

Accessibility analysis for transportation projects and plans

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1. Introduction

The concept of highway level-of-service (LOS) and associated mobility metrics, including measures of congestion-related delays and prospective value of travel time saved (as incorporated in cost-benefit analyses), have for decades shaped transportation-planning practice (Cohen, 1995; Laird et al., 2014; Schrank et al., 2015; Weiner, 2012). As recently as 2016, the Federal Highway Administration proposed a set of performance measures for the national highway system pursuant to MAP-21 legislation; seven out of the proposed eight performance measures are mobility-oriented measures, linked to vehicular speeds, whereas none are accessibility measures (U.S. Federal Highway Administration, 2017). Mobility thinking has become so ingrained within the transportation planning profession that many evaluations of transportation projects focus on mobility-related level of service without discussing the rationale or justification behind the widely accepted level-of-service measure.

The mobility-centered approach is operationalized in transportation planning's "predict-and-provide" formulation (Banister and Button, 1993) in which planners model travel flows over transportation networks, simulate the impact of future land-use and population change on those flows, and identify opportunities to improve flows through targeted expansions of capacity. In practice in the US, this has often meant expanding highway links whose forecast volume-to-capacity ratios presage unacceptable degradation in LOS.

This planning approach has been criticized for overestimating the certainty of modeling results (Zhao and Kockelman, 2002), imposing an overly narrow technical rationality on the transportation planning process (Willson, 2001), and ignoring the futility of a strictly supply-based approach to transportation problems (Downs, 2005; Meyer, 1997). Less common is the critique of the standard transportation paradigm, with its focus on the goal of preserving and expanding mobility, rather than accessibility (Levine et al., 2012). The accessibility-oriented critique argues that planning and evaluation frameworks that are not grounded in the fundamental purpose of transportation threaten to generate perverse transportation outcomes.

An accessibility-based view starts from the idea first articulated early in the 20th century (Bonavia, 1936) that the demand for

transportation is largely derived from people's demand to reach their destinations, rather than for the sake of movement per se. Though this view enjoys near-consensus status within the transportation professions, transportation planning practice has rarely confronted its full implications: metrics of the quality or quantity of movement alone do not indicate how well transportation is serving the purpose of accessibility. Moreover, since transportation infrastructure expansion can induce distance-increasing land-use change (Cohen, 1995), mobility improvements can sometimes translate, in the longer term, into degraded accessibility when increased distances are not compensated for by improved travel speeds (Levine et al., 2012).

While this outcome would be undesirable based on the accessibility perspective, it would be judged a mobility success so long as roadway delays were reduced in the process. Standard state-of-the-practice mobility metrics may be insensitive to the accessibility outcomes of plans. The conventional mobility framework, rather than presuming positive accessibility outcomes from mobility improvements, is quite indifferent to accessibility implications.

Aligning transportation planning with transportation's fundamental purpose thus demands a shift from mobility to accessibility as the core goal. In some ways, this shift is underway. Regional planning agencies have begun to evaluate alternative development scenarios based on the accessibility each provides. Less common is the accessibility-based analysis of individual projects or groups of associated projects; neither proposed land-use changes nor proposed transportation infrastructure or service changes are typically evaluated from an accessibility perspective. Yet the shift from the regional-scenario level to the project level is vital, since it is the aggregation of multiple incremental decisions that ultimately forms altered regional transportation and land use futures. In other words, operationalizing accessibility in practice depends in part on bringing accessibility-based analysis to applied transportation and land-use decisions, roles currently filled by mobility-based level-of-service or traffic-impact analyses.

This shift, in the context of land-development decisions, is the subject of a companion article (Levine et al., 2017). For transportation decisions, the shift from the regional-scenario to the project level would allow planners to distinguish between transportation investments that are likely to increase accessibility over the longer term from those that

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may degrade it and is the subject of this article. Transportation projects quite obviously influence the speed of travel, but less obvious are the influence transportation projects have on the land-use system: if a transportation investment induces greater proximity of origins and destinations (compared with a no-build alternative), the land-use impact can amplify the effect of the transportation investment in enabling accessibility. By contrast, when the transportation investment induces greater spread of origins and destinations, the land-use effect can diminish, negate, or even reverse a transportation project's mobility-based accessibility gains. An accessibility-based evaluation of a transportation project requires appropriate tools to distinguish between accessibility-enhancing and accessibility-degrading transportation investments.

This article defines and demonstrates such tools, testing them out for two sets of affiliated roadway projects in metropolitan San Antonio, Texas, a rapidly growing sunbelt region in the United States. The first is the highway elements of the Long-Range Transportation Plan for the San Antonio metropolitan area for 2015, incorporating multiple projects throughout the region. The second is a series of expansions and improvements to a suburban ring road, referred to as Loop 1604. The analyses forecast land-use impacts of each of these set of transportation projects using TELUM, a freely available transportation/land-use model funded by the Federal Highway Administration and housed at the New Jersey Institute of Technology. Impacts on each suite of projects on future auto accessibility to employment are then gauged based on the projected changes to land use patterns. The results show in both cases that taking an accessibility-based approach reveals outcomes that differ substantially from the standard mobility-based approach.

This article seeks to develop an approach to accessibility analysis of transportation projects that is relevant to planners in applied practice; for this reason, availability and usability of the land-use model is central to our goal. This is the principal benefit of TELUM, an implementation of a transportation/land-use interaction model that has been in broad planning use since the 1970s. Our approach is available to researchers employing more advanced models including those based on microsimulation, yet for the reason described above we chose to demonstrate it with a model that is already embedded in planning practice.

2. Accessibility evaluation of transportation projects

Accessibility is broadly defined as the ease of access to destinations of interest. A growing number of researchers and analysts have been arguing for a shift from mobility-based evaluation to accessibility-based evaluation for years (Cervero, 1996). Accessibility measures can take into account up to four components: A transportation component, a land-use component, a temporal component and an individual component, though often the temporal and individual components are omitted due to methodological complexities (Geurs and Van Wee, 2004). Accessibility can be measured through various formulae, including the cumulative opportunity, gravity, person-based, and utility measures. In this paper, we focus on gravity-based measures of accessibility to all employment as a succinct summary measure of the performance of the transportation-land use system (Ahlfeldt, 2011). In a more detailed analysis, accessibility to other, more specific types of destinations, or the distribution of accessibility benefits across the population may be of interest as well.

Accessibility-based analysis has made some inroads in the practice of regional scenario planning. Seattle, Chicago, and San Francisco metropolitan regions are among those that have employed accessibility performance measures to evaluate potential regional futures (Chicago Metropolitan Agency for Planning, 2010; Metropolitan Planning Commission, 2009; Puget Sound Regional Council, 2008). Accessibility metrics have been employed to understand the economic, equity, and multimodal performance of future regional transportation/land-use scenarios. In other words, accessibility measures have been used to

understand how transportation and land-use systems facilitate or impede access to opportunities spread across metropolitan areas for specific population segments.

Regional scenario-based accessibility analysis is made easier by the fact that these future scenarios are typically “what if” possibilities rather than predicted futures. Planners can characterize how the future might look in terms of both land-use patterns and transportation infrastructure at a particular point in time according to desired patterns, and from these data, the relative accessibility performance of various scenarios can be readily compared.

This contrasts with the analysis of transportation projects, an analysis that demands forecasting of induced land-use changes before accessibility impacts can be meaningfully gauged. Accessibility-based analysis has rarely been used for project-level analysis of this type. Transportation projects can be thought to have two effects on accessibility, one short term and direct and the other longer term and indirect. Traditionally only the short-term, mobility-based impacts have been considered in transportation project evaluations. The short-term impact is the reduction in travel times which increases accessibility by reducing generalized travel costs. The long term impact is from the induced land use effects, which may counteract or further enhance the short-term mobility benefits (Boarnet and Haughwout, 2000).

In metropolitan area travel-demand modeling, analysts commonly take the future spatial pattern of employment and households as fixed and exogenous, and then predict trip patterns based upon that spatial pattern. This was the case for the study area of this article. The Alamo Area Metropolitan Planning Organization has a single land-use forecast each 5-year period between 2020 and 2040. This future land-use forecast is not contingent on the adopted transportation plan (Alamo Area Metropolitan Planning Organization, 2015). The transportation infrastructure is then planned in response to the predicted trip patterns that result from the exogenously provided land use pattern.

