation

Once researchers collected the data and inputted them into an Azure cloud database, they had to review and clean the data to minimize the number of potential issues when calculating the performance measures. The trips data consist of a wide range of trip records, including very short trips of less than one minute and extremely long trips. To obtain a reasonable set of trips that fits the scope of this study, researchers only considered trips between 2 and 60 minutes in duration. These cutoff boundaries were determined after researchers examined travel time distributions and found that a significant number of trips (91.37%) lie within these boundaries (0.85% below 2 minutes and 7.78% greater than 60 minutes). Figure 15 displays the distribution of all trip times and their cutoff points.

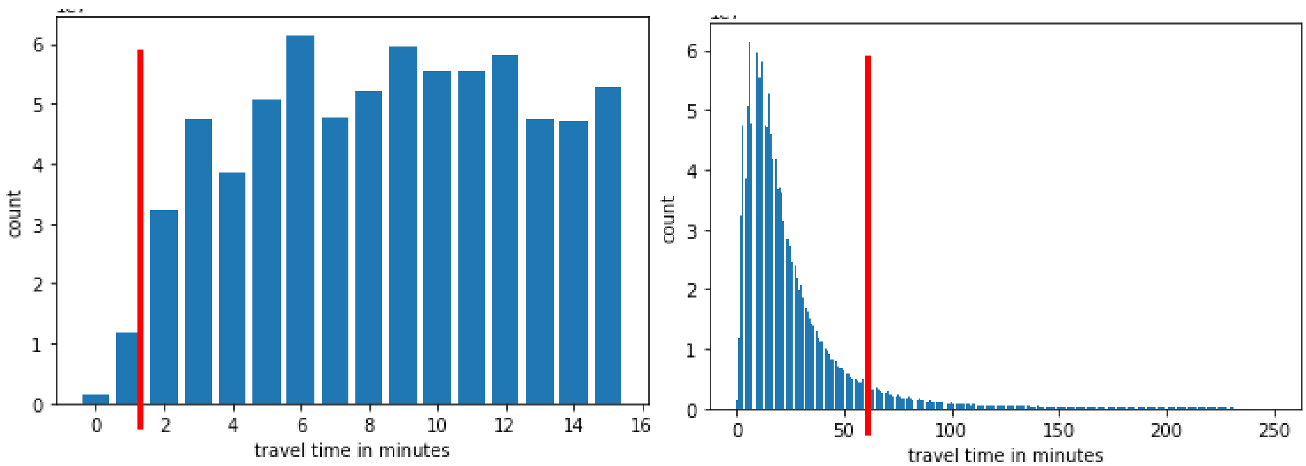

Figure 15. Trip length analysis and cutoff thresholds.

Researchers further investigated trips under two minutes and found that the majority of these trips likely contain errors in trip recognition from the algorithms that assess the mobile data. Nearly no vehicle trip could occur in less than two minutes; however, researchers would like to examine commercial vehicle trips under two minutes to determine if these are last-mile delivery stops. Many of the longer trips were assumed to fall outside of the urban area boundaries, as only trips that begin and end in the urban areas were considered. Additionally, it was decided early in the process to only examine three time periods: trips less than 15 minutes, trips less than 30 minutes, and trips less than 60 minutes.

INRIX does not chain trips and changes the unique identifier for each trip, even if it comes from the same vehicle; however, stop trips are available to create a rough estimate of what a chained trip would represent if needed. For this project and initial development of the measures, researchers assumed every trip was unique and meaningful, so no trip chaining was needed.

Researchers also chose to exclude through trips[3] from this analysis, using only trips that had origins or destinations within the urban area. They found that through trips would only be identifiable if trajectory data were also included in the dataset; efforts to keep measure development and calculation simple should not depend on this larger and more comprehensive dataset. Additionally, researchers theorized that while through trips impact a region's accessibility, they would not register in any proposed measure and would not directly benefit from any improvements in access within an urban area past the extent of their reduced trip time entering and leaving the area. Including through trips would also skew measures of trip density by creating

[3] Through trips are trips that neither start nor stop in any regard within an urban area.

values greater than 1, which would no longer make sense and would shift the measure away from accessibility concepts and toward mobility of the area.

Other cleaning and data validation steps were also completed to verify that each trip contained the necessary metadata, data attributes, and fell within U.S. boundaries. Future expansion of this research could include a deeper examination and understanding of the trips dataset to include a larger sampling of trips.

H3 Method

One of the major challenges in processing the billions of data points representing all trips that occurred in a two-month period across the United States lies in the processing time and feasibility of using this data for accessibility calculations. Simply put, the trips dataset is so large that it hinders efficient calculation at a national scale and would consume a large percentage of the project's budget.

An additional issue to overcome rested in the common zone conundrum: many accessibility measures (including the ones developed by this project) require the use of sub-city zones to measure intra-urban access between neighborhoods or districts. Many accessibility measures use U.S. Census Bureau geographies like census tracts, block groups, or blocks, while others employ transportation analysis zones (TAZs) used in modeling. However, using these geographies presents a few issues. First, boundaries change and change often. This makes comparing year-to-year changes extremely difficult, adding to the complexity of the measures. Second, using these geographies hinders the comparison from city to city because these zones do not share standard dimensions in each urban area. Third, many of the most useful geography types (TAZs or census tracts) that have the most readily available companion data are too geographically large to use in a meaningful way. These issues required researchers to figure out a method for using a standardized geography that is relatively stable, scalable, and universal across all U.S. urban areas.

To overcome this challenge, researchers chose to adopt the H3 method, also known as Uber's Hexagonal Hierarchical Spatial Index. H3 is a geospatial indexing system developed by Uber that divides the world into hexagons of varying resolutions, enabling efficient and accurate geographic data analysis. H3 is open-source and can be used in various applications, including ride-hailing services, navigation, and logistics (Uber, 2018).

The H3 method was appealing for this project because the hexagons will never change—their geolocations and sizes are set at different resolutions. This resolves the issues at hand and solves one other issue: repeatability. If a nontraditional geographic zone system was used, it must be stable and repeatable by others with little to no effort.

After considering the feasibility of calculation and several rounds of testing, researchers selected resolution 8 for generating hexagons inside the urban areas. This resolution averages a hexagonal edge length of 0.33 miles with an average area of 0.28 square miles. Researchers examined the city of Austin, Texas, on a map with this hexagonal resolution overlaid and determined that this resolution provided enough detail without jeopardizing potential privacy issues (because the data have not been fuzzied) or data processing efficiency.

Hexagons to Urban Areas

The next step was to overlay the resolution 8 hexagons over the urban areas shapefile retrieved from the U.S. Census Bureau. As the generated hexagons were combined with the urban area shapes, researchers had to determine a method to deal with the irregular edges of the urban areas that only partially filled a hexagon.

Researchers used a tool in QGIS called “Generate H3 Inside of Polygons” to clip the hexagons to the urban area. This tool will include a hexagon if the urban area covers the centroid of the hexagon. This would generally include most of the area of the hexagon except in extreme examples where an urban area’s boundary “hooks” into the hexagon and crosses the centroid.[4] This then caused some small edges of an urban area to fall outside of an analysis zone. However, in most cases this is not a significant concern since the areas at the edge of the urban areas usually have a limited number of trips generated or ended. Figure 16 illustrates the hexagonal overlay onto an urban area boundary in Austin, Texas.

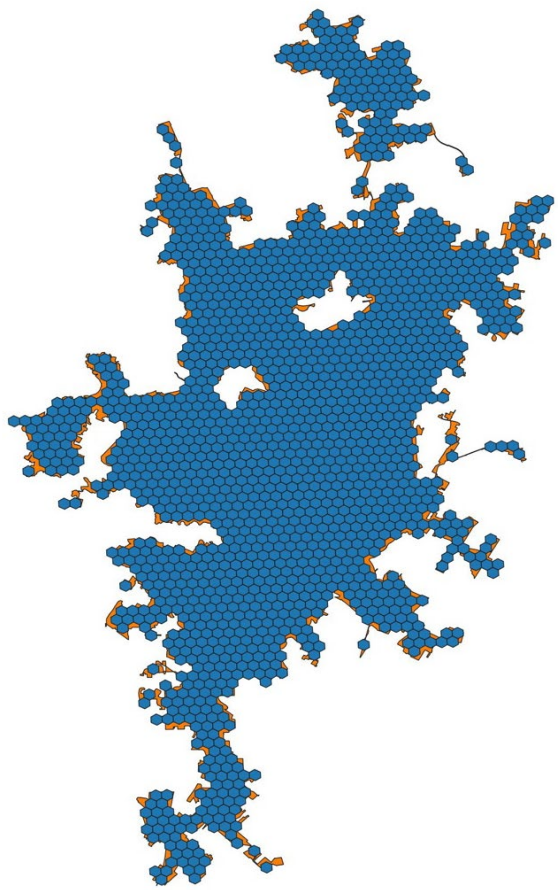

Figure 16. Austin urban area hexagonal.

Finally, researchers had to join the attributes from the original urban area shapefile to the newly generated hexagons using a spatial conflation. The resulting hexagon shapefile retained a unique hexagon ID at resolution 8 as well as the urban area name, GEOID, and other relevant information. Once finalized, this process was performed for all urban areas in the United States. The process generated 320,429 hexagons for 497 urban areas. Table 4 shows the 10 urban areas with the most hexagons.

Table 4. Urban Areas with Largest Hexagon Overlay Count

Rank	Urban Name	Hexagon Count

[4] Researchers anecdotally found this only occurred one time in Laredo, Texas, near a border crossing with Mexico. However, at a glance, a significant portion of the hexagon was still covered by the urban area.

1	New York – Newark, NY – NJ – CT	12,738
2	Atlanta, GA	9,970
3	Chicago, IL – IN	8,661
4	Philadelphia, PA – NJ – DE – MD	7,188
5	Boston, MA – NH – RI	6,655
6	Dallas – Fort Worth – Arlington, TX	5,732
7	Los Angeles – Long Beach – Anaheim, CA	5,545
8	Houston, TX	5,320
9	Miami, FL	5,183
10	Washington, DC – VA – MD	4,888

Data Integration and Measure Calculation

Once researchers converted all urban areas to hexagonal zones, they assigned the latitude and longitude of each trip's start and end points to a specific trip start and trip end hexagon ID (Figure 17). As a result, the H3 ID became the common key linking the urban area hexagons and all trip data. This common key enabled the proposed accessibility indexes to be calculated.

