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At the nexus of equity and transportation modeling: Assessing accessibility through the Individual Experienced Utility-Based Synthesis (INEXUS) metric

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ABSTRACT

We propose the Individual Experienced Utility-Based Synthesis (INEXUS) accessibility metric, which is developed to leverage an open-source agent-based regional transportation model. We include two specifications: the Potential INEXUS, which relates to an individual's potential set of mode alternatives and the Realized INEXUS, which reflects the optimal mode chosen by the agent. One advantage of using an agent-based approach is that it enables us to estimate individual agent-level behavior and travel needs. This addresses a commonly identified limitation of many existing accessibility metrics, which exhibit insensitivity to the heterogeneity of transportation preferences, opportunities, and constraints across subpopulations. While many system-level outcomes of interest may inform transportation planning, arguably an equally important consideration is that the system provides adequate and equitable access to goods and services for the broad spectrum of those traveling along its network. In many cases, average results do not reflect the experience of a majority – or even a significant – portion of the population. We apply our methods in a case study of alternative ridehail price scenarios to demonstrate the value of INEXUS distributions in evaluating differences in accessibility within and between population groups.

1. Introduction

When examining the effects of a new transportation policy, system-level outcomes summarizing congestion, capacity, aggregate or average vehicle miles traveled, person miles traveled, or mode splits can usefully inform planning. However, arguably an equally important consideration is that the system provides adequate and equitable access to jobs, goods, services, and education, for the broad spectrum of people traveling its network. Thus, we are concerned with more than average population-level impacts, as they may not reflect the experience of a significant portion of the population. Additionally, a policy, technology, or system design change may be intended to increase transportation system equity, e.g., by focusing on increasing accessibility of low-income groups to high-quality jobs, childcare, or grocery stores. In the transportation context, reporting only system-level impacts of new technologies such as autonomous vehicles (AVs) or ridehail service penetration masks the heterogeneity in experiences at the individual level, and precludes evaluating equity considerations.

Existing metrics are often location-based, driven by observational data, and describe location-based accessibility (Hou et al., 2019) or transportation affordability (Center for Neighborhood Technology, 2017). Moreover, many of these metrics or applications employ more normative definitions of accessibility, relying on assumptions about what should be considered a reasonable benchmark for travel distance, travel time, or cost (Páez et al., 2012). While these metrics offer valuable insights into the transportation system, they fall short of representing the full distribution of policy impacts across individuals, and often do not fully account for the behavioral responses that may more realistically underpin actual accessibility. Observational mode use data and surveys may provide information on variation across outcomes for

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different individuals, e.g., the chosen mode, travel times, or costs, for different population groups (Karlström and Franklin, 2009). However, these metrics do not assess an individual's happiness or "satisfaction" with their choices, including day-to-day level of satisfaction with their transportation experience and which set of transportation choices allow access to various destinations. A primary limitation of revealed measures of access or well-being is the lack of a baseline understanding against which to compare the outcomes. Though commonly used as accessibility measures, an individual's observed outcomes (e.g., mode chosen) only reveal part of the story. External factors constrain mode choice, including family wealth and car ownership, transportation system options, cost, congestion and travel time, hassle, etc. Research on voluntary versus involuntary car-free households indicates that these two groups make different residential location choices (Delbosc and Currie, 2012) and that, particularly in California, 79% of no-car households are involuntarily so (Brown, 2017), with car ownership strongly influenced by parking ratios and transportation accessibility (Millard-Ball et al., 2022).

We propose two individual-level metrics, collectively called the Individual Experienced Utility-Based Synthesis (INEXUS). These metrics capture the Potential—the value of the complete choice set of available transportation modes for each person for every trip they take during a typical day—as well as the Realized—the achieved "happiness" from the selected mode of a given trip. The INEXUS specifications provide an agent-trip-level utility-based set of accessibility metrics that can complement other types of location-based accessibility metrics to generate a holistic understanding of variation in potential and realized experiences, and how they are valued by the individual travelers, across population groups and transportation scenarios.

To estimate these proposed metrics, we use an integrated set of agent-based models called BEAM CORE, where CORE stands for Comprehensive Regional Evaluator. This integrated modeling workflow consists of an agent-based regional transportation model, Behavior, Energy, Autonomy, and Mobility (BEAM), an open-source model developed by the Lawrence Berkeley National Laboratory (LBNL). BEAM is integrated with: ActivitySim, an open-source activity-based travel demand model; UrbanSim, an agent-based land-use model; and ATLAS, an agent-based household fleet and vehicle choice model. Unlike other techniques, agent-based models facilitate examination of both system-level results as well as the outcomes for all individual agents that utilize the system.

Advantages of this approach include 1) the ability to model the impact of a multitude of hypothetical and future transportation scenarios; 2) estimation of heterogeneous outcomes for each person or group and resulting (in)equity. Leveraging this approach to generate the INEXUS set of metrics, each converted into dollar units to enhance interpretability, enable transportation planners to understand not only how potential policy scenarios could change the overall system outcomes, but also individual or subpopulation-level behavior, wellbeing, and accessibility. This application of utility-based accessibility metrics implemented in a fully disaggregated agent-based regional simulation modeling framework enables a positivistic analysis of accessibility, thereby addressing a dearth of research taking this approach to accessibility (Páez et al., 2012). In addition, unlike most of the research applying positivistic accessibility analyses, which tend to focus on empirical or survey data as summarized in Paez et al. (2012) (Páez et al., 2012), the application of our metric in a simulation framework enables a more flexible exploration of a range of potential what-if scenarios, policies, or system design changes.

The contributions of our development of the INEXUS metric include: 1) creating a framework to gain more value from the detailed, disaggregated, agent-based model outcomes and thereby contribute to accessibility research that is less well-represented, namely positivistic accessibility, accounting for a more complete representation of empirically-derived travel preferences and endogenous behavior change, 2) creating a set of building block metrics at the agent-trip level enabling reporting of distributions of individual outcomes allowing for identification of differential impacts on subgroups of interest, which can be examined ex-post by agent and trip attributes, 3) recognition of the potential for substantial differences between planned transportation choice expected utility and realized utility under system constraints, 4) the ability to compute differences in monetized values of consumer surplus and welfare across scenarios, 5) a consistent framework to compare accessibility, consumer surplus, and welfare across a broad range of policy, technology, and system design scenarios using the BEAM CORE integrated modeling system (BEAM and ActivitySim in particular); and 6) providing a multi-dimensional utility-based set of metrics that synthesize numerous trip characteristics, all of which contribute to the outcome.

Our paper proceeds as follows: Section 2 provides background information defining types of metrics used to characterize transportation accessibility and orients our proposed INEXUS metric within the literature discussing similar metrics. In Section 3, we describe our methods, including the transportation system and choice models used to define the agents, dataset format, construction of the INEXUS specifications, and extension of INEXUS to examine shifts in consumer and social welfare. In Section 4, we present the rationale for several case studies of accessibility and welfare change under potential policy interventions and transportation utilization shifts; we discuss findings from these case studies, noting insights provided by the INEXUS metric. Section 5 concludes with discussion of potential applications of INEXUS in future research and policy analysis.