However, this common practice of assuming fixed future land uses is problematic, since the pattern of future land uses is itself influenced by the provision of transportation infrastructure. If new development significantly decentralizes due to new transportation infrastructure, the speed benefits of such infrastructure may be partially or completely counteracted in accessibility terms by increasing travel distances (Grengs et al., 2010; Levine et al., 2012). An accessibility analysis of a transportation plan that does not allow for induced land-use change implicitly assumes none; such analysis amounts to a mobility analysis in another form, since all mobility improvements will translate into accessibility improvements if land use patterns remain unaltered.

To ascertain the full accessibility impacts of a transportation project, a land-use forecast sensitive to the impacts of the proposed transportation projects is required. That is, an accessibility analysis of the proposed projects must account for both the short-term mobility impacts and the longer-term land use changes.

Fig. 1 illustrates the method used here to address these requirements. On the bottom the current state of the practice is diagrammed, where a future land use forecast serves only as an input into describing future travel patterns. This assumes that proposed infrastructure has no role in shaping future land use patterns. The new proposed method is on the top. It assumes that the proposed transportation infrastructure will reshape land-use patterns. It builds on existing procedures of mobility-based analysis but incorporates both changes to travel patterns and changes to land use patterns within the broader framework of an accessibility analysis.

3. Project-level analysis: the differences between transportation and land use project evaluation

A companion article (Levine et al., 2017) argues that project-by-project decision-making is an essential component of most transportation and land-use planning decisions. It argues that project-level analysis is conceptually different from regional-scenario analysis and

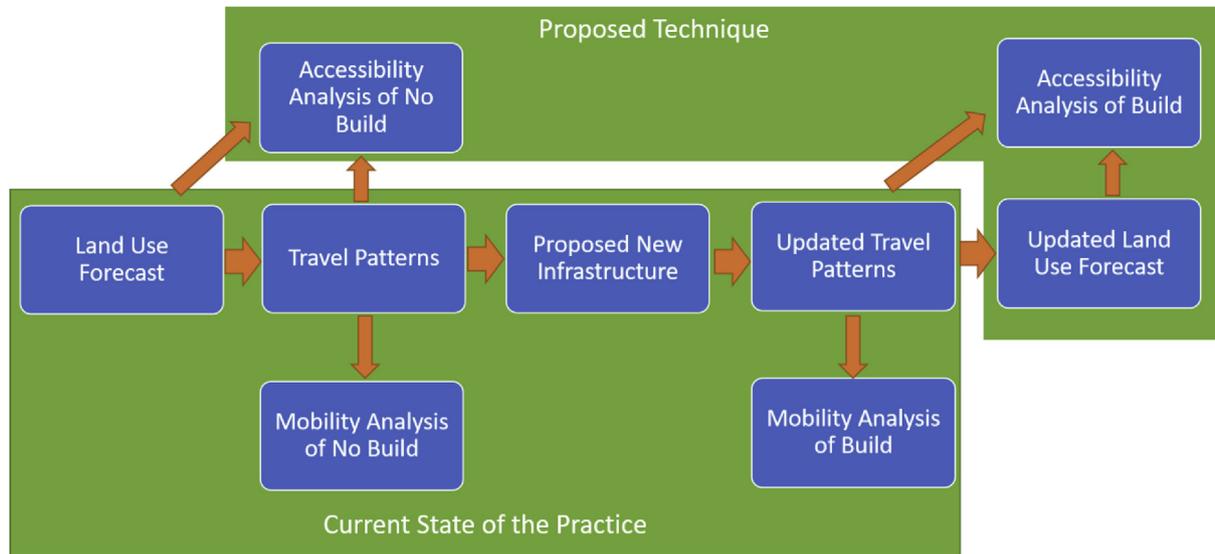


Fig. 1. Accessibility-based transportation Project evaluation.

requires distinct tools and methods. Therefore, the companion piece proposes a method for carrying out accessibility-based evaluation of individual land-use projects.

To summarize the key argument of this companion piece briefly, the key difference between regional-scenario analysis and project-level analysis is that the impact of proposed, marginal projects must be projected into the future. That is an individual land-use project, such as a proposed development in a specific location, must have its marginal transportation impacts forecast to assess its accessibility impact. Likewise, an individual transportation project, such as a proposed new rail line or highway, must have its marginal land use impacts forecasts. Such forecasts are not usually part of regional scenario analyses; scenarios are often constructed via a “what if” method for the purpose of maximizing policy contrasts. Also, in scenarios land-use and transportation changes are envisioned as occurring in concert, rather than incrementally and marginally. The companion article also emphasizes the need for practical methods that can be put into widespread use by planners with a minimum of technical sophistication required. Simpler, easy-to-adopt tools will abet wider adoption of these new methods. These key differences between regional-scenario analysis and project-level analysis are detailed in Table 1 below. Where the companion article proposed a new approach to accessibility-based analysis for land-use projects, this article focuses on the prospective accessibility-based analysis of transportation projects.

Accessibility analysis for transportation projects differs from that of land-use projects in three fundamental ways: 1) Basis of comparison 2) Scale of effect and 3) Technical requirements. The basis of comparison refers to what the transportation projects are compared to in the evaluation process. Transportation projects are generally the product of public planning and investment, an attribute that facilitates analysis because alternatives are readily identified that would form a basis for

comparison. For example, the accessibility impacts of transportation project “X” may be judged in comparison with a No-Build scenario, or possibly in comparison with transportation project “Y.” By contrast, land-development, while regulated through public planning, is typically a private affair. This impedes the delineation of clear basis for comparison for land-use projects, as discussed in more detail in the companion piece.

The second difference between accessibility analysis of transportation projects and land-development projects is one of scale. The companion paper demonstrated the accessibility analysis of land-development projects as small as around 200 residential units or 100,000 square feet of retail. Any land-use change whose mobility impacts can be analyzed through traffic-impact analysis can be evaluated in accessibility terms. By contrast, small transportation projects (such as an intersection improvement) are not as readily evaluated for their land-use impacts. For this reason, this paper analyzes large groupings of transportation projects: the 2015 Long-Range Transportation Highway Projects for the San Antonio region, and a series of corridor projects associated with Loop 1604, a suburban ring road.

Such large bundles of transportation projects have a discernible impact on regional measures of average household accessibility. This contrasts with land-development projects, whose accessibility impacts are likely to be a “drop in the ocean” relative to total regional accessibility. The land-development case addressed the problem of small size via an accessibility-elasticity. However, this accessibility-elasticity metric is not necessary in the analysis of sizable transportation projects, and it is not used in the current study.

The third difference that makes the evaluation of transportation projects more challenging than land-use projects is that projecting future land-use impacts is technically more difficult than projecting future transportation impacts. For the case of land-use projects, planners and

Table 1
Different types of accessibility analysis.

	Scenario Plan	Project
Land Use	Future transportation and land use changes are envisioned as part of a holistic set of changes; Future state is evaluated for accessibility benefits	Individual development proposal is incorporated as a marginal change to land-use patterns. A model is used to forecast accompanying changes to travel patterns; Marginal difference to transportation and land use systems is input to accessibility analysis
Transportation		One or more transportation projects (i.e. new or expanded roadways) is assessed for how it will change travel patterns; A model is used to forecast accompanying changes to land use patterns; Marginal difference to each is input to an accessibility analysis.

engineers can readily project transportation impacts by turning to the widely available and accepted method of traffic impact analysis (Institute of Transportation Engineers, 2006). By contrast, for the case of transportation projects, practitioners have no widely adopted method for projecting land-use impacts. Projecting land-use impacts typically requires complex software tools and a range of data – often including parcel-level land categories and small-scale employment – that are not readily within reach of most local and even many regional transportation or land-use planning agencies (Brown and Lee, 2013).

3.1. Examples of accessibility-based transportation project analysis

We evaluated the peer-reviewed literature for similar project-level analysis by examining it along three dimensions. First, does it analyze a specified project or bundle of proposed transportation projects? This is the criterion by which we distinguish project-level analysis from scenario analysis. Second, is it a prospective analysis? That is, is the analysis of accessibility impacts a forward-looking evaluation of the impacts of the proposed set of projects. Retrospective analysis is of interest for researchers but is not useful for the evaluation of proposed transportation projects in practice. And third, are induced land-use impacts forecast? For a method to be useful for the prospective accessibility-based evaluation of transportation projects, it must meet all three of the above criteria.