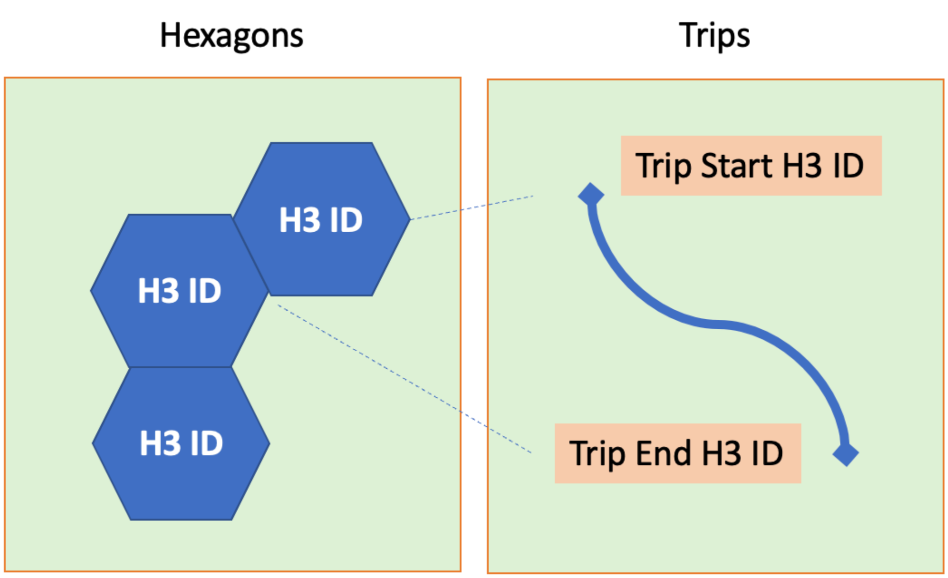

Figure 17. Origin and destination hexagon assignment.

From this point, researchers were able to easily program each performance measure's formula to generate values for each zone and each urban area. Measures were stratified and calculated in several ways to provide the most detail possible. All measures were calculated from either the origin or destination perspective using standard trip time bins of less than 15 minutes, less than 30 minutes, and less than 60 minutes.

Additionally, all measures were stratified by vehicle type, as some vehicle classification data were included. However, the limited nature of the data only allowed for a separation between consumer vehicles and freight vehicles. Therefore, measures were calculated for all vehicles, consumer vehicles only, and freight vehicles only.

Finally, because the data included trip start and end times, researchers were able to classify trips based on the time of day in broad categories. For initial simplicity, these included trips during all periods of the day, trips during the peak hours (6:00 a.m. to 10:00 a.m. and 3:00 p.m. to 7:00 p.m.), and trips during non-peak hours. Additional contextual information might be obtained through a separation of the peak periods into morning and evening peaks and a separation of weekend and weekday trips in addition to overnight trips.

Once the measures for each zone and urban area were calculated, researchers compiled the values into two primary tables: zone level results and urban area level results. Upon completion, the data were reviewed, the results of which are presented in the following sections.

Chapter 6. Measure Results: Austin, Texas

Researchers chose to focus preliminary testing and assessment on the Austin, Texas, urban area as most of them live and work in the area and are familiar with the nuances and neighborhoods Austin offers its residents. This approach proved useful in the iterative process of measure development, measure calculation, and measure assessment and review.

Researchers applied and calculated the new accessibility concepts and measures for motor vehicle trips in the Austin, Texas, area and assessed the results for logical cohesion to determine validity. Ultimately, since the measures reflect real behavior—barring any major data or computational flaws—the values are what they are; researchers simply needed to determine if the results made logical sense based on knowledge of the area and on comparisons with other accessibility maps of the region.

After calculating the core zone-level measures for coverage, density, and reach for motor vehicles, researchers built a Tableau data visualization to display the zone level measures for assessment. Since each measure has several user type and temporal variations, it was decided to display the ones most relevant to audiences who also use the Urban Mobility Report and most like common accessibility maps based on more traditional measures for comparison purposes. These include:

- **Accessibility Perspective:** Origins
- **Time of Day:** All day
- **Trip Length:** Trips less than 30 minutes
- **Vehicle Type:** Consumer vehicles only

When zonal measures are displayed as part of the UMR, users will be able to modify any variables to match the analysis of their choosing. However, the options listed above will be the preset default values.

The following sections offer a brief discussion of each concept and maps displaying the relevant measures for Austin, Texas.

Coverage

As discussed earlier, the concept of coverage at the zone level is represented by the area coverage ratio. When based by origins, this value displays the percent of the urban area each zone can reach within a certain trip time (in this case, 30 minutes for consumer vehicles at all times of the day).

In Austin, the ACR_O quickly reveals that the most accessible zones based on origins include the downtown area, which also includes the State capitol complex and the University of Texas campus (Figure 18). These zones provide access to approximately 65% of the urban area for trip origins and trips under 30 minutes. The zones with the highest access are concentrated in the north-northwest portions of the city known as the Domain and the Arboretum, which can reach approximately 74% and 70% of the urban area, respectively. These areas are known to be popular high-end residential, shopping, and employment centers (the Domain being a second CBD in Austin).

Other important aspects to note are the relative accessibility of the central portion of the city, known for older and more compact housing and development, the surprising accessibility of the city's northwest suburbs of

Cedar Park and Leander, and increased access surrounding freeway and interstate corridors. The relative accessibility matches traditional views of accessibility for the city. However, the accessibility of Cedar Park and

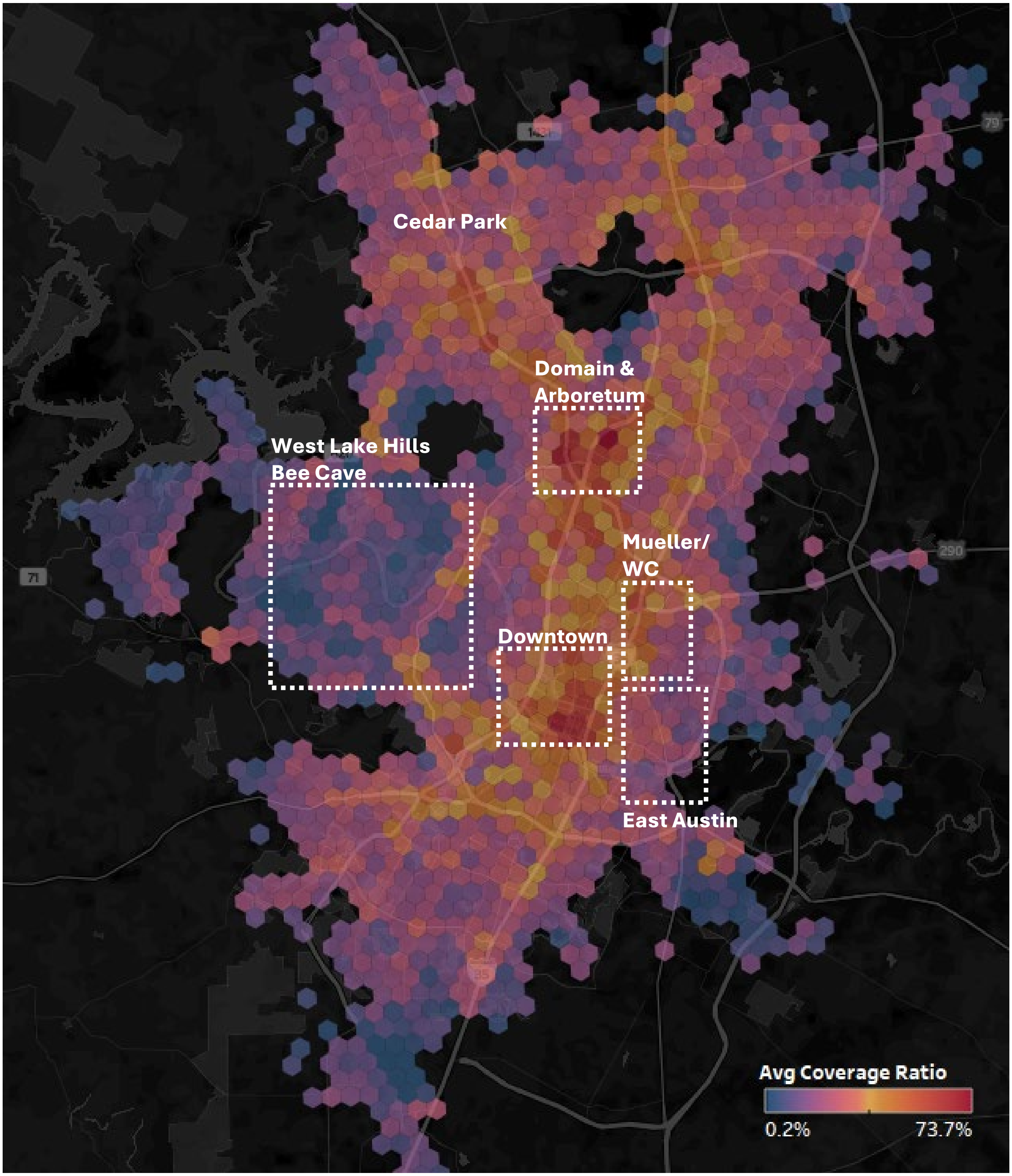

Figure 18. Area coverage ratio (origins) for Austin, Texas, for trips under 30 minutes.

Leander first surprised researchers. Much of the area of those suburbs can access between 25% and 60% of the city within 30 minutes. Upon reflection, the transportation facilities in these areas for motor vehicles (and transit) have been well-developed over time, so the relative accessibility of the area makes sense.

Another aspect of note with the ACR_O is the lack of access for many parts of the urban area. Much of the neighborhoods east of IH 35 cannot access much of the urban area compared to those well-built areas. These areas are historically segregated, and low-income neighborhoods were cut off from the city and its growth with the development of the interstate corridor. These areas of the city have ACR_O scores of 25% or less, indicating a significant transportation and access equity issue.

Only two areas—the Mueller neighborhood and the Walnut Creek Business Park—have any significant increases in access east of IH 35. These areas have been heavily gentrified over time. Researchers were surprised to find, however, that the Mueller area did not score higher as the master-planned development boasts high accessibility and compact development patterns. Much of this could be due to the auto-focus of the data that does not include alternate modes at this time.