2. Background on accessibility metrics

This section presents a brief survey of existing metrics of accessibility that motivated the development of the INEXUS. Fig. 1 provides a conceptual overview of the types of accessibility metrics established in the literature. Broadly, access can be measured from a geographic location (isochrone- or gravity-based) or for an individual traveler (utility- or activity-based). Each type provides insight into transportation system performance, albeit at different levels of analysis.

2.1. Location-based metrics

Location-based metrics estimate potential achievable outcomes, such as access to opportunities, for specific geographic locations based on geographic and transportation system attributes. Common types of location-based metrics include gravity-based measures, which calculate a location's accessibility by considering proximal opportunities weighted by a measure of effort required for access (Geertman and Ritsema Van Eck, 1995), isochrone measures, which estimate cumulative opportunities available within a given travel time, distance, or generalized cost (Vickerman, 1974; Wachs and Kumagai, 1973), and composite indicators of energy and travel times (Hou et al., 2019). Location-based indicators are useful for identifying the maximum accessibility for travelers with unconstrained mobility. They can be either normative or positivistic, though are more likely to have normative definitions in which key thresholds of travel distance, time, or cost are assumed to be relevant benchmarks of access (Páez et al., 2012). They are typically measured with publicly available data and enable comparisons of land use, transit level of service, and potential access across different locations within a region. The more broadly applied location-based accessibility measures tend to be static and atemporal in their nature. However, recent studies such as Wang et al. (2018) (Wang et al., 2018) and Järv et al. (2018) (Järv et al., 2018) have introduced location-based space-time accessibility measures to capture temporal variation. Although location-based measures are widely used, they generally overlook the nuances of behavioral differences (Bills and Carrel, 2021). These measures often assume uniform accessibility for all travelers originating from the same starting point. Bills and Carrel (2021) (Bills and Carrel, 2021) propose an alternative perspective on

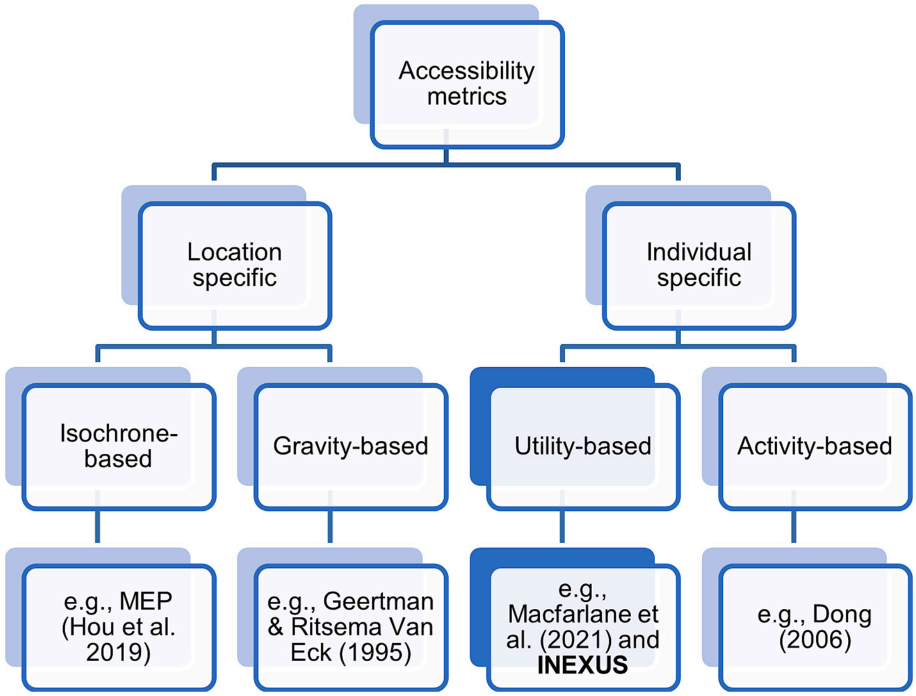

Fig. 1. Accessibility metric overview (Hou et al., 2019; Geertman and Ritsema Van Eck, 1995; Macfarlane et al., 2021; Dong et al., 2006).

measuring transit accessibility, focusing on the behavioral adaptations of individual travelers to travel time unreliability. Nevertheless, they acknowledge that more research is needed to refine the approach and explore its equity implications.

2.2. Individual-based metrics

Individual-based metrics provide an opportunity to understand not only how access varies across demographics, but also how transportation needs are distributed within the same or across different locations. These metrics are largely understudied because they require detailed, individual-level data on transportation needs, and tend to reflect accessibility that is positivistic, accounting for traveler preferences and behavioral responses—an area that has been less well-represented in the literature historically (Páez et al., 2012). Individual-based metrics are typically utility-based (Niemeier, 1997; Ben-Akiva and Lerman, 1979; Demitiry et al., 2022), but may be estimated using stated or revealed preference surveys (Farber et al., 2016). Individual-based metrics can be activity-based or path-dependent.

Utility-based measures are based on random utility theory (Domencich and McFadden, 1975), in which a portion of the traveler's utility (e.g., modal attributes) is observable and a portion is unobserved by the researcher. Logsums of the denominator of utility models are frequently used as a proxy for accessibility (Niemeier, 1997; Ben-Akiva and Lerman, 1979). This formulation generally implies that larger choice sets with higher utility alternatives result in higher levels of accessibility. The multinomial logit (MNL) specification of accessibility benefits from transferability to consumer welfare, as it can be viewed as the demand curve for a particular mode-destination alternative. Consumer surplus differences can be calculated for two scenarios based on the difference in expected maximum utility between a base condition and policy change scenario (Williams, 1976). Utility-based measures differ in complexity, ranging from selecting among available destinations for a single trip to accounting for an individual's entire daily activity pattern choice set, inclusive of trip purposes, departure times, destinations, and modes.

Activity-based accessibility measures, introduced by Ben-Akiva and Bowman (Ben-Akiva and Bowman, 1998), are derived from random utility theory and generated from the traveler's daily activity schedule. In contrast to other measures of accessibility, which traditionally capture only a single trip purpose at a time, Dong et al. (Dong et al., 2006) introduced a utility and activity-based accessibility measure that takes into account the expected maximum utility from all activity patterns for the day, including destinations, modes, departure times, and subtours. Such rich detail provides a more holistic understanding of the individual's actual access to opportunities, which requires granular data on both the individual's activities and transportation system attributes.

Path-dependent measures of accessibility augment individual-based metrics by utilizing both the trip-tour origin as well as points along the route to define individual-level access (Páez et al., 2012; Kwan, 1998). They can also provide individual-path-specific accessibility measures, which require detailed data collection reflecting current and desired travel behavior.