We found a small body of work that examines the impacts of large transportation infrastructure projects on accessibility (Fan et al., 2010; Geurs et al., 2012; Gjestland et al., 2012; Gulhan et al., 2014). However almost all these papers examine only the mobility effects of the transportation projects they analyze (see Table 2 below). In other words, these analyses assume there is no induced land-use change, only improvements or changes to travel times. This is a very limiting analysis, because if only mobility effects are accounted for any transportation project that improves speeds will be accessibility enhancing.

Interestingly, most of the prospective studies of the impact of proposed transportation projects on accessibility focus on transit and railways projects. Presumably if such projects induced additional development near their transit stations, their accessibility impacts might be greater than stated in these analyses, because each of these assumed no land use impact. The possible under-scoring of the accessibility benefits of transit projects highlights the significance of considering induced land use change as part of an integrated accessibility analysis.

Geurs et al., 2012 is a rare example of a prospective analysis for the accessibility impacts of a transportation project that includes anticipated impacts to land use change. This study employs a land-use model to forecast variation in employment locations as a result of the proposed transportation projects and thus exemplifies an approach to accessibility-based transportation project analysis proposed in the present

article. The goals of the present article are similar but include the demonstration of the general applicability of accessibility-based analysis to transportation projects and the illustration of the consequences of this approach by directly contrasting how accessibility and mobility analyses can lead to divergent results.

4. Data and methods

We selected the San Antonio, Texas metropolitan area, also known as the Alamo Area, for analysis because it is a fast-growing metropolitan region with significant investment planned in new highways. According to the Alamo Area's long range transportation plan, the Alamo Metropolitan Area expects growth from a population of 2.0 million in 2010 to 3.4 million by 2040 (Alamo Area Metropolitan Planning Organization, 2015). Employment is likewise expected to grow rapidly from 0.9 million jobs in 2010 to 1.7 million by 2040. Fig. 2 illustrates the current employment density in the 5-county metropolitan region, with employment centers located in historic downtown San Antonio as well as along a band across the northern suburbs. The metropolitan San Antonio region embodies a strong decentralization trend, with the highest population and employment growth in recent years occurring in suburban locations and along major highway corridors.

Analyzing highway projects was of particular interest because these offer the potential to improve mobility without necessarily producing concomitant accessibility benefits. Highway projects usually can improve vehicular speeds, but they are also prone to inducing decentralized land use patterns. Therefore, analyzing sets of highway projects potentially allows for the distinction between transportation projects that enhance mobility from those that enhance accessibility.

We analyze two sets of transportation projects for their accessibility impacts. The first set of projects includes the highway components of the region's long-term transportation plan adopted in 2014, known as “Mobility 2040” (Alamo Area Metropolitan Planning Organization, 2015). Note that we only consider effects of these projects for the period from 2010 to 2020. The goals of the plan are typical for a metropolitan long-range transportation plan, and include decreasing traffic congestion, improving public transit, mitigating environmental impacts, supporting economic growth, improving safety, and coordinating with local land use plans. The 25-year LRTP (Long Range Transportation Plan) includes a total of \$17.2 billion in transportation funding for operations, maintenance, safety improvements, and roadway expansions. Approximately \$2.1 of this total is applied to roadway expansions. A map of the proposed roadway expansions is included below in Fig. 3.

The second set of transportation projects is a series of transportation improvements along San Antonio's outer loop known as “Loop 1604.” For this analysis, we assume that the rest of the region's planned

Table 2
Literature incorporating the prospective accessibility analysis of transportation projects.

Author Year	Project Level	Prospective	Land Use Forecast	Transportation Project Type
(Jiang, 2016)	X			Transit
(Gulhan et al., 2014)	X	X		Transit
(Bocarejo et al., 2014)	X			Transit
(Hensher et al., 2014)	X	X		High Speed Rail
(Stepniak and Rosik, 2013)	X			Highway
(Bocarejo and Oviedo, 2012)	X			Transit
(Kilby and Smith, 2012)		X		NA
(Geurs et al., 2012)	X	X	X	Transit
(Gjestland et al., 2012)	X			Bridge
(Tiwari and Jain, 2012)	X			Transit
(Curtis, 2011)		X		Transit
(Fan et al., 2010)	X			Transit
(Bertolini et al., 2005)		X		NA
(Department for Transport (UK), 2005)	X			NA
(Gutiérrez, 2001)		X		High Speed Rail
(Lomax, 1997)	X	X		NA

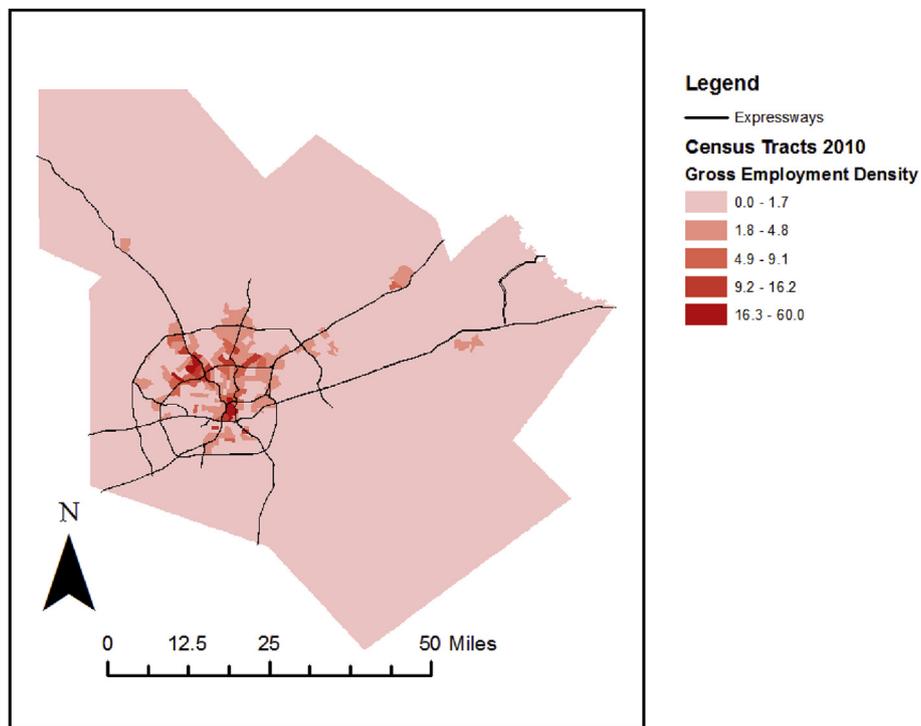


Fig. 2. Employment density for Alamo region, 2010

transportation projects go ahead as planned but subtract out the associated Loop 1604 projects to examine their marginal impacts. The analysis is framed this way because we take the existing long-range transportation plan as the status quo. Loop 1604 is in most locations a 4-lane expressway with frontage roads running parallel. The Loop 1604 projects primary consist of expansions from 2-lane to 4-lane expressway in select locations, with occasional expansion to 6 lanes. The Loop 1604 projects are displayed below in Fig. 4.

4.1. The TELUM land use model

An objective of this study is to develop a methodology that could be widely used with minimum demand for technical capacity or data-intensive input requirements, and this goal guided the selection of a land-use model for this project.