Comparison with a Traditional Measure

The ACR_O is most closely related theoretically to what is likely the most-used traditional accessibility measure: access to jobs within 30 minutes. Figure 19 displays auto accessibility to jobs within 30 minutes in the Austin area during the same time period (2019) as the calcualted ACR_O measure (Owen & Murphy, 2021). One will quickly note that the two images differ significantly within the calculation boundaries.

The traditional measure heavily inflates accessbility to employment in the Austin area from the access that actually occurred. This inlcudes the neighborhoods of West Lake Hills, the northeastern shore of Lake Travis, and the far western areas of Bee Cave. However, contextually these areas are isolated due to extreme topography and limited transportation network development. While spatially close to the Austin core, they are difficult to reach in reality. These are also highly affluent areas where most residents have a significant amount of location choice opportunity.

Conversely, the traditional accessibility map also grossly overstates accessibility for low-income and segregated neighborhoods. Referring again to the areas of Austin east of IH 35, the map scores these areas with some of the highest accessbility ratings in the city. However, that is simply not the case based on real observed behavior. This contradiction points to one of the fundamental issues with the traditional accessibility theory: it measures a hypothetical universe of access and does not reflect actual access. In this case, issues with transportation equity would not be discoverable without an extensive amount of additional context and data sources.

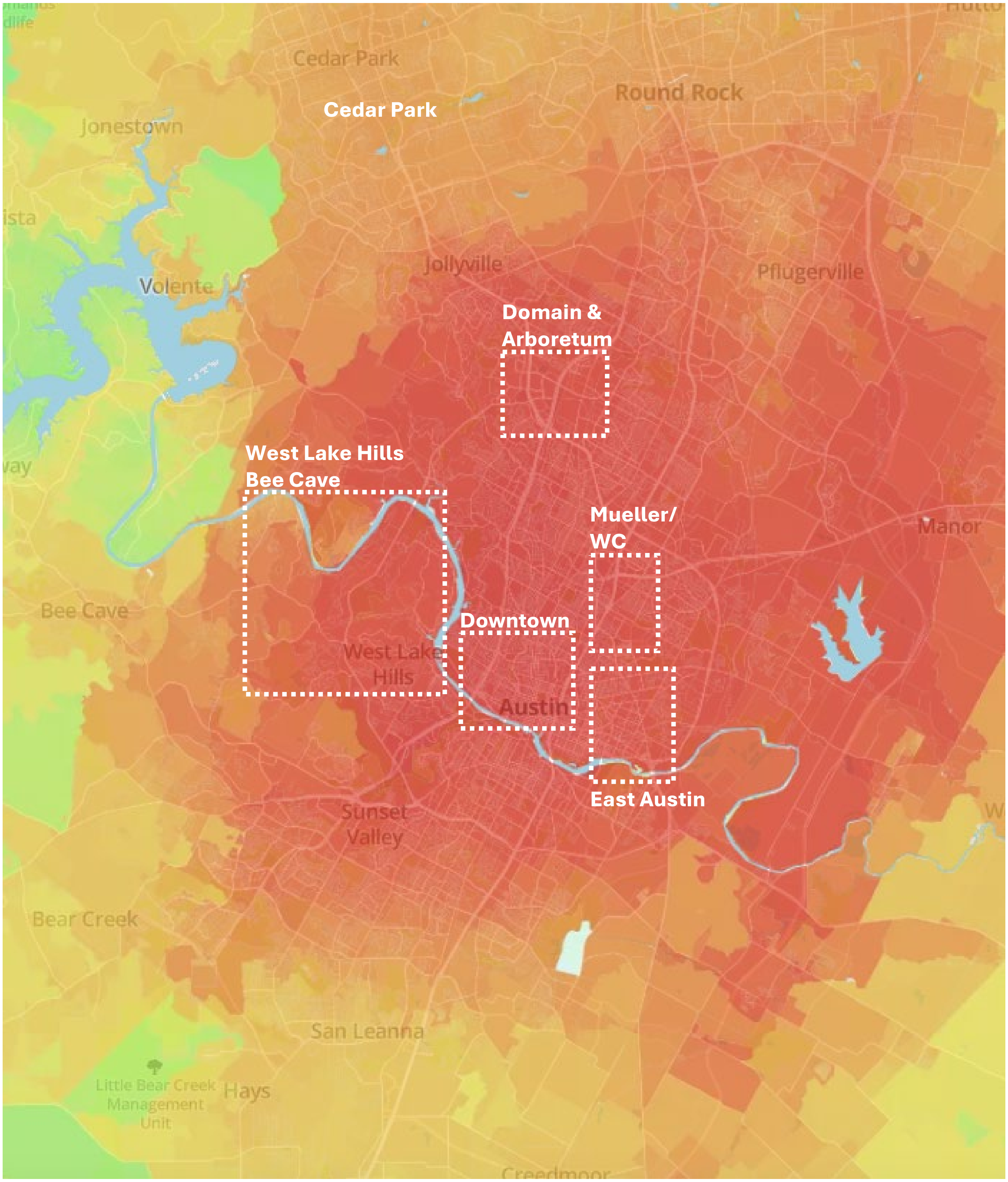

Figure 19. Auto accessibility to jobs within 30 minutes, Austin Texas.

Density

Meaures of density at the zone level, in this case zonal trip origin density, reflects the proportion of trips that begin in each zone relative to the entire urban area. The intent of this measure displays where an area's primary trip generators are located (and trip attractors, when examining the measure from a destination perspective). While the value of the measure itself is neither good nor bad, it can reveal areas of importance or areas where improvement could be needed—all based on the region's policy objectives and goals.

In Austin (Figure 20), the areas in and immediately around the University of Texas campus and downtown hold the highest density of trip origins, with values as high as 1.3% of all trips in the Austin area beginning at the university. This surprised researchers initially because CBDs are generally expected to contain more trips than other areas. However, the university has one of the highest on-campus enrollments in the nation, a significant auto commuter population, and universities in general have many more opportunities for trips as class schedules cycle throughout the day.[5]

Other hotspots were primarily limited to high intensity retail and commercial office areas where multiple trips start and end throughout the day. When researchers examined different times of day (versus all day displayed in Figure 20), they found a distinct difference between time of day and type of land use that holds the highest densities. Non-peak hours lean more heavily toward shopping areas, while peak periods lean more heavily toward employment areas. If the peak times are split into morning and afternoon peaks, a different pattern might emerge that offers a significantly improved view into the trip density of residential areas.

Notably, the only residential areas that held any sort of significant trip origin density were those located near commercial opportunities, such as along primary freeways and arterials, or that were located near high activity centers. This would include downtown-adjacent neighborhoods; neighborhoods along South Congress Avenue, First Street, and Lamar Boulevards; areas with high-density apartment complexes; and areas near the commuter rail line.

For planning and policy purposes, there will be some areas that should never have increases in trip density. However, planners could examine areas of the city that have unused capacity for increasing trip density over time. When paired with alternative modal information, like transit counts by stop, bikeshare usage, or remote work values, more precise project alternatives could be developed to either increase or decrease trip density.

[5] The color scale in Figure 20 has been amplified by a power of 0.5 to allow colors to be more pronounced due the nature of the values.

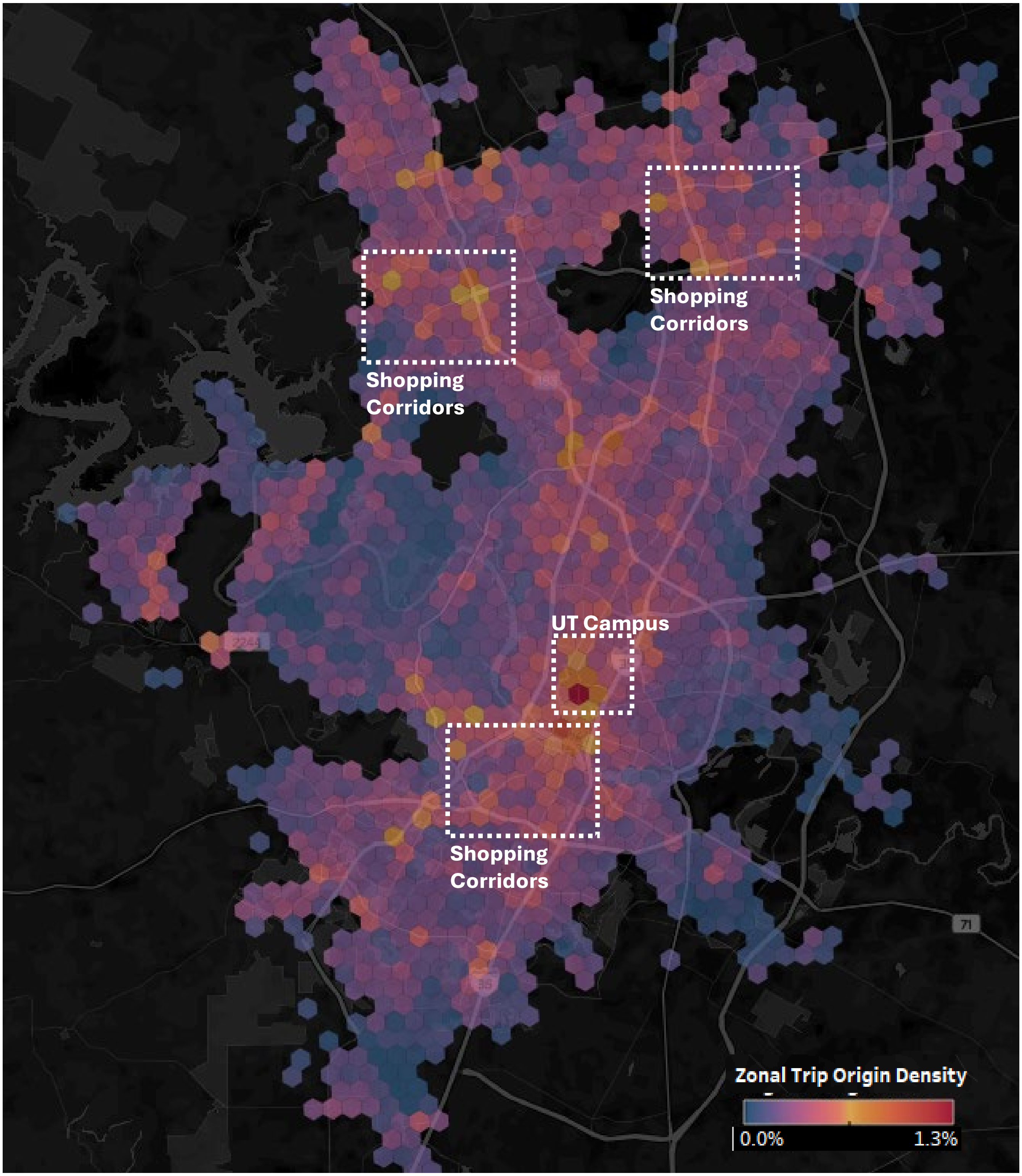

Figure 20. Zonal trip origin density for Austin, Texas, for trips under 30 minutes.