We turn now to the INEXUS metrics, explaining their value in the context of existing transportation accessibility measures. It is important to note that these metrics only measure the utility of the trip, not the intrinsic benefits of the activity (Mokhtarian et al., 2015), and they are proposed to complement more common location-based metrics. Bills and Walker (Bills and Walker, 2017) discuss the value of an individual utility metric ("distributional comparison measures… incorporating equity standards") and provide a demonstrative calculation using 2000 survey data points. They advocate for calculating equity indicators at the individual actor level, noting that mean or median indicators obscure key decision-making information. We agree that aggregate accessibility and equity measures mask important individual-level outcomes, potentially reducing their usefulness in identifying and addressing real-world disparities. We build off of (Bills and Walker, 2017) and propose two individual utility metric formulations, addressing potential and realized outcomes.

As mentioned above, the logsum measure is a well-known metric in the accessibility literature. It has been used in a variety of applications, including estimating travel demand (Harb et al., 2022), evaluating transportation projects (Guzman et al., 2023), and developing transportation policy (Gulhan et al., 2013). Our metrics and approach build from the utility-based accessibility literature, but advance the state of research on measuring transport accessibility in several ways:

1) By using data output from BEAM and ActivitySim, we enhance the analytical capabilities of these state-of-the-art transportation simulation and planning tools.
2) Because these models utilize recent data (2018), our process provides an accurate baseline for near-term calculations.
3) Scenarios can allow for multi-year analyses in which land use and travel demand can change over time. This flexibility enables INEXUS to be used to analyze cases where a range of behavioral responses—from residence and work location choices, household vehicle holdings, and trip generation, in addition to mode choice—can all be responsive to a given system intervention. It can also be applied in cases where land use, vehicle ownership, and travel plans are fixed, and only mode choice behavior is subject to change (as we demonstrate in the case study presented in this paper), or anything in between.
4) When evaluating potential impacts of untried policies on a multi-year scenario with an evolving population, agent-based modeling benefits from the ability to consider large deviations from baseline on the fly, rather than relying on an anticipatory survey. Individual preferences in agent-based models can be updated to incorporate insights from future surveys.
5) The two INEXUS specifications allow for comparison between the distributions of idealized outcomes (Potential) and outcomes under individual, household, and system constraints (Realized).
6) INEXUS metrics are intentionally calculated at the individual level. When INEXUS metrics are calculated for a dataset, the result is a distribution of individual outcomes, which may be later aggregated by attributes of interest, rather than a population-level value. Treatment at the individual level is key to "revealing the winners and losers that result from transportation improvements, in comparison with average measures" (Bills and Walker, 2017). INEXUS metrics are well positioned to evaluate the potential for policy impacts to disproportionately affect historically disadvantaged communities.

While the concept used for the INEXUS draws from existing literature and we are not introducing a completely new methodology, we have chosen to refer to it with the name "INEXUS" due to the novel application case we present, with this metric incorporated into the BEAM CORE integrated agent-based modeling workflow. This choice aids in communication around this concept with the many stakeholders leveraging the BEAM CORE capabilities.

3. Methods

In this section, we outline the methods used to develop INEXUS distributions. We explain our use of BEAM and ActivitySim models, both of which interact with and draw from several other models, to derive the data necessary to estimate distributions of individual accessibility metrics (Fig. 2). We define the Potential and the Realized INEXUS specifications, and explain how to derive welfare and equity computations and scenario comparisons using INEXUS.

Fig. 2 illustrates how different models are integrated and leveraged to calculate the INEXUS metrics. These models interact to result in a transportation equilibrium defining mode choices and resulting system impacts of every individual and vehicle, at every time, within a typical weekday travel day. This equilibrium results from modeling the interaction, for every person and every trip, between residence location choice, household vehicle fleet composition choice, activity selection (including timing and location), and mode choice for accessing those activities (including both mandatory and non-mandatory trip purposes). Travel plans of individuals, including destination and mode selections, collectively exert pressure on both road and public transit networks, resulting in congestion and crowding. Key modules in the integrated suite then iterate until the system reaches equilibrium.

As discussed in the previous section, BEAM CORE can be used to conduct multi-year scenario analyses in which all of these modules iterate and update each year, with behavioral responses leading to changes in residential and work location choice, vehicle ownership, travel demand and trip plans, and mode choice in response to a given system intervention. In such a case, all of the modules depicted in Fig. 2 are run each simulation year. Alternatively, a short-run analysis can be conducted where only a subset of these models iterate as different scenarios are examined. For instance, in the case study presented in Section 4, in order to isolate only behavioral shifts in mode choice in response to ridehail price variations explored in the examined sensitivities, only the blue boxes in Fig. 2 are re-run with each scenario, whereas the modules indicated as gray boxes are not re-executed. Outputs from the baseline run of the full set of models are used as static inputs to the sequence represented by the blue boxes for each scenario. The flexibility to apply the INEXUS in a wide variety of long or short-run analyses, depending on the needs of a given policy-maker, planner, or research question, is one of the strengths of this accessibility application.

3.1. Dataset: Deriving an agent-level transportation choice

The INEXUS input dataset is composed primarily of outputs from BEAM and ActivitySim. The models are run for 10% of the 2018 population of the San Francisco Bay Area, defined as the nine California counties of Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma. The modeled output describes one typical weekday, and includes, by agent, every trip that the agent would take on a representative day. Our baseline scenario dataset consists of 2.5 million trips and 639,000 agents, with an average of about 4 trips per day per person. The modeled outputs include many variables, but we focus on those in Table 1.

3.1.1. Activity-based model: ActivitySim

ActivitySim is an open-source activity-based travel demand model used by many Metropolitan Planning Organizations (MPOs) in the United States (Waddell et al., 2018; Macfarlane and Lant, 2021). In

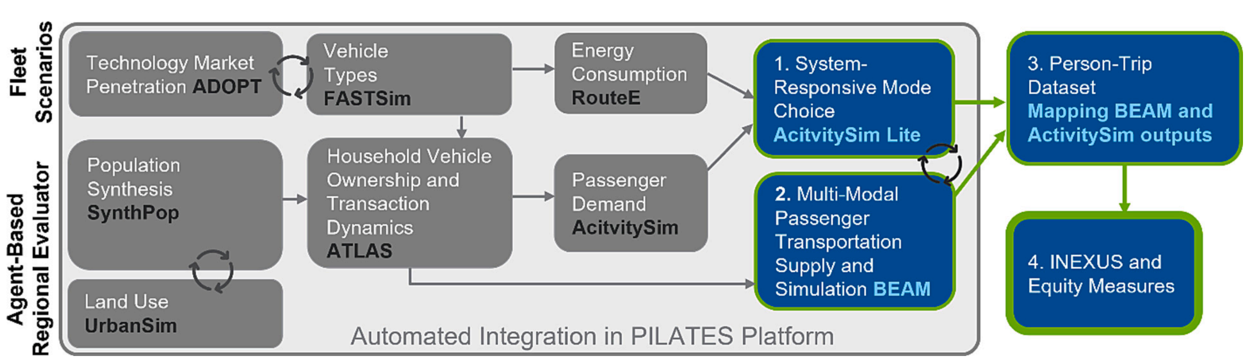

Fig. 2. Developing INEXUS distributions from BEAM CORE outputs.