A variety of land use models have been used in planning research and practice. These include the California Urban Futures Model, the

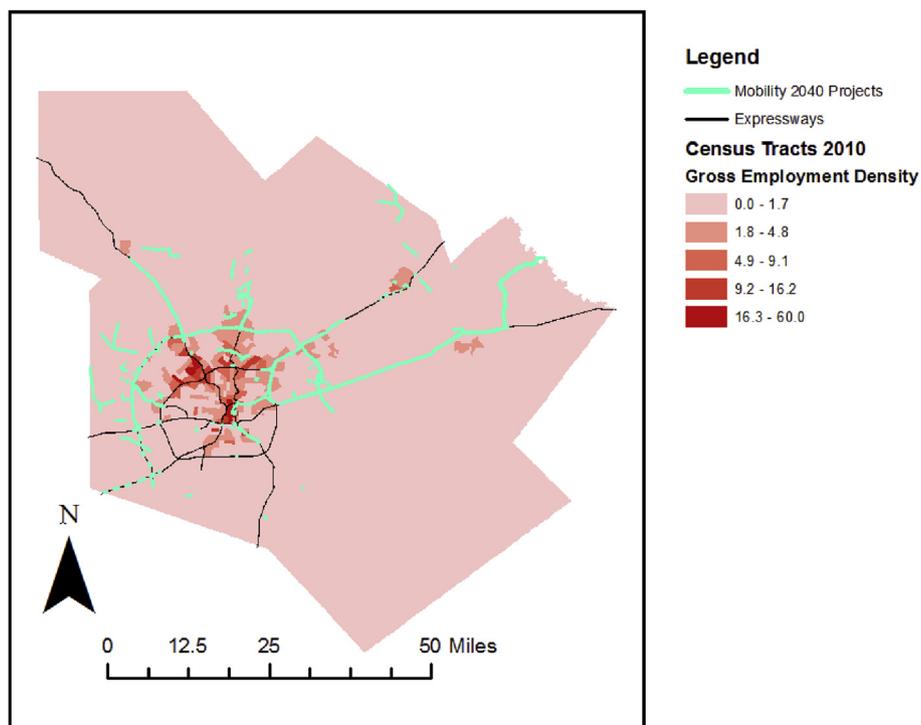


Fig. 3. Mobility 2040 roadway projects.

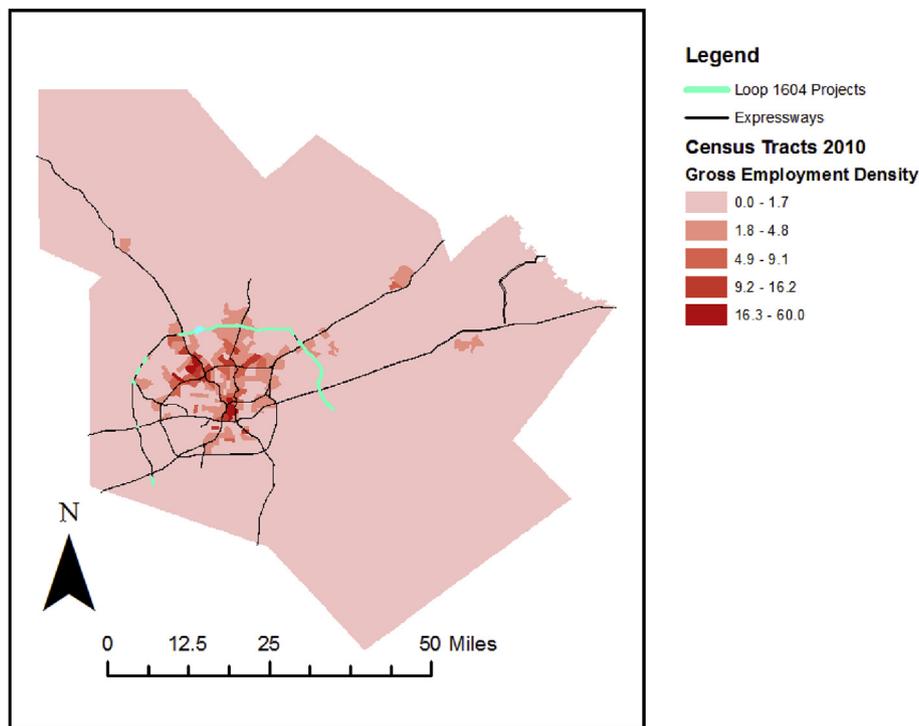


Fig. 4. Loop 1604 projects.

Human-Induced Land Transformations Project (HILT), the Land Use Evolution and Impact Assessment Model (LEAM), MEPLAN, TRANUS, and UrbanSim (Clarke et al., 1997; Deal and Pallathucheril, 2008; Hunt and Simmonds, 1993; Johnston and de la Barra, 2000; Landis and Zhang, 1998; Waddell, 2002). Nevertheless, land use modeling is still unusual among MPOs. A recent survey of 100 MPOs found that just 39% of MPOs that examined future scenarios had a functional land use model available to help construct those scenarios (Brown and Lee, 2013). UrbanSim is the land use modeling system that has most likely had the longest effort to become a readily adaptable tool for MPO analysis (“UrbanSim: Our Story, 2017”). As of 2017, there were 20 out of more than 340 MPOs that had experience using UrbanSim (personal communication with Paul Waddell). Hopefully, land use models such as UrbanSim will continue to improve in usability and adoption; but as our goal was to demonstrate the possibility of accessibility analysis with the most accessible land use modeling tools available, we opted for TELUM instead. The concepts illustrated here do not depend upon using TELUM and are completely transferable across land use modeling platforms.

TELUM was developed under the guidance of the Federal Highway Administration to allow middle-range MPOs the capability to conduct their own land-use modeling in house (New Jersey Institute of Technology, 2005). TELUM is a software program that incorporates data from Microsoft Excel and Microsoft Access, and produces land use forecast data that can be visualized in ArcGIS. A disadvantage of TELUM is that it is not integrated with any travel demand model, so land use forecasting and travel demand forecasts must be fed iteratively back and forth, limiting the level of synchronization between the transportation forecast and the land use forecast.

TELUM is an aggregate, zonal-based model rather than a micro-simulation model. Provided zonal data on households and employment from two time periods and land use consumption data for one time period, the TELUM land use model calibrates parameters explaining land use change based upon recent trends. Then based upon these calibrated parameters, future land use can be forecast via the same zonal structure up to 6 time increments into the future. TELUM allows for a distinction of up to 6 household types and 8 employment types in its zonal forecasts.

As an aggregate, zonal land use model, TELUM can mostly be calibrated with commonly available US Census data. Land use data must be analyzed via a GIS system to associate different household and employment activity types with their land consumption requirements. The underlying causal framework of the TELUM model assumes that newly located households are attracted by accessibility to employment, other similar type households, available land, and zonal-specific factors. New employment is attracted to the availability of local workforce, proximity to other employment locations, land availability, and zonal-specific factors.

For this case study, the launch year (the year from which the forecasts begin (Smith, 2001)) for the land use models was 2010 while the base year (the prior year from which data trends are extrapolated) was 2005. For each of these two years, we gathered information on households by income category and employment by industrial grouping for the 436 Census Tracts in the region. Household data by Census Tract for 2005 and 2010 are from the American Community Survey. Employment data by industry and by Census Tract are from the LEHD Origin-Destination Employment Statistics (LODES) Dataset. These data are used to calibrate the attractiveness of different features for future growth, including land supply and accessibility to employment and workforce.

Land consumption is determined by a different model within TELUM. This model is calibrated based upon launch-year (2010) land-use patterns in relation to launch-year employment and population patterns. Land use parcel data were provided by the Alamo Area Metropolitan Planning Organization (AAMPO) with the following land use categories: Residential, Commercial, Industrial, Undevelopable, Right of Way, and Vacant Developable.

The TELUM model uses a single zone-to-zone impedance matrix to define how employment accessibility influences future residential growth and how accessibility to workers influences future employment growth. We used peak-hour auto-based travel times provided from the AAMPO travel demand model as the source of these impedance matrices. The travel demand model was run with different transportation plan configurations for future years by the AAMPO at our request. The AAMPO's travel demand model is a traditional four-step travel demand

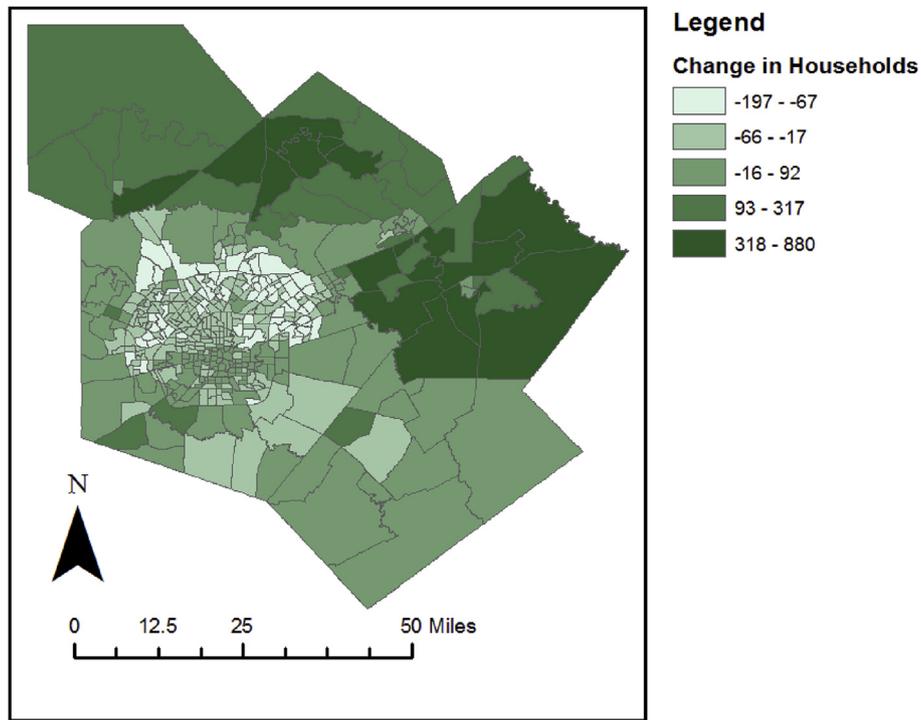


Fig. 5. Forecast household shift due to Alamo transportation plan to 2020.

model calibrated to year 2005 data (Alamo Area Metropolitan Planning Organization, 2011).