Reach

The final concept, reach, at the zone level is represented by the average origin zonal trip distance (ATD_O). This measure calculates the average path distance for all consumer vehicle trips starting in a zone that last under 30 minutes.

In Austin, the ATD_O reveals areas of relative self-containment, where most core trips likely occur close to home (Figure 21). This can clearly be seen in the areas in and around the University of Texas campus. Again, this area experiences a high density of trips, but many of these trips likely are to nearby locations, with the lowest trip distance of 1.9 miles. Interestingly, the next lowest trip distance region is the area around Zilker Park (the main and most popular park in the area). The park area is surrounded by shops, apartments, and restaurants that allow for most activities to be contained within the area. This type of pattern can be marginally seen in other smaller areas of interest, generally near breweries and neighborhood centers.

Additionally, areas with generally low coverage because of topography (hills and the north bank of Lake Travis) and areas on the outskirts of the city have the highest average trip distances. This makes sense as they have the lowest amount of access to key destinations. Also of note, low-income areas (mostly to the east of IH 35 and the far southeast) have some of the longest trip distances, again revealing a transportation equity issue. Planners and policy makers could focus on efforts to decrease the average trip distance for these inequitable areas. Conversely, depending upon the community's goals, planners and policy makers could focus on increasing average trip distance (or access) for areas that make sense to do so.

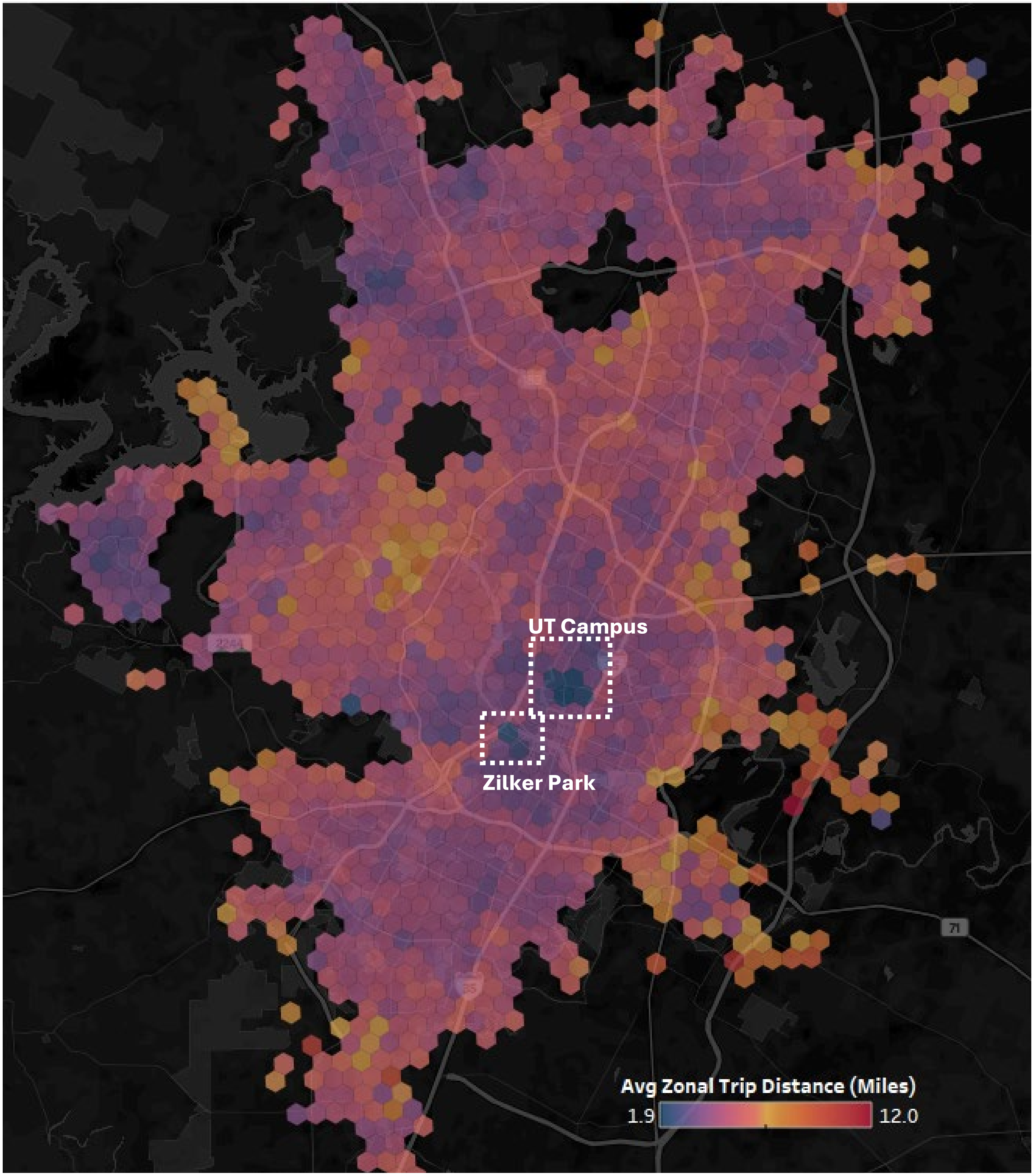

Figure 21. Average origin zonal trip distance for Austin, Texas, for trips under 30 minutes.

Chapter 7. National Results

The new accessibility concepts and measures are just as useful at a national level as they are within an urban area. One of the primary goals of this project was to create a set of accessibility measures that could be flexible enough to transcend different geographic scales and to be comparable with one another. The core measures of coverage, density, and reach do just that.

After researchers calculated zone-level measures for all urban areas in the United States, they calculated the urban-area scaled measures for assessment. Since each measure has several user type and temporal variations, researchers have chosen to display the ones most relevant to audiences who also use the Urban Mobility Report. These include:

- **Accessibility Perspective:** Origins
- **Time of Day:** All day
- **Trip Length:** Trips less than 30 minutes
- **Vehicle Type:** Consumer vehicles only

When measures are displayed as part of the UMR, users will be able to modify any of those variables to match the analysis of their choosing. However, the options listed above will be the preset default values.

The following sections provide the top 10 results for each measure in two different ways. The first will be the overall top 10 based on the 101 primary urban areas covered by the UMR. The second will be the top 10 based on urban areas considered "Very Large" by the UMR, as these cities are most discussed and compared historically within the UMR's mobility measures. However, because of the normalization within each measure, all urban areas can be compared correctly to one another. These values represent motor-vehicle value only; urban areas with high transit use may not appear to be representative by reputation.

Coverage

Coverage is covered by the total real urban coverage (TRUC) value. Similar to the ACR, this value reports the percentage of an urban area that can be reached; it differs in that the ACR performs this for only a single zone whereas the TRUC combines the ACRs for all zones within the urban area.

Table 5 displays the top 10 national TRUC coverage cities and their values (in addition to their reach values) for 2019. The TRUC values can be interpreted as the following: Consumer vehicle trips that begin in Laredo, Texas, can reach 78.6% of the urban area within 30 minutes.

Table 5. Total Real Urban Coverage (Origins) for UMR 101 Urban Areas

Rank	Urban Area	*$TRUC_O$	Reach (Miles)
1	Laredo, TX	78.6%	4.0
2	Boulder, CO	72.6%	3.1
3	McKinney, TX	58.4%	3.8
4	Bakersfield, CA	57.6%	4.4
5	Salem, OR	53.2%	3.9
6	Fresno, CA	51.8%	4.8
7	Brownsville, TX	51.4%	4.4
8	Stockton, CA	50.3%	4.5
9	Boise City, ID	48.5%	4.2
10	Eugene, OR	48.0%	4.2

The list in Table 5 conveys two relatively distinct messages. First, some urban areas represent small to medium-sized cities with well-developed roadway networks and (likely) relatively low issues with mobility. These would include places like Laredo, Brownsville, Stockton, and Fresno. Note the reach (average trip path length in miles) value next to these. In these cases, the reach score is relatively high indicating that travelers are traveling further to reach accessible destinations.

However, there is also a second distinct grouping of urban areas. These—also small to medium-sized—urban areas represent more compactly developed areas that may benefit from their land development patterns (as indicated by their lower reach scores). The urban areas of Boulder, Salem, McKinney, Boise, and Eugene all have relatively low average trip lengths, but travelers can still access a high percentage of the urban area. This indicates a relative measure of self-containment and compact development.

Table 6. Total Real Urban Coverage (Origins) for UMR's Very Large Urban Areas

Rank	Very Large Urban Area	*$TRUC_O$	Reach (Miles)
1	San Diego, CA	16%	5.1
2	San Francisco--Oakland, CA	14%	4.0
3	Phoenix--Mesa, AZ	12%	5.3
4	Los Angeles--Long Beach--Anaheim, CA	9%	4.2
5	Miami, FL	9%	4.7
6	Dallas--Fort Worth--Arlington, TX	8%	5.3
7	Detroit, MI	8%	5.1
8	Houston, TX	7%	5.0
9	Seattle, WA	6%	4.7
10	Washington, DC--VA--MD	6%	4.6

The Very Large urban area list from the UMR (Table 6) reveals a similar pattern of cities: some represent areas with well-developed auto infrastructure while others are more compact—most corresponding well with their reach values as well. However, there are a couple of oddities that require further explanation. Urban areas like San Diego and Seattle have relatively high TRUC values but also have high reach values—even though historically they are known for being more compact in nature. This could be attributed to their geography. Both urban areas are built around significant geographic constraints (the ocean and mountains for San Diego and Puget Sound and other lakes in Seattle). The geographic constraints could help explain their relatively higher reach values. San Diego may differ from Seattle in another way: mobility. Recall that mobility is contained as a factor under a broader accessibility umbrella. These values are calculated during the entire day; San Diego's peak period may be significantly shorter or less intense than Seattle's, allowing travelers to reach a higher percentage of the area during off-peak periods.