Table 1
Key variables by process stage.

Process:	Stage:	Key variables	Variable description
1. ActivitySim	Mediating & Moderating Variables	Income	Ranges from loss of 14,600 dollars to earning 1,397,000 dollars. mean = 121,427 standard deviation (sd) = 109,008
		Race	black, white, Asian, etc. (refer to PUMS data dictionary)
		Gender	male, female
		Age	0 to 94 years-old mean = 40 sd = 21
		Car ownership	none, one, two or more
		Household composition	household size, household income, number of workers, etc.
		Purpose of trip	work, shopping, school, etc.
2. BEAM	Trip Level Data	Departure and arrival time	Trips happen over one day starting at 5:00 am and ending at 11:59 pm.
		Fuel type	gasoline, electricity, diesel, etc.
		Vehicle type	conventional vehicles, hybrid electric vehicles, etc.
		Number of passengers	0 to 121
		Distance	mean = 11.1 km
		Mode choice (realized)	car, ride-hail, walk-transit, bike, etc.
3. Mapping BEAM & ActivitySim	Person-Trip Level Data	Total trip duration	mean = 16.3 min
		Wait time	For transit: mean = 15.7 min sd = 9.3 min For ridehail: mean = 7 min sd = 3.2 min
		In vehicle time	mean = 15.1 min
4. Distributions	Accessibility Metrics	Potential INEXUS	
		Realized INEXUS	
		Consumer surplus	

activity-based models, each member of a population is simulated, with individuals completely disaggregated. Consequently, the model provides outputs relevant for evaluating the impact of policy changes on populations of interest, including historically marginalized groups (e.g., low-income communities) (Freedman and Hensle, 2021).

ActivitySim in its original form uses PopulationSim, an open-source population synthesizer, to create the synthetic population to forecast travel patterns (Freedman and Hensle, 2021). In the case of our implementation of ActivitySim, because it has been integrated into BEAM CORE with UrbanSim (Waddell, 2008), we use SynthPop (Ye et al., 2009) for population synthesis. SynthPop enables the efficient matching of both household-level and person-level characteristics when generating synthetic populations of interest.

ActivitySim outputs numerous moderating and mediating variables that describe each modeled agent, including demographics, travel patterns, and household characteristics. We use income to define groups of interest in the case study to follow, but any agent attribute output from ActivitySim or other upstream models in BEAM CORE could potentially be used to define a subgroup. Fig. 3 depicts relationships between ActivitySim processes and inputs.

3.1.2. Transportation system model: BEAM

We also leverage BEAM (Laarabi et al., 2023), an open-source agent-based model ideally suited to produce results capturing detailed person-specific experiences, preferences, and constraints (Hsueh et al., 2021; Szinai et al., 2020). BEAM enables disaggregation of system-level impacts to agents, specific groups, and specific geographies. BEAM improves upon other open-source options, including its foundation model MATSim (Horni et al., 2016), with increased computational performance and by enabling integration of multiple new transportation innovations and paradigms (e.g., electric vehicles, ride-hailing) into a single scenario analysis.

3.1.3. Extracting output, creating a person-trip based dataset, and analysis from integration of BEAM with ActivitySim

Output from the equilibrium of all the combined agent-based models are extracted and processed to create a dataset in which each observation is one person-trip for the entire sample population and daily activities. We used “ActivitySim Lite”, consisting of the ActivitySim mode choice model tightly integrated into the BEAM simulation such that BEAM and ActivitySim mode choice equilibrate through iteration. Using the BEAM output, we derived a new person-trip dataset, mapping trips onto people, grouping all trips for one person, and then mapping this to the ActivitySim data output to produce a rich dataset for each person-trip.

3.2. Proposed metrics: Definitions of INEXUS

We assessed the ways to adapt best practices in estimating individual-level accessibility, as opposed to a location-based metric, and identified the utility-based specification as the most feasible for capabilities with BEAM CORE. To be suitable for policy decision-making and aid in interpretation, we defined INEXUS in dollar units. This allows policy-makers to determine, for example, if a transportation project’s projected accessibility improvement benefits outweigh its costs. Following Train (Train, 2003), we use a conversion parameter α to translate utils into dollars. The parameter α_i is the marginal utility gained by consumer i from a one-dollar income increase (or cost decrease). Each person’s utility is multiplied by $1/\alpha_i$ to convert it to dollar units. Below we introduce two metrics that together constitute the INEXUS suite of metrics: the Potential INEXUS and the Realized INEXUS. The Potential INEXUS is most closely related to the majority of other utility-based accessibility metrics derived in a similar way. It is based on the mode choice logsum, normalized by the parameter α, and therefore captures the monetized expected utility across the full set of modal alternatives. In contrast, the Realized INEXUS consists of the monetized utility only from the mode actually chosen by the agent. Many valuable analyses can consist of a comparison between outcomes across these two metrics. Examples of this are provided in Section 4.4 in the case study presented. In sum, the distinction between the Realized and the Potential INEXUS allows us to disentangle the mechanisms behind accessibility improvements, providing a more comprehensive view of the impact of a given intervention.

3.2.1. Potential INEXUS

The Potential INEXUS represents the monetized expected utility of an agent having all the mode choices available at the trip’s beginning, when planning (i.e., based on the mode choice logsum) (Eq. (1)). Potential INEXUS is not limited to an agent’s preferred or actually used mode of travel. The Potential INEXUS for agent i for trip n with transportation mode choice set TC_{in} captures the full modal option utility available to the agent for the given trip, specified as:

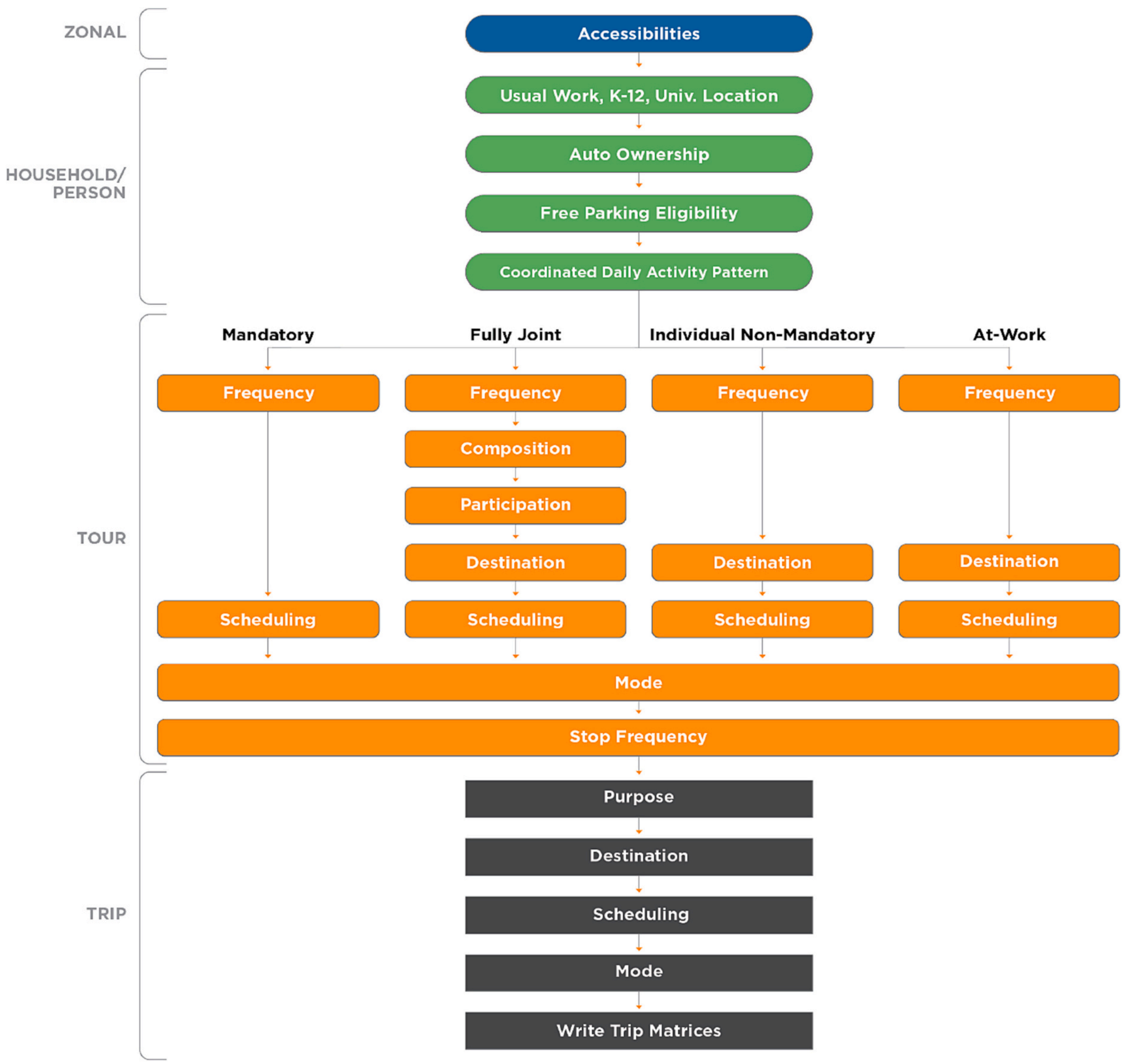

Fig. 3. Components of ActivitySim modeling.

$$\textit{Potential INEXUS}_{in} = (1/\alpha_i)\left[ln\left(\sum\nolimits_{\forall k \in TC_{in}} exp\ (V_{ink})\right) + C\right] \tag{1}$$

where TC_{in} is the transportation mode choice set available to agent i for trip n and V_{ink} is the deterministic portion of the utility of mode k for agent i for the set of modes available for trip n, $k \in TC_{in}$, and α_i is the marginal utility of an additional dollar. C is an unknown constant that represents the fact that the absolute level of utility cannot be measured. The random part of the utility is modeled through an error term ε_{ink} which is assumed to be independently and identically extreme value distributed (i.i.d.) and which, in expectation, reduces to the form above. The unit of measurement for the Potential INEXUS is dollars.

3.2.2. Realized INEXUS

The Realized INEXUS indicates the monetized utility of the trip taken, given the mode an agent actually used. Agents might take their planned mode, or may have to switch because, for example, a bus is full or no ridehail is available (Eq. (2)). The Realized INEXUS measures the utility experienced by agent i during trip n with mode choice set TC_{in} for the mode used k^*, specified as:

$$\textit{Realized INEXUS}_{in} = (1/\alpha_i)\left[ln\left(\sum\nolimits_{\forall k = k^*} exp(V_{ink^*})\right) + C\right] = (1/\alpha_i)[(V_{ink^*}) + C] \tag{2}$$

where V_{ink^*} is the observable portion of the utility function for agent i for trip n in which mode k^* is selected, and α_i is an additional dollar's marginal utility. Unknown constant C represents the immeasurability of the absolute level of utility, with the random part of the utility assumed to be i.i.d. extreme value distributed. This formulation follows the rationale explained above. The Realized INEXUS is also expressed in dollars.

3.2.3. Consumer surplus and other welfare measures using INEXUS

A number of approaches have been used to measure social welfare, e.g., the degree to which people are better or worse off in a transportation scenario relative to the baseline. INEXUS lends itself well to direct comparisons of scenario outcomes and explicitly calculates the impact of different transportation scenarios on society, using various metrics of welfare. One common metric of welfare is Consumer Surplus (CS), which is defined as the amount of money a person would be willing to pay to attain a certain state of the world; it translates consumer utility into a monetary amount. Because the INEXUS is already monetized to be in "dollar" units, INEXUS is equivalent to CS. That is, the INEXUS represents each agent's individual CS for each trip they take.

Usually, CS is discussed as an average or overall welfare metric (i.e., INEXUS sum) for a population or a subpopulation, and policy decisions often focus on the *change* in CS — whether a particular policy makes individuals better or worse off and to what extent. To estimate how a population or subpopulation is affected by a transportation scenario relative to the baseline scenario, we subtract the total baseline CS from the total CS in the scenario of interest (Eq. (3)). The change in CS resulting from scenario V^1 changing to scenario V^2, denoted as ΔP_{in}^{12}, is specified as:

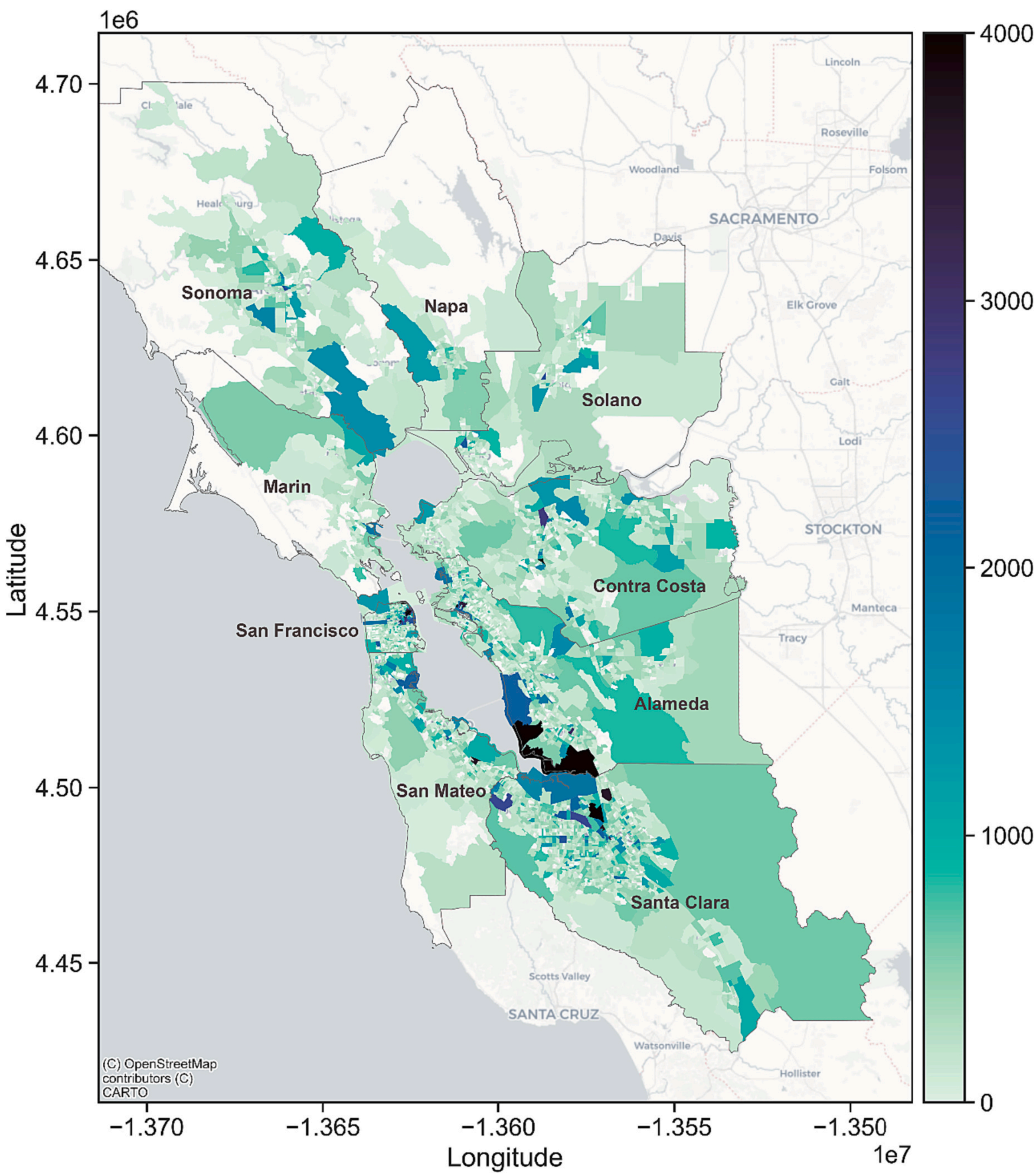

Fig. 4. Total number of ridehail trips originated from each block group across the nine counties of the San Francisco Bay Area in one day.

$$\Delta CS = \Delta P_{in}^{12} = (1/\alpha_i) \left[ln \left(\sum_{\forall k \in TC_{in}^2} exp\left(V_{ink}^2\right) \right) - ln \left(\sum_{\forall k \in TC_{in}^1} exp\left(V_{ink}^1\right) \right) \right] \tag{3}$$

When making policy decisions, we care about both the aggregate change in CS and equity. Equity assessment involves identifying which groups experience a net welfare increase and which encounter a net welfare decrease when moving from the baseline to the new scenario. A scenario in which high-income individuals benefit while low-income people are slightly worse off may result in an overall increase in welfare (i.e., aggregate CS increase), but this scenario may be undesirable from an equity perspective. This highlights the importance of assessing the change in CS for different subpopulations of interest. INEXUS is a metric that can be used to evaluate equity using a variety of different definitions, including equality, proportionality, and Rawlsian justice (Bills, 2022). The specific definition of equity used depends on the priorities specific to each application of the INEXUS in different policy or research settings.

4. INEXUS case study application

To serve as a proof-of-concept of the value of INEXUS metric specifications in policy scenario simulation, we present a case study, and resulting INEXUS distributions for several subgroups of interest. We discuss insights regarding equity revealed through the power of the INEXUS metric.

4.1. Case study scenarios: Ridehail price

We evaluated the comparative impacts of hypothetical changes to ridehail price compared to baseline by using a sensitivity analysis in BEAM CORE in which the price of ridehail varied from 800% to 0% of baseline. Ridehail pricing makes for a compelling case study because of its flexibility and on-demand nature. We made a deliberate choice to use a single lever (ridehail price) and introduce an exaggerated range of variation for this case study to showcase the versatility and applicability of the INEXUS metric in this experimental setting. Exploration of the results from these scenarios may be relevant for transportation authorities and other stakeholders to assess future endogenous price changes, or to inform decisions with direct price effects. Plausible explanations for such alterations to ridehail price, though likely not to the extremes simulated for this example, include: policy-based (e.g., additional fees per ride to support public transit), market-based (e.g., business model change responding to market entrants), or technology-based (e.g., potential future ridehail automation).

Our case study takes place in the nine counties of the San Francisco Bay Area, as listed in Section 3.1. In our simulation, ridehail services are available everywhere in the region. However, vehicles tend to reposition themselves in such a way as to locate themselves in the highest demand areas, resulting in variation in the concentration and availability of ridehail vehicles designed to mimic real-world ridehail services (Fig. 4). To calibrate our ridehail simulator, we utilized data recently released by the California Public Utilities Commission (CPUC) which includes detailed ride-level data on one year of all rides Uber provided throughout California (California Public Utilities Commission (CPUC), 2020). We analyzed the 33 million weekday rides provided in the San Francisco Bay Area from September 2019 through March 2020, and used the analysis to calibrate the ridehail module in BEAM. Using the CPUC data, we established the baseline number of ridehail drivers/vehicles operating per day (17,000), and the baseline scenario base and per mile and per minute prices of solo and pooled ridehail rides. Furthermore, we calibrated various parameters for ridehail positioning and operation in BEAM to better match six target values observed in the CPUC data: total number of ridehail rides per day; average ride distance and wait time; fraction of ridehail VMT that was deadhead miles; fraction of rides that were matched pool requests; and number of daily rides provided per driver. There are about 35,000 ridehail trips and 415,000 km of ridehail vehicle kilometers traveled (VKT) in the simulation with the 10% subsample of the population. These values therefore scale to 350,000 trips and 4,150,000 VKT representation of the baseline with a full population.

We examine changes to both the Potential and the Realized INEXUS, across different subgroups within the modeled population. We evaluate changes to the aggregated full utility of the modal options available to the individual for their trip as the price of ridehail changes (Potential), as well as the utility associated with the mode used (Realized).