The TELUM land use model was used to forecast 2020 land-use patterns for both the Build and No-Build scenarios for each set of transportation projects evaluated. The model was calibrated based upon population and employment data from 2005 to 2010, land-use consumption data from 2010, and travel impedance data from 2010. Then two different 2020 travel impedances were fed into the model to produce two distinct land use forecasts, one for the Build Scenario and one for the No-Build Scenario for each project set.

We calculated accessibility to employment by automobile for each of the two scenarios with a gravity potential measure (See equations (1.1) and (1.2)). Accessibility to employment was analyzed because it was the most readily available measure from the land use forecasts, and because accessibility to employment is of concern for promoting economic opportunity and reducing the length and cost of commutes (Hu, 2016; Levinson, 1998). Because TELUM produces population forecasts by household type and employment forecasts by industry type, a variety of accessibility measures are possible; for example, it is possible to calculate the accessibility impacts on low-income households separately from high-income households. However, we report only aggregate accessibility impacts here for purposes of brevity. The travel cost for the accessibility calculations in this case only accounts for peak-hour auto travel times. If the data were available, other types of accessibility such as transit accessibility could be calculated. The coefficient of impedance (-0.14) is derived from AAMPO's travel demand model impedance curves (San Antonio-Bexar County Metropolitan Planning Organization, 2011). Fig. 8.4 of the model documentation provides the Friction Factors for Home-Based Work travel times. With the friction factor declining by 50% between 7 and 12 min, resulting in an impedance coefficient = $-\ln(0.5)/5 = 0.14$.

Equations (1.1) and (1.2):

$$A_i = \sum_j D_j f(c_{ij}) = \sum_j D_j e^{-0.14 * t_{ij}} \quad (1.1)$$

$$A_{Region} = \sum_i A_i H_i / \sum_i H_i \quad (1.2)$$

For equations (1.1) and (1.2), A_i is accessibility for zone i , H_i is the number of households residing in zone i , D_j is the total number of jobs located in zone j , t_{ij} is the auto-based, peak-hour travel time between zone i and j , and -0.14 is the impedance coefficient with units in inverse minutes.

We also examined the changes to mobility for each of the two scenarios by examining aggregate travel time for 2020 vehicle flows across the metropolitan region. This was done by summing up all projected zone-to-zone vehicle flows by the peak-hour vehicular travel time between all zones for each scenario.

$$T = \sum_{i,j} F_{ij} * t_{ij} \quad (2)$$

In equation (2), T is the aggregate travel time in minutes, F_{ij} is the flow of vehicles from zone i to zone j over the peak hour and t_{ij} is the peak-hour travel time from zone i to zone j .

5. Results

The results section details the implications of the Mobility 2040 LRTP Highway Projects and the 1604 Loop Projects. For each set of projects, the spatial implications in terms of household locations, employment locations, and accessibility shifts is mapped. Then accessibility and mobility impacts of these projects is also summarized in tabular format. The accessibility impacts take into account both changes to travel speeds and land-use patterns, whereas the mobility impacts only take into account changes to travel speeds. "Speed-Only" accessibility impacts display the impacts to accessibility if no land use change had occurred.

5.1. Analysis 1: Mobility 2040 transportation plan vs. No-Build

Our first analysis examined the accessibility implications of the Mobility 2040 Highway Projects versus a No-Build Scenario. We examined how mobility and accessibility change between the Build and No-Build scenarios for the year 2020, which involved a 10-year land-use forecast from launch-year 2010 data. Although 2040 data were

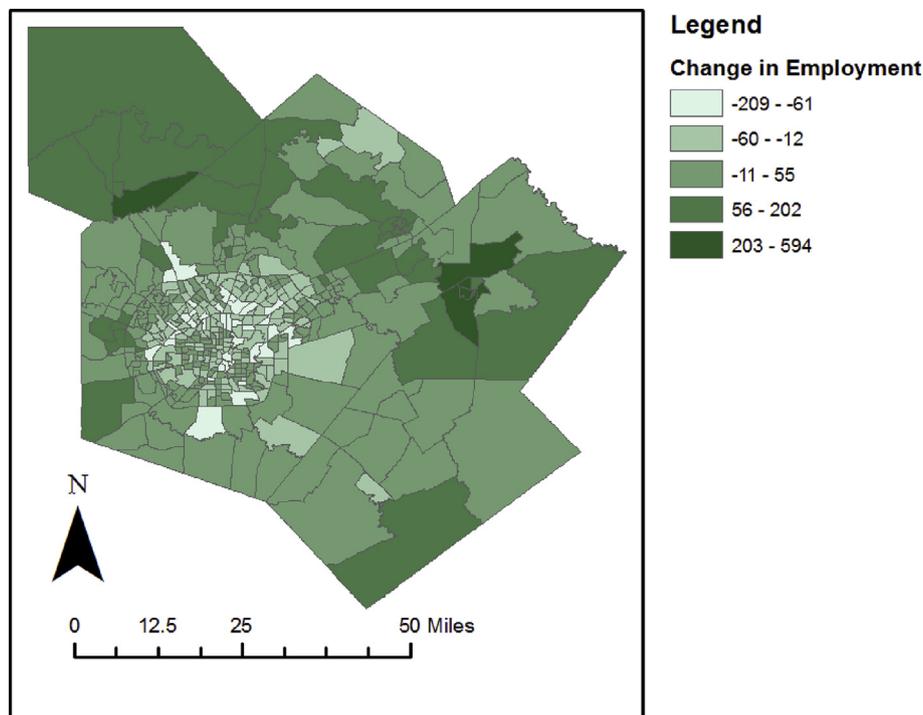


Fig. 6. Forecast employment shift due to Alamo transportation plan to 2020.

available for land use forecasting, we found that extrapolating the land-use forecast over 30 years produced exaggerated results; on the other hand, a land-use forecast over less than 10 years might not show enough land-use change for a meaningful accessibility analysis.

5.1.1. Land use forecast and accessibility shifts

Forecast land-use shifts due to Mobility 2040 are illustrated in Fig. 5 and Fig. 6. These shifts illustrate how the Build Scenario differs from the No-Build Scenario by taking the difference between the two for each zone. Household and employment shifts are shown with total population change rather than percent change. Household gains for the Mobility 2040 projects are concentrated along the northern metropolitan fringe, in particular the far northeast. Household losses are concentrated on the northern, inner ring suburbs, but also encompass much of the central city. Employment gains due to the transportation plan cluster in the northwest and northeast, while employment losses are scattered throughout the central city and the northern inner ring.

The resultant geography of accessibility changes is illustrated in Fig. 7. Accessibility losses are greatest for the central city, but also there are some accessibility losses along the metropolitan fringe. The accessibility gains occur along the outer-edge suburbs. These accessibility shifts are largely explained due to shifts in employment location away from central areas and towards peripheral areas illustrated in Fig. 6. However, this map shows the geography of accessibility change without accounting for population weights. Aggregate accessibility impacts weighted based on resident population in each tract are presented in Table 3, discussed below.