Density

The concept of density is conveyed by area trip density (ATD) at the urban scale. In this case, ATD reports the average number of trips that begin per zone in an urban area. While it resembles the zonal trip density value, ATD does not average zone densities on their own (i.e., an average of an average). Table 7 and Table 8 display the top 10 urban areas for density for the UMR 101 and the UMR Very Large urban areas.

Table 7. Area Origin Trip Density for UMR 101 Urban Areas

Rank	Urban Area	Trip Density
1	Laredo, TX	7,700
2	Los Angeles--Long Beach--Anaheim, CA	7,229
3	San Jose, CA	6,085
4	Las Vegas--Henderson, NV	5,605
5	San Francisco--Oakland, CA	4,748
6	New York--Newark, NY--NJ--CT	4,729
7	Miami, FL	4,628
8	Dallas--Fort Worth--Arlington, TX	4,604
9	San Diego, CA	4,578
10	McKinney, TX	4,298

Table 7 displays the top 10 urban areas and their ATD values for 2019. The ATD values can be interpreted as the following: Laredo, Texas, averaged 7,700 consumer vehicle 30-minute-or-less trip starts per zone.

Motor vehicle trip densities in urban areas based on the top 10 can be viewed as a function of the urban area's relative and general population and development density and the likelihood for many smaller trips. The Los Angeles area is known for being one of the densest urban areas in the United States among others in the list; it is no surprise that it and others like San Jose, San Francisco, and New York score highly in this value.

One surprising find is Laredo, Texas, at the top spot. While further investigating the nuances of the trips data for more information, researchers postulate that the high average trip density is a factor of Laredo being a relatively small urban area but a major border crossing area. Potential nuances with data collection or just sheer volume of daily border crossings could weight this area greatly.

Table 8. Area Origin Trip Density for UMR Very Large Urban Areas

Rank	Very Large Urban Area	Trip Density
1	Los Angeles--Long Beach--Anaheim, CA	7,229
2	San Francisco--Oakland, CA	4,748
3	New York--Newark, NY--NJ--CT	4,729
4	Miami, FL	4,628
5	Dallas--Fort Worth--Arlington, TX	4,604
6	San Diego, CA	4,578
7	Houston, TX	4,177
8	Phoenix--Mesa, AZ	3,750
9	Chicago, IL--IN	3,204
10	Washington, DC--VA--MD	2,735

Examining the top 10 list for Very Large urban areas in the UMR bring no surprises. All urban areas make logical sense when compared to their values. However, a critical examination of the values may raise an issue with both Chicago and Washington, which have relatively low trip origin densities. Upon further examination, researchers believe this could be due to many commuters living outside the urban area and many short trips taken by transit or another mode than by motor vehicles (especially in Washington). However, New York may still have a high trip density due to taxis and ride share trips that are still included in this vehicle-only dataset.

Reach

Finally, the concept of reach is conveyed by area reach at the urban scale. Area reach represents the average trip path length for each zone in the urban area and is expressed in miles. Table 9 and Table 10 display the top 10 urban areas for area reach for the UMR 101 and the UMR Very Large urban areas.

Table 9. Area Origin Reach for UMR 101 Urban Areas

Rank	Urban Area	Reach
1	Tulsa, OK	5.8
2	Louisville/Jefferson County, KY--IN	5.8
3	Jacksonville, FL	5.7
4	Columbia, SC	5.6
5	St. Louis, MO--IL	5.6
6	Minneapolis--St. Paul, MN--WI	5.6
7	Little Rock, AR	5.6
8	Birmingham, AL	5.6
9	Jackson, MS	5.6
10	Memphis, TN--MS--AR	5.6

Table 9 displays the top 10 urban areas and their reach values in 2019. The reach values can be interpreted as the following: Consumer vehicle trips starting in Tulsa, Oklahoma, of less than 30 minutes could travel an average of 5.8 miles.

Similar to other measures discussed thus far, the national top 10 list follows a consistent pattern of the urban areas that bubble to the top of the list. However, in this case, the urban areas represent medium-sized and low-density urban areas with well-developed transportation networks and generally many freeways and interstates. This extension of reach indicates a level of motor vehicle accessibility due to transportation priorities and policies realized over many decades. Several of these urban areas also have geographic constraints such rivers/bridges or protected areas that many may have to drive through, thereby lengthening distance traveled.

Table 10. Area Origin Reach for UMR Very Large Urban Areas

Rank	Very Large Urban Area	Reach
1	Atlanta, GA	5.32
2	Phoenix--Mesa, AZ	5.30
3	Dallas--Fort Worth--Arlington, TX	5.28
4	Detroit, MI	5.10
5	San Diego, CA	5.08
6	Houston, TX	5.01
7	Seattle, WA	4.73
8	Miami, FL	4.67
9	Philadelphia, PA--NJ--DE--MD	4.65
10	Washington, DC--VA--MD	4.63

When examining the Very Large urban areas, a similar pattern emerges: low density and well-developed transportation networks of freeways and interstates. Additionally, urban areas with geographic constraints, such as Seattle, San Diego, and Miami, can again be seen with a larger reach compared to other peer urban areas.

A complete list of the UMR 101 urban areas and their scores can be found in Appendix A. The full set of 497 U.S. urban areas will be available upon release of the next edition of TTI's Urban Mobility Report in the fall of 2023.

Chapter 8. Next Steps and Future Research

The development of this new theoretical framework and accompanying accessibility measures would be incomplete without the implementation and adoption of the theory and measures in real and practical applications. Only when planners, modelers, policy makers, and the public begin to use and integrate the measures into existing processes and broader transportation planning use cases will the implementation be considered a success.

To do so, researchers plan to publish this research through several different avenues:

1. **New Chapter of TTI's Urban Mobility Report (UMR):** First, the concepts presented in this report will be incorporated into a new chapter on accessibility in TTI's Urban Mobility Report. The UMR has been an established authority in mobility performance measurement for more than 40 years. The report is held in high regard as an authority for urban-area scale delay and reliability measures; the addition of accessibility measures to the report will broaden its reach and impact among a wider range of audiences—both existing and new. Care must be given to properly explain the nuances of each measure and how to properly interpret the results.

2. **New UMR Data Visualization Dashboard:** In addition to adding the concepts and measures in print, researchers will create and integrate the accessibility measures and values for the 101 UMR urban areas into the existing interactive Tableau visualization (https://mobility.tamu.edu/umr/congestion-data/). This high-visibility option provides planners, practitioners, and the public a simple way to access their own city's scores without having to purchase data or perform any computational effort. The values are presented with limited interpretation inside the visualization.

3. **Academic Settings:** To promote the spread of knowledge, ideas, and creativity in the further development of accessibility theory, researchers plan to publish versions of this research through scholarly academic journals, conferences, and meetings. Efforts to publish will specifically target the Transportation Research Board (TRB) through the Standing Committees on Highway Traffic Monitoring (ACP70), Equity in Transportation (AME10), Statewide/National Transportation Data and Information Systems (AED10), and the City Transportation Issues Coordinating Council (A0030C) and TRB's journal, the *Transportation Research Record*. Other related planning journals may also be targeted.

4. **Speaking Engagements:** Finally, researchers propose to promote the uptake and implementation of the theory by targeting conferences and speaking engagements to relevant stakeholders. This would include city and MPO officials through avenues such as the Association of Metropolitan Planning Organizations (AMPO), the American Planning Association (APA), and other related entities. The concept and results of this research will also be disseminated through the Federal Highway Administration's pooled fund study, Support for Urban Mobility Analysis (SUMA), which has a reach of 18 State DOTs.

Furthermore, researchers plan to continue this research and expand the scale and scope of the theory and measures developed through the project by applying the measures to corridor and roadway segment scales. Additional research on this topic will amplify the reach of the implementable products exponentially over time.

Future Research

The development of new performance measures includes a vast amount of additional research that could be performed to improve the use, accuracy, and understanding of the concepts and measures. Researchers in this project identified several areas needing additional research and thought to promote the ideas developed here.

1. **Freight Accessibility Framework:** Since freight vehicles (both long-haul and delivery) are included in the trips and trip traces datasets, the development of a freight accessibility framework could introduce an entirely new field of freight access consideration in the planning process. Other freight issues, like freight fluidity, truck parking, last-mile delivery, commodity corridor planning, and supply chain management, all touch on and would greatly benefit from freight accessibility concepts. Freight-specific measures could be developed to advance freight planning and monitoring.

2. **Delivered Goods Accessibility:** With a significant portion of the population's shift to online shopping, access to delivered goods offers a new avenue by which transportation and supply chain equity could be examined and measured. The development of delivery-specific or related equity measures would provide a first view into this issue.

3. **Methods Expansion:** To expand the scope of this project, long trips (greater than 60 minutes) could be included in addition to trips that either start or end outside of the urban area boundaries. This could offer a different window into super commutes, commutes from neighboring urban areas (such as in Washington, D.C.), and rural access to urban areas. Information about longer trips could also identify and inform potential opportunities for public transport or long-range freight movement. Additionally, researchers could further stratify data by morning and evening peak periods, which may show additional context during peak travel hours.

4. **Use Case Methodology:** One element the scope of this project could not include was the development of a set of use cases and the methodology for using the measures within existing transportation planning and equity assessment. Providing guidance on measure interpretation, integration into existing processes, and how they more effectively relate to transportation equity research and implementation will dramatically improve implementation outcomes. One initial concept would be methodology describing the use of multiple measures at once. Researchers quickly discovered utility in doing so (e.g., combining TRUC with reach to identify if an urban area has a well-developed network or is a compact and self-contained area).

5. **Modal Integration:** Finally, the integration of alternative modes with relevant data would dramatically improve the broad power of the measures developed in this project. Including alternate modes—such as work-from-home options—would increase the ability of these measures to assess equity within an urban area and provide planners with valuable contextual information that is lost by examining only a single mode.