4.2. Potential INEXUS: Baseline scenario distribution in aggregate and by subgroup

We begin by examining the Potential INEXUS distribution under the baseline scenario (Fig. 5). Panel A presents the baseline Potential INEXUS distribution across the entire population. To provide further insights, we stratify the baseline scenario by trip distance (Panel B), trip type (Panel C), and transport mode (Panel D). Notably, substantial differences emerge between various groups based on trips' characteristics. For instance, non-mandatory trips have 78% higher Potential INEXUS values compared to mandatory trips, as observed from the distributions for those trips having more bulk to the positive side of the distribution. Outcomes are highly variable within distance, type, and mode choice groupings. The Potential INEXUS can highlight differences in transportation-related utility for subpopulations of individuals and trips, which can be defined across household, traveler, and trip characteristics (e.g., trip length, trip type, household income, vehicle ownership, transportation mode).

4.3. Change in Potential INEXUS across scenarios

A multitude of factors such as residence location, mode availability, budget constraints, vehicle ownership, etc. contribute to inequities in the current transportation system. The ability to identify variation in accessibility distributions for different groups of interest can allow for more thorough examination of the degree of inequity in the baseline transportation system. Moreover, it facilitates the strategic design of policies to align the distribution of potential impacts more equitably.

Here, we examine how different types of individuals fare under modeled ridehail price increases and decreases. Fig. 6 highlights how increasing the affordability of the backup mode (i.e., ridehail) disproportionately benefits low-income individuals. The top panel of Fig. 6 shows how the distribution of the Potential INEXUS changes for the highest and lowest 10% income decile groups. Specifically, moving from baseline price to no-cost ridehail results in a 33% improvement in the median Potential INEXUS for the lowest income decile compared to 11.5% for the highest income decile (consistent with the fact that the distribution for the lowest income decile in the top panel of Fig. 6 is shifted more towards the right than for the highest income decile). On the other hand, the change in the Potential INEXUS after increasing ridehail prices to 800% relative to the baseline is more similar in terms of distribution between these two income groups (bottom panel of Fig. 6). The intuition behind these patterns is discussed further in

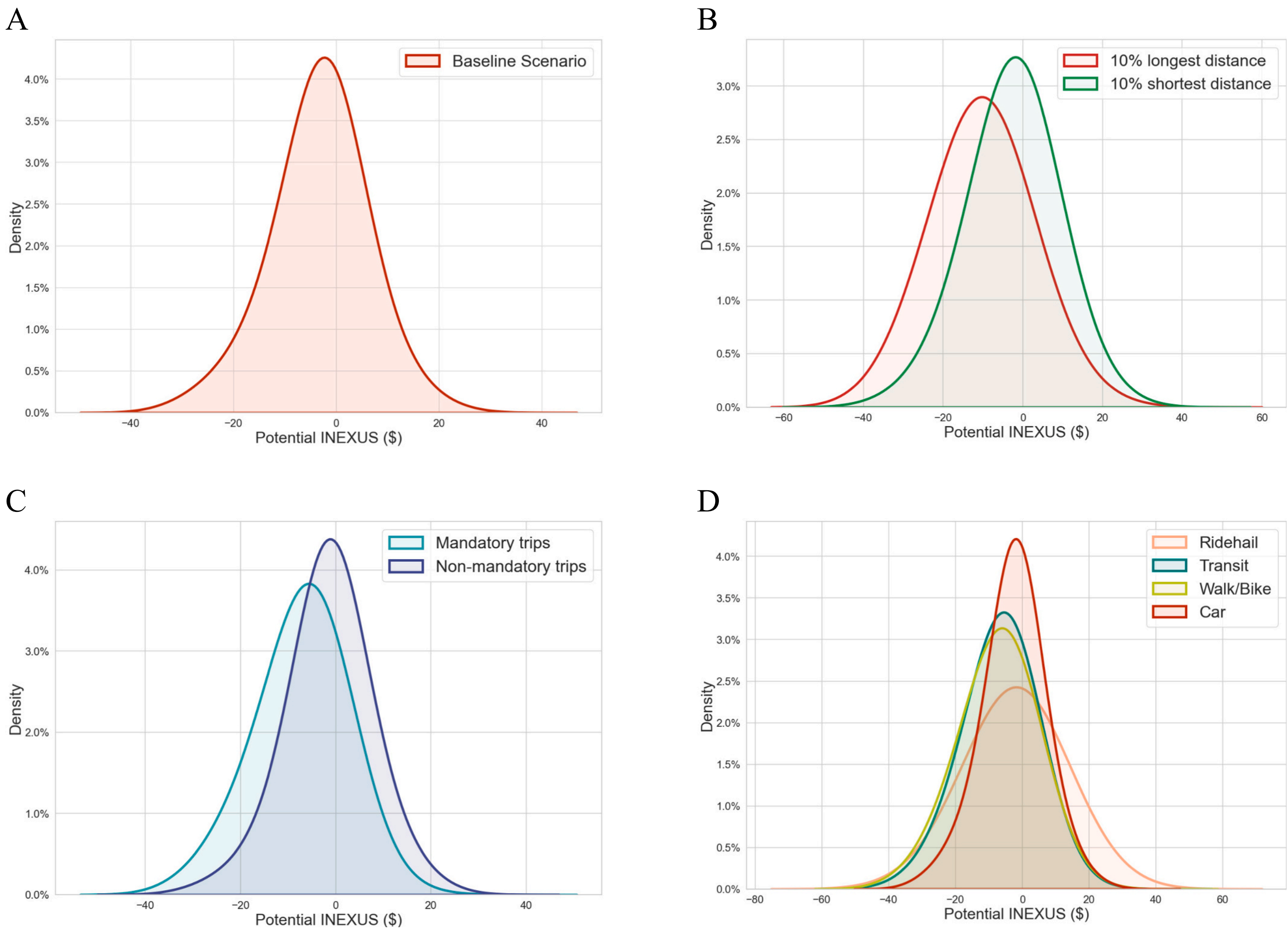

Fig. 5. Potential INEXUS distributions of the baseline scenario (A: aggregate, B: by trip distance, C: by trip type; D: by travel mode chosen).

Section 4.5.

4.4. *Insights from comparing Potential and Realized INEXUS across scenarios*

INEXUS metrics can be used to identify different types of benefits for various scenarios. We identify two types of benefits associated with changes in ridehail pricing: 1) freeride direct benefit, whereby travelers who utilized ridehail in both the baseline and pricing scenario received benefits without modifying their behavior, 2) indirect benefit, whereby some travelers who did not reoptimize their mode choice to take ridehail still benefit from the availability of a more appealing backup option. Figs. 7 and 8, respectively, depict the Realized and the Potential INEXUS for individuals who *did not* modify their behavior in response to changing ridehail prices. The top cluster of individuals in Fig. 7 used ridehail in all scenarios, and they experienced a direct freerider benefit from lower prices, as they received the benefit of lower prices without changing anything about their behavior. For the Potential INEXUS, individuals who utilized non-ridehail modes under all scenarios experienced increased Potential INEXUS values as ridehail became more affordable, demonstrating the value of a more affordable backup mode. This illustrates an indirect benefit associated with greater accessibility, even if a particular option is not actually utilized, which is similar to the option value concept discussed in Van Wee (2016) (van Wee, 2016). It can be viewed as a measure of household resilience to mode disruptions.