5.1.2. Accessibility and mobility effects

Table 3 illustrates mobility and accessibility performance across four scenarios: Build, No-Build, Speed-Only Effects, and Year 2010. Speed-Only Effects show what the impact would be on accessibility if the proposed transportation projects had no land-use impacts but only speed impacts. Year 2010 mobility and accessibility are included as a baseline for comparison. The primary mobility effects are reported via aggregate peak-hour travel time and average peak-hour trip time. The primary accessibility effects are reported via population-weighted

accessibility. Although accessibility changes are illustrated via Fig. 7, this map can be misleading because accessibility gains can be concentrated in areas which are spatially large but low in population. To summarize the region-wide accessibility performance, the number of people residing in each Census Tract is taken as the weight for that Census Tract, and the job accessibility score is averaged over all Census Tracts; this produces the average job accessibility experienced across all residents of the metropolitan region. Percent differences are reported for the Build Scenario in comparison with the No-Build Scenario and the Year 2010 baseline.

The mobility impacts of the Alamo's Mobility 2040 Plan through 2020 are significant, however despite this, its accessibility impacts are negligible. The Build Scenario reduces aggregate travel time by 5.5%, so travel times are quite improved. In addition, if the associated transportation projects had no land-use effect—if they only changed interzonal speeds—they would increase accessibility by 3.1%. The reason the accessibility improvement is less than the mobility improvement is that accessibility creates greater weights where current households reside, and presumably the speed improvements are predominantly weighted towards less-populated areas of the region.

However, after also considering the land-use effects of the Mobility 2040 Plan through the year 2020, the net accessibility benefits are -0.2% . There is no discernible benefit to the average households' accessibility as a result of the Mobility 2040 Plan.

5.2. Analysis 2: Loop 1604 vs. No loop

The second analysis focuses on the accessibility effects of a series of related transportation projects, a bundle of expansions and improvements to a suburban ring road known as Loop 1604. The existing transportation plan is examined with all Loop 1604 projects included versus the same transportation plan but with all Loop 1604 projects excluded. The first scenario we will refer to in shorthand as “Loop 1604” or “Build” and the second as “Plan Minus Loop 1604.”

5.2.1. Land-use forecast and accessibility shifts

The Loop 1604 projects as a whole result in more centralized

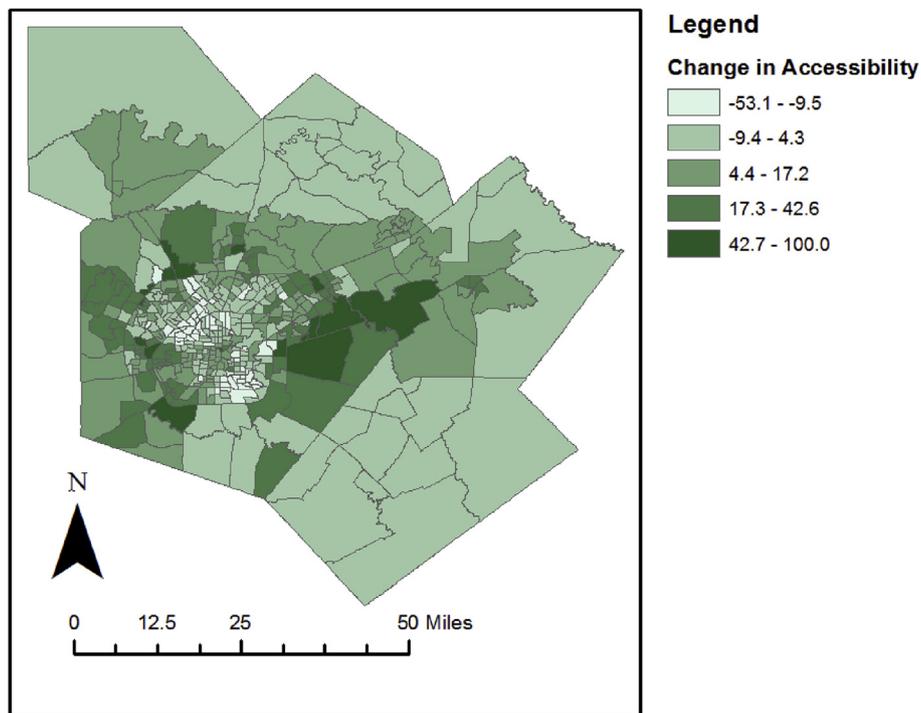


Fig. 7. Accessibility shift due to Alamo transportation plan to 2020.

locations for households as illustrated in Fig. 8. Household increases are found throughout the central city and along the northern inner ring suburbs. Household losses are found throughout the metropolitan fringe, both to the north and to the east. Employment changes are more centralized (see Fig. 9), with employment gains occurring in a crescent from the central city to the northern edge. The largest employment losses are in the far northwest, the far north, and the far east of the metro area.

The geographic area that benefits from these shifts in terms of accessibility is the central city, as shown in Fig. 10. Although the geographic area with accessibility losses is much larger, from the perspective of residential population the area with accessibility gains is larger in magnitude.

5.2.2. Comparison of accessibility and mobility effects

Loop 1604 is the opposite kind of case from the Mobility 2040; it has fairly strong mobility benefits, but its accessibility benefits are much higher than these mobility benefits alone. The centralizing (and proximity-increasing) effect that building the Loop 1604 Projects have relative to the Plan Minus Loop 1604 Scenario compounds its positive

mobility effects.

Table 4, like Table 3, examines mobility and accessibility impacts across four scenarios: Build, Plan Minus Loop 1604, Speed-Only Effects, and Year 2010, and compares the Build Scenario's performance as a percent change relative to Plan Minus Loop 1604 and Year 2010. The mobility effect, as measured via average trip times, is an improvement of 2.5% in comparison with the Plan Minus Loop 1604 Scenario. Shifting to the accessibility impacts of Loop 1604 with respect to the Speed-Only Effects, the improvement to the average household's accessibility is 5.0%. Accessibility benefits exceed mobility benefits because these accessibility calculations weigh such benefits in locations where households and jobs are clustered. (see Table 4).

Total accessibility impacts, including the effects of land-use changes in addition to speed effects, raise the accessibility impact of Loop 1604 projects to +9.5% for Build in comparison to Plan Minus Loop 1604.

6. Discussion

The Mobility 2040 Projects demonstrate mobility benefits through decreased average travel times, however despite this they offer no net

Table 3
Mobility 2040 plan mobility and accessibility impacts through 2020.

	Build Scenario	No-Build Scenario	Speed-Only Effects	Year 2010
Mobility Impacts	Aggregate Travel Time			
Vehicular Travel Time, Minutes	82,098,736	86,908,769	NA	73,189,146
Average Trip Time, Minutes	24.59	26.03	NA	21.92
Percent Diff. No-Build	- 5.5%	NA	NA	NA
Percent Diff. with 2010	12.2%	18.7%	NA	NA
Accessibility Impacts	Gravity-Weighted Accessibility to All Employment			
Minimum Zone	22	21	21	66
Maximum Zone	96,340	96,069	97,071	107,978
Mean Zone	28,105	27,790	28,298	29,330
Standard Deviation	23,335	23,635	23,553	25,382
Population Weighted	24,406	24,446	25,194	27,988
Percent Diff. No-Build	- 0.2%	NA	3.1%	NA
Percent Diff. with 2010	- 12.8%	- 12.7%	- 10.0%	NA

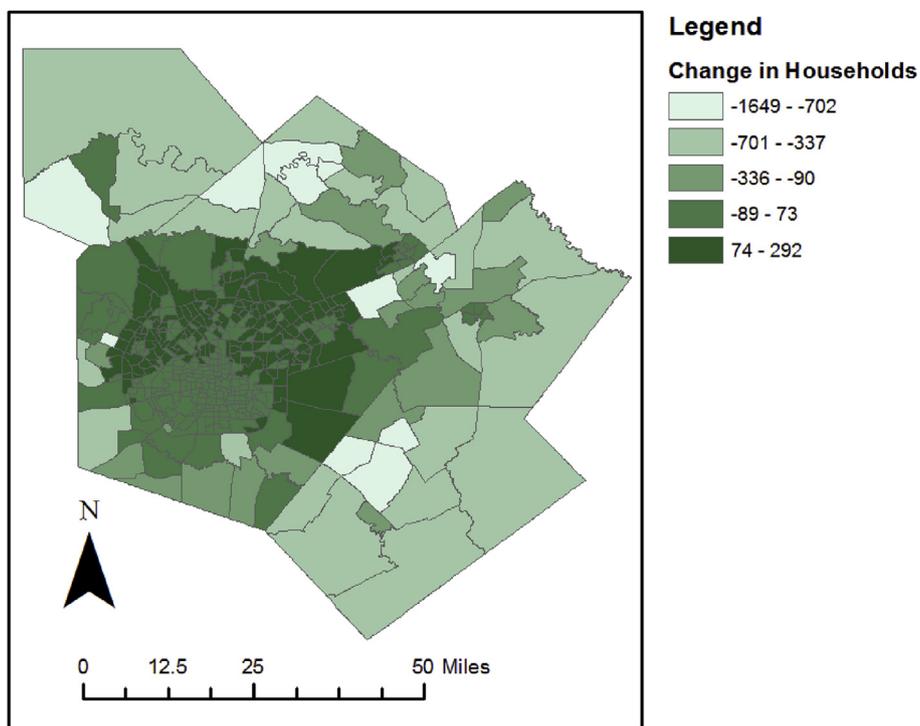


Fig. 8. Household changes due to loop 1604 to 2020.