Chapter 9. Conclusion

While new developments in accessibility performance measurement could greatly impact how planners, policy makers, practitioners, and the public view transportation—especially considering how it interacts with land use—there is still no direct connection between access and equity. This lack of connection is similar to mobility concepts and connecting broader equity goals. While certain groups are quick to point out the failings of transportation planning—using the correct measures—there have yet to be practical recommendations for using performance measures to truly impact transportation equity in a manner that is simple to implement and fits well within the entrenched transportation planning and programming framework.

This lack of connection stems from the issue that transportation equity, livability, and other similar concepts have yet to be adequately defined in transportation terms. This is the difficulty with much of the current equity discussion occurring in the United States: multiple definitions, theories, and perspectives on transportation equity paralyze planners, practitioners, and policy makers into meaningful inaction. Both mobility and accessibility concepts could be operationalized in an equity-sensitive manner depending upon how equity is defined and how measures are used within specific contexts.

However, researchers hope that progressing the theory of accessibility into one that reflects real behavior, is simple to measure, and is simple from which to set policy, will ultimately push the discussion of transportation equity forward. Accessibility holds much promise—when used in context and appropriately with other concepts like mobility, reliability, and connectivity—to address many transportation equity concerns. Providing those responsible with proper tools to make better transportation and land use decisions will set them up for success in the long term.

At the end of the day, planners and other transportation professionals need to make complex programming and investment decisions and therefore will rely on those performance measures that aid in the decision-making process.

References

Albacete, X., Olaru, D., Paül, V., & Biermann, S. (2017). Measuring the accessibility of public transport: A critical comparison between methods in Helsinki. *Applied Spatial Analysis and Policy*, *10*, 161–188.

Apparicio, P., Cloutier, M. S., & Shearmur, R. (2007). The case of Montreal's missing food deserts: evaluation of accessibility to food supermarkets. *International Journal of Health Geographics, 6*(1), 1–13.

AVV, 2000. NVVP beleidsopties verkend [the National Traffic and Transport Policy options explored]. AVV Transport Research Centre, Rotterdam.

Axhausen, K. W. (2007). Activity spaces, biographies, social networks and their welfare gains and externalities: some hypotheses and empirical results. *Mobilities, 2*(1), 15–36.

Ben-Akiva, M., & Lerman, S. R. (1979). Disaggregate travel and mobility choice models and measures of accessibility. In D. A. Hensher & P. R. Sopher (Eds.), *Behavioural Travel Modelling* (pp. 654–679).

Ben-Akiva, M., & Lerman, S. R. (1985). Discrete choice analyses: theory and application to travel demand. Cambridge: MIT Press.

Bertolini, L., Clercq, F., & Kapoen, L. (2005). Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making Two test-applications in the Netherlands and a reflection on the way forward. *Transport Policy, 12*, 207–220.

Blumenberg, E., & King, H. (2021). Jobs–housing balance re-re-visited. *Journal of the American Planning Association, 87*(4), 484–496.

Breheny, M. J. (1978). The measurement of spatial opportunity in strategic planning Regional Studies, 12.

Buliung, R. N., & Kanaroglou, P. S. (2006). A GIS toolkit for exploring geographies of household activity/travel behavior. *Journal of Transport Geography, 14*(1), 35–51.

Calabrese, F., Diao, M., Lorenzo, G. D., Ferreira, J., Jr., & Ratti, C. (2013). Understanding individual mobility patterns from urban sensing data: a mobile phone trace example. *Transportation Research Part C, 26,* 301–313.

Casas, I. (2007). Social exclusion and the disabled: An accessibility approach. *The Professional Geographer*, *59*(4), 463–477.

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: density diversity and design. *Transportation Research Part D: Transport and Environment, 2*, 199–219.

Cervigni, F., Suzuki, Y., Ishii, T., & Hata, A. (2008). Spatial accessibility to pediatric services. *Journal of Community Health*, *33*, 444–448.

Chen, C., Ma, J., Susilo, Y., Liu, Y., & Wang, M. (2016). The promises of big data and small data for travel behavior (aka human mobility) analysis. *Transportation Research Part C Emerging Technologies, 68,* 285–299.

Curl, A., Nelson, J. D., & Anable, J. (2011). Does accessibility planning address what matters? a review of current practice and practitioner perspectives. *Research in Transportation Business & Management, 2,* 3–11.

DETR, 2000. Transport 2010. The background analysis. Department of the Environment, Transport and the Regions, London.

Federal Highway Administration. (2017). 2017 National household travel survey. U.S. Department of Transportation. https://nhts.ornl.gov

Geurs, K. T., & Ritsema van Eck, J. R. (2001). Accessibility measures: review and applications. Evaluation of accessibility impacts of land-use transportation scenarios, and related social and economic impact, RIVM Report 408505 006 edn, National Institute of Public Health and the Environment.

Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography, 12*, 127–140.

Gonzalez, M. C., Hidalgo, C. A., & Barabasi, A. L. (2008). Understanding individual human mobility patterns. *Nature, 453*(5), 779–782.

Gutiérrez, J., & Urbano, P. (1996). Accessibility in the European Union: the impact of the trans-European road network. *Journal of transport Geography*, *4*(1), 15–25.

Gutierrez, J., & Gomez, G. (1999). The impact of orbital motorways on intra-metropolitan accessibility: the case of Madrid's M-40. *Journal of Transport Geography*, *7*(1), 1–15.

Halden, D., McGuigan, D., Nisbet, A., & McKinnon, A. (2000). Accessibility: Review of Measuring Techniques and their application, Scottish Executive Central Research Unit.

Handy, S. L. (2002). Accessibility- vs. mobility-enhancing strategies for addressing automobile dependence in the U.S. UC Davis: Institute of Transportation Studies. https://escholarship.org/uc/item/5kn4s4pb

Handy, S. and Niemeier, D. (1997). Measuring accessibility: an exploration of issues and alternatives. *Environment and Planning A, 29*(7): 1175–1194.

Hägerstrand, T. (1970). What about people in regional science? *Papers in Regional Science, 4*(1), 6–21.

Horner, M. W., & Mascarenhas, A. K. (2007). Analyzing location-based accessibility to dental services: an Ohio case study. *Journal of public health dentistry*, *67*(2), 113–118.

Ingram, D. R. (1971). The concept of accessibility: a search for an operational form. *Regional Studies*, 5, 101–107.

Järv, O., Ahas, R., & Witlox, F. (2014). Understanding monthly variability in human activity spaces: A twelve-month study using mobile phone call detail records. *Transportation Research Part C: Emerging Technologies*, *38*, 122–135.

Kamruzzaman, M., & Hine, J. (2012). Analysis of rural activity spaces and transport disadvantage using a multi-method approach. *Transport Policy, 19*(1), 105–120.

Kwan, M. P. (1998). Space-time and integral measures of individual accessibility: A comparative analysis using a point-based framework. *Geography Annals, 30*, 191–217.

Kwan, M. P. (1999). Gender and individual access to urban opportunities: A study using space–time measures. *Professional Geography, 51*, 211-227. 10.1111/0033-0124.00158.

Kwan, M. P., Murray, A. T., O'Kelly, M. E., & Tiefelsdorf, M. (2003). Recent advances in accessibility research: Representation, methodology and applications. *Journal of Geographical Systems, 5*, 129–138. 10.1007/s101090300107.

Lasley, P. (2017). Influence of Transportation on Residential Choice: A Survey of Texas REALTORS® on Factors Affecting Housing Location Choice. Texas A&M Transportation Institute, Policy Research Center. https://policy.tti.tamu.edu/congestion/influence-of-transportation-on-residential-choice/

Lasley, P., Guo, S., Graham, M., & Peng, Y. (2019). How close to reality are they: a comparison of traditionally calculated accessibility measures with real-world origin-destination data. *TRB 98th Annual Meeting Compendium of Papers Transportation Research Board of the National Academies*.

Lee, J., & Miller, H. J. (2019). Analyzing collective accessibility using average space-time prisms. *Transportation Research Part D: Transport and Environment*, *69*, 250–264.

Levine, J., (1998). Rethinking accessibility and jobs-housing balance. *Journal of American Planning Association, 64*(2), 12–25.

Moya-Gómez, B., & García-Palomares, J. C. (2015). Working with the daily variation in infrastructure performance on territorial accessibility. The cases of Madrid and Barcelona. *European Transport Research Review*, *7*, 1–13.

Moya-Gómez, B., & García-Palomares, J. C. (2017). The impacts of congestion on automobile accessibility. What happens in large European cities? *Journal of Transport Geography*, *62*, 148–159.

Miller, H. J. (1998). Measuring space-time accessibility benefits within transportation networks: Basic theory and computational procedures. In 37th annual meeting of the Western Regional Science Association, Monterey, California. Western Regional Science Association.

Moiseeva, A., Timmermans, H., Choi, J., & Joh, C. H. (2014). Sequence alignment analysis of variability in activity travel patterns through 8 weeks of diary data. *Transportation Research Record*, *2412*(1), 49–56.

Owen, A., & Murphy, B. (2021). Access Across America: Auto 2019. Center for Transportation Studies, University of Minnesota. https://access.umn.edu/research/america/auto/2019/

Owen, A., & Murphy, B. (2020). Access Across America: Transit 2019. Center for Transportation Studies, University of Minnesota. https://access.umn.edu/research/america/transit/2019/

Páez, A., Scott, D. M., & Morency, C. (2012). Measuring accessibility: positive and normative implementations of various accessibility indicators. *Journal of Transport Geography*, *25*, 141–153.

Pas, E. I., & Koppelman, F. S. (1987). An examination of the determinants of day-to-day variability in individuals' urban travel behavior. *Transportation*, *14*(1), 3–20.

Pas, E. I., & Sundar, S. (1995). Intrapersonal variability in daily urban travel behavior: some additional evidence. *Transportation, 22,* 135–150.

Patterson, Z., & Farber, S. (2015). Potential path areas and activity spaces in application: A review. *Transport Reviews*, *35*(6), 679–700.

Pratt, R., & Lomax, T. (1996). Performance measures for multimodal transportation systems. *Transportation Research Record: Journal of the Transportation Research Board, 1518*(1), 85–93.

Randall, T., & Baetz, B. (2001). Evaluating pedestrian connectivity for suburban sustainability. *Journal of Urban Planning and Development 127*(1), 1–15.

Schrank, D., Albert, L., Eisele, B., & Lomax, T. (2021). Urban mobility report 2021. Texas A&M Transportation Institute. https://mobility.tamu.edu/umr/report/

Scott, D. M., & Horner, M. W. (2008). Examining the role of urban form in shaping people's accessibility to opportunities: An exploratory spatial data analysis. *Journal of Transport and Land Use, 1*, 89–119.

Schönfelder, S., & Axhausen, K. W. (2003). Activity spaces: measures of social exclusion? *Transport policy*, *10*(4), 273–286.

Silm, S., & Ahas, R. (2014). Ethnic differences in activity spaces: A study of out-of-home nonemployment activities with mobile phone data. *Annals of the Association of American Geographers*, *104*(3), 542–559.

Susilo, Y. O., & Kitamura, R. (2005). Analysis of day-to-day variability in an individual's action space: exploration of 6-week Mobidrive travel diary data. *Transportation Research Record*, *1902*(1), 124–133.

Sweet, M. N., Harrison, C. J., & Kanaroglou, P. S. (2015). Gridlock in the Greater Toronto Area: Its geography and intensity during key periods. *Applied Geography*, *58*, 167–178.

Texas A&M Transportation Institute. (2022). Texas' most congested roadways. Texas Department of Transportation. https://mobility.tamu.edu/texas-most-congested-roadways/

Uber. (2018). H3: Uber's hexagonal hierarchical spatial index. Uber Blog. Retrieved from https://www.uber.com/blog/h3/#:~:text=H3%20enables%20the%20user%20to,area%20of%20the%20coarser%20resolution

U.S. Census Bureau. (2022). TIGER/Line shapefile, 2019, 2010 nation, U.S., 2010 census urban area national. U.S. Department of Commerce. https://catalog.data.gov/dataset/tiger-line-shapefile-2019-2010-nation-u-s-2010-census-urban-area-national

Wang, Z., He, S. Y., & Leung, Y. (2018). Applying mobile phone data to travel behaviour research: A literature review. *Travel Behaviour and Society*, *11*, 141–155.

Xu, Y., Shaw, S. L., Zhao, Z., Yin, L., Lu, F., Chen, J., ... & Li, Q. (2016). Another tale of two cities: Understanding human activity space using actively tracked cellphone location data. *Annals of the American Association of Geographers*, *106*(2), 489–502.

Appendix A

Origin-Based Measures for the UMR's 101 Urban Areas[6]

Urban Area	$TRUC_O$	Trip Origin Density	Area Reach (Miles)	Avg Trip Time (Minutes)	Total Trips
Akron, OH	16.7%	1,547	4.8	14.0	1,800,248
Albany—Schenectady, NY	18.2%	1,429	5.0	14.3	1,459,497
Albuquerque, NM	33.9%	2,434	5.2	14.6	1,883,749
Allentown, PA—NJ	14.7%	1,641	4.9	14.5	2,008,152
Anchorage, AK	17.4%	202	4.0	11.6	68,012
Atlanta, GA	3.0%	2,186	5.3	14.9	21,795,447
Austin, TX	20.0%	3,713	5.1	14.5	6,037,911
Bakersfield, CA	57.6%	3,955	4.4	13.6	1,744,165
Baltimore, MD	10.4%	2,187	5.0	14.5	5,840,939
Baton Rouge, LA	19.7%	2,472	5.2	14.8	3,025,300
Beaumont, TX	45.1%	2,314	4.6	13.5	698,897
Birmingham, AL	13.7%	2,477	5.6	14.9	4,686,474
Boise City, ID	48.5%	2,549	4.2	14.0	1,195,380
Boston, MA—NH—RI	3.1%	1,701	4.6	14.2	11,310,756
Boulder, CO	72.6%	3,075	3.1	12.6	319,789
Bridgeport—Stamford, CT—NY	11.5%	2,095	4.4	13.6	3,503,489
Brownsville, TX	51.4%	3,436	4.4	14.3	883,154
Buffalo, NY	17.3%	1,776	5.1	14.4	2,299,687
Cape Coral, FL	15.3%	1,646	5.2	14.9	2,337,443
Charleston—North Charleston, SC	18.2%	2,019	4.9	14.9	2,459,288
Charlotte, NC—SC	9.2%	2,131	5.3	14.7	6,562,150
Chicago, IL—IN	3.8%	3,204	4.5	14.3	27,746,786
Cincinnati, OH—KY—IN	10.7%	2,464	5.2	14.8	7,110,782
Cleveland, OH	9.5%	1,964	4.9	14.4	5,298,475
Colorado Springs, CO	42.8%	2,646	4.9	14.2	1,605,853
Columbia, SC	15.5%	1,785	5.6	14.8	2,710,763
Columbus, OH	19.6%	3,065	5.1	14.5	5,633,872
Corpus Christi, TX	45.0%	3,586	5.1	13.8	1,387,846
Dallas—Fort Worth—Arlington, TX	7.9%	4,604	5.3	14.5	26,385,682
Dayton, OH	19.5%	1,950	5.2	14.2	2,451,290
Denver—Aurora, CO	16.8%	3,480	4.7	14.2	7,687,736
Detroit, MI	7.8%	2,641	5.1	14.5	12,353,845
El Paso, TX—NM	28.1%	2,368	5.3	14.5	1,778,442
Eugene, OR	48.0%	2,234	4.2	13.5	714,887
Fresno, CA	51.8%	3,920	4.8	14.0	2,195,253
Grand Rapids, MI	26.6%	2,146	5.3	14.0	2,089,814
Greensboro, NC	27.6%	1,554	5.3	14.0	1,147,024
Hartford, CT	10.5%	1,343	4.9	14.2	2,450,537

[6] Values are for trips 30 minutes or less originating in the urban area during all periods of the day for consumer vehicles only.

Urban Area	$TRUC_O$	Trip Origin Density	Area Reach (Miles)	Avg Trip Time (Minutes)	Total Trips
Houston, TX	7.4%	4,177	5.0	14.7	22,217,586
Indianapolis, IN	12.1%	2,255	5.2	14.6	5,805,896
Indio—Cathedral City, CA	39.5%	2,131	4.4	13.2	941,999
Jackson, MS	24.3%	2,093	5.6	14.9	1,741,488
Jacksonville, FL	11.6%	1,989	5.7	15.2	4,618,867
Kansas City, MO—KS	15.8%	3,416	5.5	14.4	7,983,624
Knoxville, TN	14.1%	1,973	5.5	14.7	3,316,747
Lancaster—Palmdale, CA	42.5%	2,267	4.7	13.4	816,281
Laredo, TX	78.6%	7,700	4.0	13.7	1,532,267
Las Vegas—Henderson, NV	37.1%	5,605	4.9	14.5	7,365,488
Little Rock, AR	25.3%	2,936	5.6	14.5	2,595,277
Los Angeles—Long Beach—Anaheim, CA	9.4%	7,229	4.2	14.0	40,048,526
Louisville/Jefferson County, KY—IN	16.3%	2,202	5.8	15.1	4,029,424
Madison, WI	34.5%	2,081	4.7	13.9	1,086,339
McKinney, TX	58.4%	4,298	3.8	12.7	1,018,697
Memphis, TN—MS—AR	17.5%	2,458	5.6	14.8	4,263,953
Miami, FL	8.9%	4,628	4.7	14.6	23,923,243
Milwaukee, WI	15.5%	2,196	5.3	14.2	4,195,948
Minneapolis—St. Paul, MN—WI	9.1%	2,336	5.6	14.4	8,842,676
Nashville-Davidson, TN	11.7%	2,133	5.2	14.8	4,489,205
New Haven, CT	14.3%	1,261	4.7	13.8	1,370,584
New Orleans, LA	27.1%	3,823	4.6	14.5	3,418,039
New York—Newark, NY—NJ—CT	2.7%	4,729	4.4	14.1	60,223,125
Oklahoma City, OK	26.3%	3,601	5.4	14.6	4,778,200
Omaha, NE—IA	36.7%	3,563	5.1	14.2	3,420,436
Orlando, FL	13.0%	3,001	4.6	14.7	7,529,699
Oxnard, CA	45.5%	2,662	3.9	13.2	734,798
Pensacola, FL—AL	24.3%	1,981	5.2	14.8	1,628,664
Philadelphia, PA—NJ—DE—MD	3.8%	2,354	4.6	14.4	16,918,616
Phoenix—Mesa, AZ	12.1%	3,750	5.3	14.3	13,160,979
Pittsburgh, PA	5.8%	1,582	4.6	14.3	5,153,013
Portland, OR—WA	14.8%	2,792	4.5	14.2	5,707,341
Poughkeepsie—Newburgh, NY—NJ	8.4%	778	4.8	14.2	933,790
Providence, RI—MA	9.0%	1,475	4.8	14.2	2,967,202
Provo—Orem, UT	35.6%	2,821	4.4	13.5	1,546,097
Raleigh, NC	13.3%	2,006	5.4	14.6	4,082,553
Richmond, VA	13.9%	1,906	5.5	14.7	3,530,439
Riverside—San Bernardino, CA	15.2%	2,990	4.6	14.0	5,142,100
Rochester, NY	22.0%	1,778	5.4	14.2	1,967,903
Sacramento, CA	22.3%	3,862	4.8	14.2	6,198,474
Salem, OR	53.2%	2,319	3.9	13.4	656,192
Salt Lake City—West Valley City, UT	40.2%	3,511	4.8	13.9	3,237,326
San Antonio, TX	22.8%	4,295	5.4	14.6	7,872,366
San Diego, CA	16.2%	4,578	5.1	14.5	10,721,850
San Francisco—Oakland, CA	14.1%	4,748	4.0	13.8	8,546,480

Urban Area	$TRUC_O$	Trip Origin Density	Area Reach (Miles)	Avg Trip Time (Minutes)	Total Trips
San Jose, CA	46.1%	6,085	4.3	13.9	5,859,979
Sarasota—Bradenton, FL	14.8%	1,714	4.7	14.3	2,374,560
Seattle, WA	6.3%	2,224	4.7	14.7	9,462,604
Spokane, WA	30.4%	1,734	4.7	14.3	1,092,303
Springfield, MA—CT	11.5%	1,061	4.7	14.1	1,305,738
St. Louis, MO—IL	10.5%	2,817	5.6	14.6	9,355,942
Stockton, CA	50.3%	2,319	4.5	13.5	749,024
Tampa—St. Petersburg, FL	7.5%	2,527	4.9	14.7	9,821,138
Toledo, OH—MI	28.1%	2,002	5.1	14.3	1,713,907
Tucson, AZ	21.9%	1,921	5.2	14.6	2,036,530
Tulsa, OK	29.2%	3,248	5.8	14.7	3,625,055
Virginia Beach, VA	11.1%	1,967	5.2	14.9	4,379,191
Washington, DC—VA—MD	6.0%	2,735	4.6	14.7	13,361,669
Wichita, KS	39.6%	2,533	5.4	14.1	1,813,709
Winston-Salem, NC	14.0%	1,139	5.5	14.4	1,436,469
Worcester, MA—CT	10.5%	872	4.8	14.0	948,318