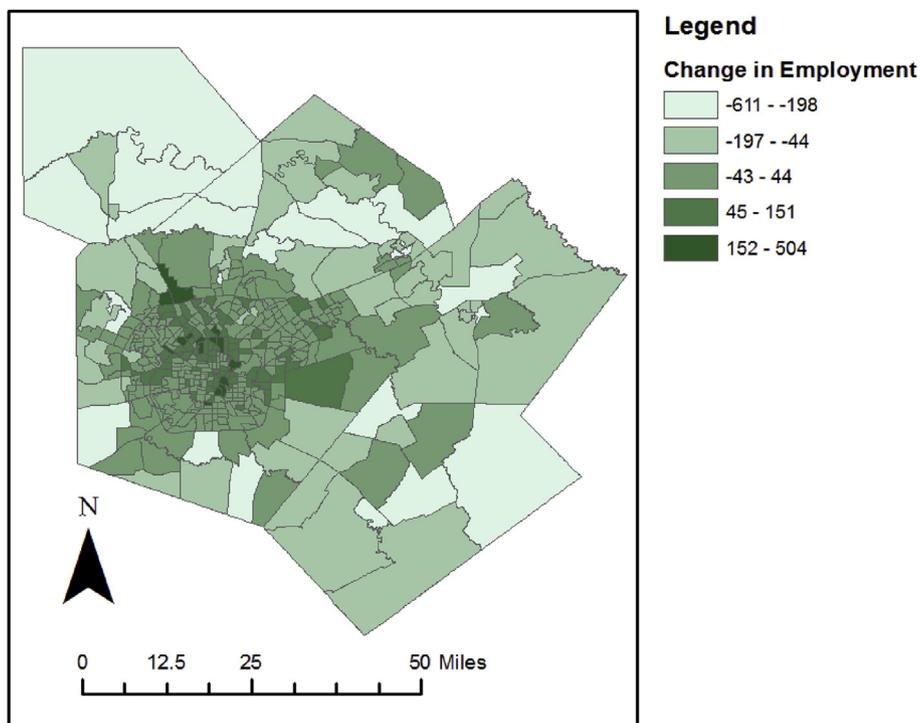


Fig. 9. Employment changes due to loop 1604 to 2020.

accessibility benefits. A major reason for this is that the Mobility 2040 Highway Projects decentralize both households and employment; after factoring in these land-use shifts, the average household has no greater accessibility in 2020 than if no transportation projects were completed at all (i.e. the No-Build Scenario). The advantage of faster speeds, which are documented in the mobility analysis above, are completely counterbalanced by the land use decentralization induced by the transportation plan.

The Loop 1604 Projects, on the other hand, illustrate accessibility benefits greater than their purported mobility benefits. Nearly half of its accessibility benefits are due to induced land-use changes – i.e. a 4.3% increase in accessibility is attributable to land use changes, while a 5.0% increase is due to mobility changes.

The reason that the Loop 1604 projects are particularly effective for improving auto-based accessibility is because they offer a triply compounded benefit. First, average travel speeds are increased. Second,

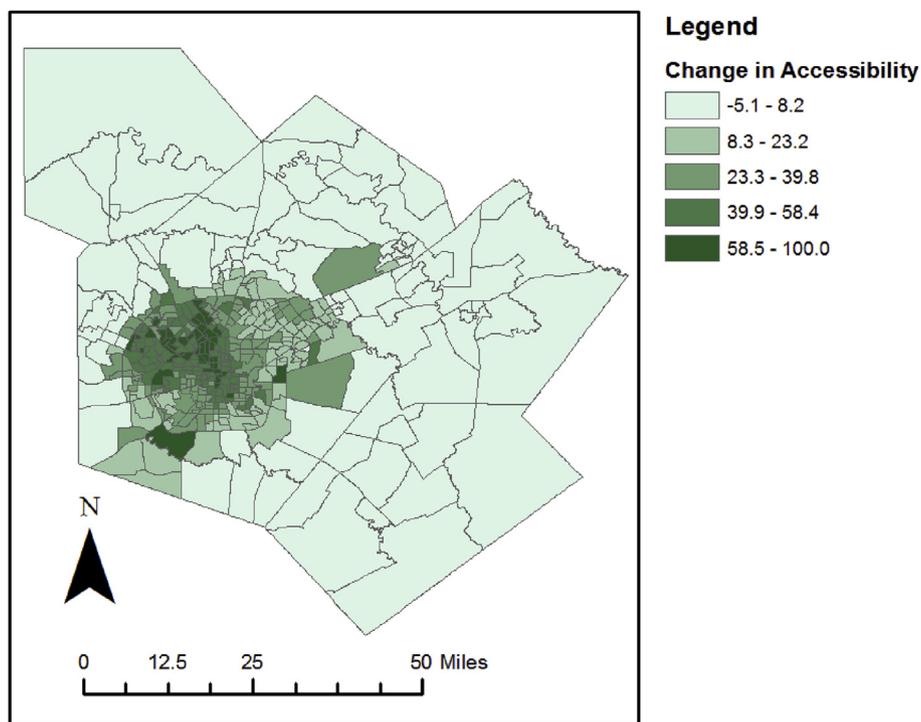


Fig. 10. Accessibility changes due to loop 1604 to 2020.

Table 4
Loop 1604 mobility and accessibility impacts through 2020.

	Build	Plan Minus Loop 1604	Speed-Only Effects	Year 2010
Mobility Impacts				
Aggregate Trip Time, Minutes	81,890,310	83,949,731		73,189,146
Average Trip Time, Minutes	24.5	25.1	–	21.9
Percent Diff Baseline	–2.5%	NA		
Percent Diff with 2010	11.9%	14.7%		NA
Accessibility Impacts				
Minimum	19	26	26	66
Maximum	88,860	85,630	87,130	107,978
Mean	28,380	26,770	27,980	29,330
Standard Deviation	22,949	21,982	22,478	25,382
Population Weighted	25,108	22,939	24,094	27,988
Percent Diff Plan Minus Loop 1604	9.5%	NA	5.0%	NA
Percent Diff with 2010	–10.3%	–18.0%	–13.9%	NA

these travel speed improvements are focused on areas of concentrated population and employment. And third, the Loop 1604 projects spur centralization of population and employment relative to the Plan Minus Loop 1604 Scenario. Accessibility benefits of this suite of projects are therefore created by changes to speeds and induced land use shifts as well.

As evidenced here, the mobility-based benefits of major transportation projects do not necessarily correspond with their accessibility benefits. While we verified that a major set of highway investments does produce mobility benefits as expected, after considering induced land-use change the net effect on average household accessibility to employment was virtually zero. On the other hand, we found that a mobility-based analysis of the Loop 1604 suite of projects would significantly *underestimate* its accessibility benefits in comparison with a Plan Minus Loop 1604 Scenario. In sum, this paper demonstrates that mobility-based analysis alone cannot provide a meaningful indicator of whether a plan provides transportation benefits to households (as measured by accessibility changes), nor can it indicate the relative size of those benefits.

The implications of this result are that shifting from mobility

analysis to accessibility analysis will result in a new prioritization across proposed transportation projects. Projects that improve speeds but encourage decentralization will score more poorly under an accessibility-based evaluation system. Projects that capitalize on existing concentrations of population and employment will perform better and be more likely to be selected for implementation. In other words, the goal of a shift to accessibility-based project evaluation is to change which transportation projects are selected for implementation based upon their anticipated accessibility benefits.