Destination-Based Measures for the UMR's 101 Urban Areas[7]

Urban Area	$TRUC_D$	Trip Destination Density	Area Reach (Miles)	Avg Trip Time (Minutes)	Total Trips
Akron, OH	16.7%	1,547	4.7	14.0	1,800,248
Albany—Schenectady, NY	18.2%	1,429	4.9	14.2	1,459,497
Albuquerque, NM	33.9%	2,434	5.1	14.5	1,883,749
Allentown, PA—NJ	14.7%	1,641	4.9	14.3	2,008,152
Anchorage, AK	17.2%	202	4.0	11.7	68,012
Atlanta, GA	3.0%	2,186	5.2	14.7	21,795,447
Austin, TX	20.0%	3,713	5.0	14.4	6,037,911
Bakersfield, CA	57.5%	3,955	4.4	13.5	1,744,165
Baltimore, MD	10.4%	2,187	4.9	14.4	5,840,939
Baton Rouge, LA	19.7%	2,472	5.1	14.7	3,025,300
Beaumont, TX	45.1%	2,314	4.6	13.4	698,897
Birmingham, AL	13.7%	2,477	5.4	14.8	4,686,474
Boise City, ID	48.5%	2,549	4.1	13.9	1,195,380
Boston, MA—NH—RI	3.1%	1,701	4.6	14.1	11,310,756
Boulder, CO	73.3%	3,075	2.9	12.3	319,789
Bridgeport—Stamford, CT—NY	11.5%	2,095	4.3	13.5	3,503,489
Brownsville, TX	51.4%	3,436	4.4	14.2	883,154

[7] Values are for trips 30 minutes or less with destinations in the urban area during all periods of the day for consumer vehicles only.

Urban Area	$TRUC_D$	Trip Destination Density	Area Reach (Miles)	Avg Trip Time (Minutes)	Total Trips
Buffalo, NY	17.3%	1,776	5.0	14.3	2,299,687
Cape Coral, FL	15.3%	1,646	5.1	14.7	2,337,443
Charleston—North Charleston, SC	18.2%	2,019	4.9	14.7	2,459,288
Charlotte, NC—SC	9.2%	2,131	5.2	14.5	6,562,150
Chicago, IL—IN	3.8%	3,204	4.5	14.3	27,746,786
Cincinnati, OH—KY—IN	10.7%	2,464	5.2	14.7	7,110,782
Cleveland, OH	9.5%	1,964	4.9	14.3	5,298,475
Colorado Springs, CO	42.7%	2,646	4.8	14.1	1,605,853
Columbia, SC	15.5%	1,785	5.5	14.6	2,710,763
Columbus, OH	19.6%	3,065	5.1	14.4	5,633,872
Corpus Christi, TX	45.0%	3,586	5.0	13.8	1,387,846
Dallas—Fort Worth—Arlington, TX	7.9%	4,604	5.2	14.4	26,385,682
Dayton, OH	19.5%	1,950	5.1	14.2	2,451,290
Denver—Aurora, CO	16.8%	3,480	4.6	14.1	7,687,736
Detroit, MI	7.8%	2,641	5.1	14.5	12,353,845
El Paso, TX—NM	28.2%	2,368	5.2	14.4	1,778,442
Eugene, OR	47.8%	2,234	4.1	13.5	714,887
Fresno, CA	51.9%	3,920	4.8	14.0	2,195,253
Grand Rapids, MI	26.6%	2,146	5.3	14.0	2,089,814
Greensboro, NC	27.6%	1,554	5.2	13.9	1,147,024
Hartford, CT	10.5%	1,343	4.9	14.1	2,450,537
Houston, TX	7.4%	4,177	5.0	14.6	22,217,586
Indianapolis, IN	12.1%	2,255	5.1	14.5	5,805,896
Indio—Cathedral City, CA	39.5%	2,131	4.3	13.1	941,999
Jackson, MS	24.3%	2,093	5.5	14.7	1,741,488
Jacksonville, FL	11.6%	1,989	5.6	15.0	4,618,867
Kansas City, MO—KS	15.8%	3,416	5.4	14.3	7,983,624
Knoxville, TN	14.1%	1,973	5.4	14.6	3,316,747
Lancaster—Palmdale, CA	42.5%	2,267	4.6	13.3	816,281
Laredo, TX	79.0%	7,700	3.9	13.7	1,532,267
Las Vegas—Henderson, NV	37.1%	5,605	4.9	14.4	7,365,488
Little Rock, AR	25.3%	2,936	5.5	14.4	2,595,277
Los Angeles—Long Beach—Anaheim, CA	9.4%	7,229	4.2	13.9	40,048,526
Louisville/Jefferson County, KY—IN	16.3%	2,202	5.6	14.9	4,029,424
Madison, WI	34.5%	2,081	4.6	13.8	1,086,339
McKinney, TX	58.4%	4,298	3.8	12.7	1,018,697
Memphis, TN—MS—AR	17.5%	2,458	5.4	14.7	4,263,953
Miami, FL	8.9%	4,628	4.6	14.5	23,923,243
Milwaukee, WI	15.5%	2,196	5.3	14.2	4,195,948

Urban Area	$TRUC_D$	Trip Destination Density	Area Reach (Miles)	Avg Trip Time (Minutes)	Total Trips
Minneapolis—St. Paul, MN—WI	9.1%	2,336	5.5	14.3	8,842,676
Nashville-Davidson, TN	11.7%	2,133	5.1	14.6	4,489,205
New Haven, CT	14.3%	1,261	4.6	13.7	1,370,584
New Orleans, LA	27.1%	3,823	4.6	14.4	3,418,039
New York—Newark, NY—NJ—CT	2.7%	4,729	4.3	14.0	60,223,125
Oklahoma City, OK	26.3%	3,601	5.3	14.6	4,778,200
Omaha, NE—IA	36.7%	3,563	5.0	14.2	3,420,436
Orlando, FL	13.0%	3,001	4.6	14.5	7,529,699
Oxnard, CA	45.5%	2,662	4.0	13.2	734,798
Pensacola, FL—AL	24.5%	1,981	5.1	14.7	1,628,664
Philadelphia, PA—NJ—DE—MD	3.8%	2,354	4.6	14.3	16,918,616
Phoenix—Mesa, AZ	12.1%	3,750	5.2	14.2	13,160,979
Pittsburgh, PA	5.8%	1,582	4.6	14.3	5,153,013
Portland, OR—WA	14.8%	2,792	4.5	14.1	5,707,341
Poughkeepsie—Newburgh, NY—NJ	8.4%	778	4.7	14.0	933,790
Providence, RI—MA	9.0%	1,475	4.8	14.1	2,967,202
Provo—Orem, UT	35.7%	2,821	4.4	13.5	1,546,097
Raleigh, NC	13.3%	2,006	5.3	14.5	4,082,553
Richmond, VA	14.0%	1,906	5.4	14.5	3,530,439
Riverside—San Bernardino, CA	15.2%	2,990	4.5	13.9	5,142,100
Rochester, NY	22.0%	1,778	5.3	14.1	1,967,903
Sacramento, CA	22.3%	3,862	4.8	14.1	6,198,474
Salem, OR	53.4%	2,319	3.9	13.3	656,192
Salt Lake City—West Valley City, UT	40.2%	3,511	4.7	13.8	3,237,326
San Antonio, TX	22.8%	4,295	5.3	14.5	7,872,366
San Diego, CA	16.2%	4,578	5.0	14.3	10,721,850
San Francisco—Oakland, CA	14.1%	4,748	3.9	13.7	8,546,480
San Jose, CA	46.0%	6,085	4.3	13.7	5,859,979
Sarasota—Bradenton, FL	14.8%	1,714	4.6	14.1	2,374,560
Seattle, WA	6.3%	2,224	4.7	14.6	9,462,604
Spokane, WA	30.3%	1,734	4.6	14.2	1,092,303
Springfield, MA—CT	11.5%	1,061	4.6	14.0	1,305,738
St. Louis, MO—IL	10.5%	2,817	5.5	14.5	9,355,942
Stockton, CA	50.4%	2,319	4.4	13.4	749,024
Tampa—St. Petersburg, FL	7.6%	2,527	4.8	14.5	9,821,138
Toledo, OH—MI	28.1%	2,002	5.0	14.3	1,713,907
Tucson, AZ	21.9%	1,921	5.1	14.5	2,036,530
Tulsa, OK	29.2%	3,248	5.7	14.6	3,625,055
Virginia Beach, VA	11.2%	1,967	5.1	14.7	4,379,191

Urban Area	$TRUC_D$	Trip Destination Density	Area Reach (Miles)	Avg Trip Time (Minutes)	Total Trips
Washington, DC—VA—MD	6.0%	2,735	4.6	14.5	13,361,669
Wichita, KS	39.6%	2,533	5.3	14.1	1,813,709
Winston-Salem, NC	14.0%	1,139	5.4	14.2	1,436,469
Worcester, MA—CT	10.5%	872	4.7	13.9	948,318

NICR
NATIONAL INSTITUTE FOR CONGESTION REDUCTION

The National Institute for Congestion Reduction (NICR) will emerge as a national leader in providing multimodal congestion reduction strategies through real-world deployments that leverage advances in technology, big data science and innovative transportation options to optimize the efficiency and reliability of the transportation system for all users. Our efficient and effective delivery of an integrated research, education, workforce development and technology transfer program will be a model for the nation.

CUTR CENTER FOR URBAN TRANSPORTATION RESEARCH

Berkeley UNIVERSITY OF CALIFORNIA

Texas A&M Transportation Institute

UPR Recinto Universitario de Mayagüez

www.nicr.usf.edu