In the US, policy is starting to shift away from mobility-based analyses and towards accessibility-based analyses, at least in some selected cases. The State of California has decided to omit traditional traffic impact analysis from its environmental analysis process, deemphasizing traditional mobility concerns (Governor’s Office of Planning and Research (CA), 2016). Meanwhile, the State of Virginia has adopted a new SmartScale project prioritization process that explicitly includes an accessibility component (Virginia Department of Transportation, 2016). The methods presented here are hoped to accelerate and improve this shift towards the accessibility-based evaluation of transportation projects.

In this paper we focus on a comparison of mobility and accessibility-based performance measures for transport project evaluation. In fact, the world of transport project evaluation is a complex one extending beyond either of these types of measures. Cost-benefit measures are widely used, especially in developing countries and for larger-scale projects. Cost-benefit measures, however, are often criticized because of the questionability of many of their assumptions, such as their valuation of time savings, and their inability to account for equity impacts (Jones et al., 2014; Shi and Zhou, 2012). But more fundamentally for the purposes of this study, cost-benefit analysis is most typically a form of mobility analysis, because travel-time savings, rather than accessibility gains, form the basis of transport-project benefit. By contrast, Geurs et al. (2010) demonstrate the possibility of evaluating accessibility gains in monetary terms in a fashion that would be analyzable within the cost-benefit analysis framework.

Furthermore, there is a growing trend towards the consideration of multiple criteria in transportation project evaluation using Multi-Criteria Decision Analysis (Avineri et al., 2000; Frohwein et al., 1999; Macharis and Bernardini, 2015; Sinha and Labi, 2011). This includes the capability of incorporating both quantitative as well as qualitative criteria (Avineri et al., 2000; Macharis and Bernardini, 2015). This literature focuses on the integration of numerous economic, environmental, and societal considerations in transportation evaluation, but generally employs mobility-based approaches to transportation benefits. As with cost-benefit analysis, multicriteria evaluation can be revised with an accessibility framework for transportation benefits as in the Virginia SmartScale process (Virginia Department of Transportation, 2017).

The more widespread adoption of accessibility-based performance analysis faces several obstacles. Some obstacles may be conceptual, such a misunderstanding of the accessibility concept or a confusion of the concepts of accessibility and mobility (Boisjoly and El-Geneidy, 2017a; Proffitt et al., 2017). Other obstacles may be political, that accessibility as a planning goal has no natural constituency, whereas there are obvious constituencies for the concerns of traffic congestion and environmental impacts. Yet another barrier is in relation to operationalization. In many cases accessibility is understood at the conceptual level but there is a lack of means to implement it properly within decision making (Boisjoly and El-Geneidy, 2017b). This paper aims to offer a concrete methodology for analyzing the accessibility impacts of transportation projects to help overcome this obstacle. As such, it is one of a growing family of accessibility-based analysis tools or approaches that are increasing available for practitioners (Papa et al., 2015).

7. Limitations

The analyses here are based on a single round of iterative transportation and land-use forecasts. That is, a new zone-to-zone travel time matrix is estimated for the Build and No-Build scenarios, and a different regional land-use outcome is forecast for each scenario. More iterations are possible: the new land-use forecast would alter the zone-to-zone travel time matrix, and so on. The decision to iterate travel time and land use just once each was largely a function of the core purpose of this project: demonstrating manageable tools by which transportation planners in local practice could evaluate the accessibility impacts of proposed transportation projects. Given lowered barriers to the use of integrated transportation-land use models, they could be used to forecast accessibility impacts, and presumably they would capture more comprehensively the dynamic interplay between the transportation and land use systems. In addition, any improvement to the land use forecasting enterprise itself would clearly improve the accuracy of the results. The TELUM land use model deployed here is an aggregate model and does not involve the detailed simulation of land development markets; therefore, its land use forecasts may be less accurate than other, more nuanced land use models. Analysts must continually

consider the trade-offs between model complexity and data hungriness versus demonstrated model accuracy and the strength of its theoretical basis. Our goal in this case was to focus on minimum barriers to entry for the adoption of land use modeling as a required part of an integrated accessibility analysis.

The aggregate nature of TELUM forecasts supports place-based accessibility measures, as opposed to disaggregate person-based measures such as utility-based approaches. The utility-based approaches show, on a disaggregate basis, the varying accessibility that even neighboring individuals experience based on their daily opportunities and constraints and are, for this reason, a more accurate depiction of accessibility than the highly aggregate accessibility measures used here. While these metrics can readily be estimated for an *existing* population, their use in prospective planning is limited by the unknown preferences, opportunities, and constraints of a projected future population. Basic population projections themselves are quite technically challenging and disaggregating future populations across multiple demographic and social characteristics as a high level of geographic detail is likely not feasible with any reasonable degree of accuracy. For this reason, we believe that the aggregate forecasting and accessibility measurement used here are appropriate tools for the transportation and land-use planning tasks at hand.

A second limitation is due to the baseline of comparison. We took the existing plan – Mobility 2040 – as the status quo for comparison purposes, even though our analysis shows no accessibility benefits due to the Mobility 2040 Plan. Our analysis shows that the Loop 1604 projects provide an accessibility improvement when the rest of the Mobility 2040 Plan projects are taken as the baseline of comparison. However, since we find no benefit to the Mobility 2040 Plan, a better comparison might be the Loop 1604 projects versus a true no-build scenario, i.e. no new roadway projects for the region. Only then would we be able to discern if the Loop 1604 projects are truly accessibility enhancing.

Although we only present average household accessibility impacts in this paper, the method presented here readily supports different types of disaggregate accessibility impacts, including a differentiation of accessibility impacts by household type, accessibility to work as well as non-work destinations (i.e. shopping, health care), and accessibility by transit as well as by auto modes.

Future research could improve upon the methods presented here in several ways. More sophisticated integrated transportation-land use models would improve the accuracy of forecast accessibility impacts. Sensitivity analysis of forecast future land use is warranted given the inherent uncertainty of the land use forecasting exercise. More diverse transportation projects could be analyzed, for example comparing a proposed highway project with a proposed transit project, while taking into account the expected land use impacts of each. Equity analyses are an additional layer that could be added to the evaluation of the accessibility impacts of proposed transportation projects. While the a priori evaluation of proposed transportation projects is perhaps as old as the field of transportation planning itself, the application of an accessibility lens to such evaluations is a relatively recent phenomenon and many methodological improvements are possible.

8. Conclusion

When transportation planners evaluate the transportation-related benefits of a proposed project based upon mobility alone, they miss an essential part of the dynamic relationship between transportation infrastructure and land-use patterns. Improved transportation infrastructure influences the pattern of new land uses, yet these impacts are rarely accounted for in transportation project analysis. Even though the need for accessibility-based transportation analysis has been well established, consideration of the land-use impacts of major transportation projects is routinely ignored and accessibility is either not accounted for or inadequately estimated as a consequence.

In order to understand the transportation benefits of a major transportation project, an accessibility-based evaluation framework is required. And to evaluate the accessibility benefits of such a project, induced land-use changes must be accounted for, in addition to the better-understood travel-time impacts. It is possible – as demonstrated here – that the decentralizing effects of a transportation project might counterbalance or outweigh its speed-enhancing benefits. Alternatively, if the transportation investment leads to more concentrated land development than might have occurred otherwise, the land-use impacts will magnify the accessibility benefits of the transportation investment. The practical method we present here illustrates how a land-use model can be integrated into the analysis of a transportation project to ascertain its net accessibility impacts.

Land-use impacts are by no means marginal in either of the cases we analyzed. In the Mobility 2040 case, the land-use impacts completely neutralize the purported mobility benefits. In the second case, the Loop 1604 Projects, the land-use impacts augment the mobility benefits, ultimately constituting 45% of the accessibility impacts. The land-use impacts of a major transportation project are too large to be ignored, and accessibility analysis cannot be replaced by a simple mobility analysis, which does not account for these land use shifts.

The tools we employ in the paper are widely accessible in planning practice, and there is no technical reason that practicing transportation professionals cannot evaluate transportation projects based upon their accessibility impacts. This approach can bring accessibility evaluation out of the somewhat abstract world of regional scenario planning by linking it to everyday decision making and the prioritization of proposed transportation projects.

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