4.5. *Consumer surplus as a welfare summary metric*

In this section, we provide an example of using the INEXUS to explicitly calculate and quantify the CS impact of a transportation scenario (as defined in Section 3.2.3), for the entire population and for subpopulations of interest. Table 2 and Fig. 9 illustrate the pricing scenario impacts on CS relative to the baseline. Fig. 9 displays the change in CS by income decile, with income increasing from left to right; Table 2 provides numerical values. Both demonstrate that lower ridehail prices are associated with increased CS, while higher ridehail prices are associated with decreased CS. Equity impacts can also be assessed: while all benefit from lower ridehail prices, lower income deciles gain disproportionately more than high-income deciles.

Moreover, the CS sums the benefit (or detriment) of the change and quantifies it in concrete dollar amounts. This allows a social planner to estimate, in dollars, the benefit or cost of a proposed policy-induced change to the population (or subpopulations), aiding in decision-making either between similar scenarios (price levels) or quite different ones, so long as all have been converted to dollar values (e.g., ridehail price cap vs. school lunch program).

Our findings suggest that reducing or eliminating ridehail costs could potentially reduce transportation accessibility inequalities, particularly for financially constrained travelers. As demonstrated in Fig. 9, lower ridehail prices disproportionately benefit low-income travelers (a low-income traveler on average would experience a benefit from a change from the baseline to free ridehail that is 2.35 times higher than the benefit to an average high-income traveler), in large part because

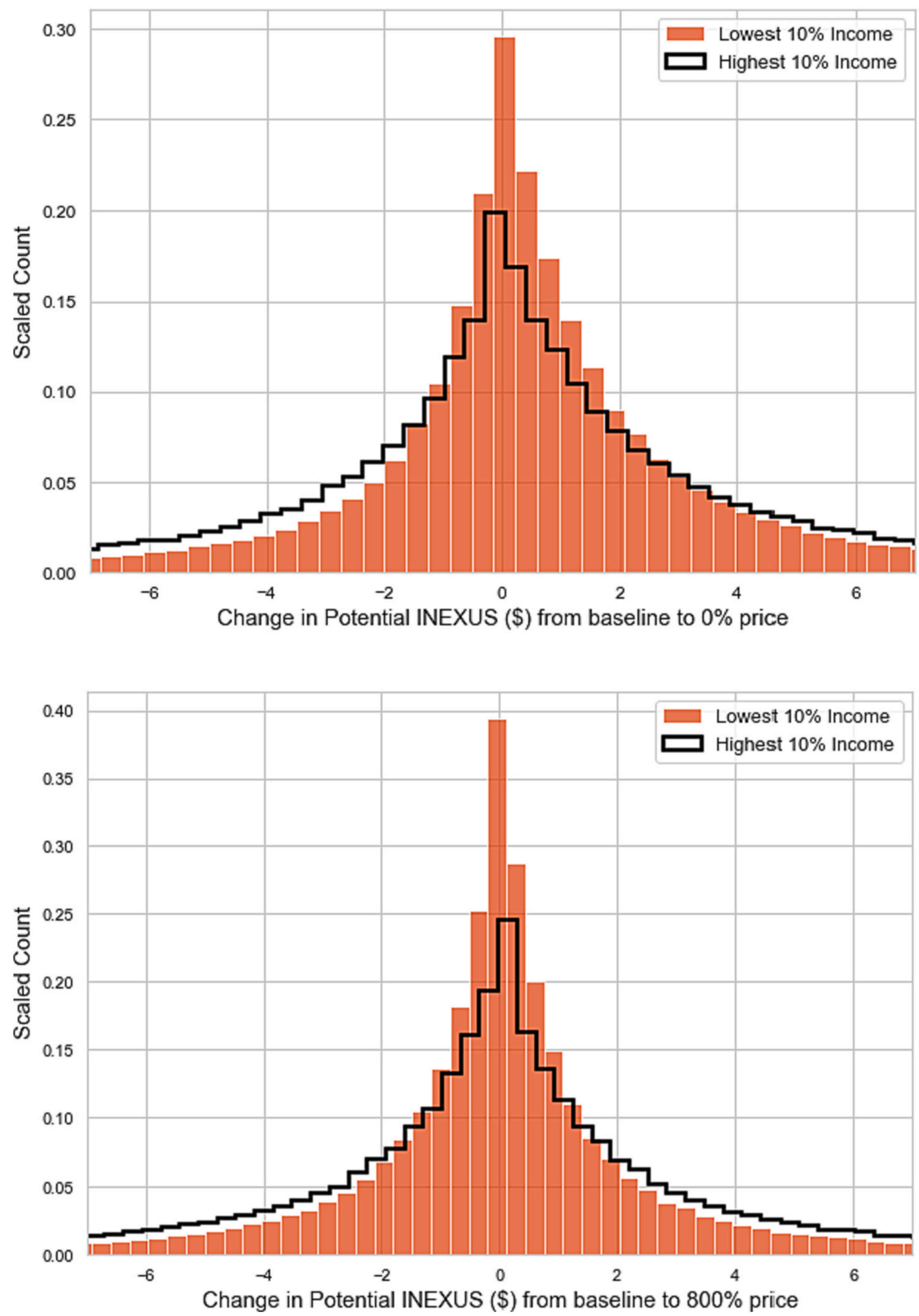

Fig. 6. Distribution of Potential INEXUS relative to baseline across ridehail price scenarios by the income of travelers.

ridehail becomes a substantially more feasible option compared to the baseline. In contrast, higher ridehail prices disproportionately reduce CS of higher income travelers (a high-income traveler on average would experience a cost from a change from the baseline to the highest ridehail price scenario that is 5.82 times the cost experienced by an average low-income traveler). Few low-income travelers used ridehail in the baseline, so this income group is not as directly affected by the price increase; a larger share of high-income travelers used ridehail in the baseline and are directly affected by a price increase.

While our scenario results hint at policy implications, our primary goal here is to demonstrate that INEXUS metrics are compatible with computing commonly used measures of equity, in addition to many other metrics. Due to the level of underlying detail, INEXUS values can be directly compared between scenarios for each person for each trip they take. Identification of exactly which people are made better or worse off allows for even deeper insights into affected groups and equity of scenario impacts.

5. Conclusions and future applications

5.1. The INEXUS metric in brief

In this study, we introduce a novel way of using models and econometric methods that expand the scope of what can be included in estimated impacts of potential policies or system design changes, using approaches to representing accessibility (utility-based, individual agent-based, and positivistic) that is understudied in the literature. In particular, our work extends the state of the art in application of accessibility metrics that meaningfully capture the distributional effects of transportation interventions on key subpopulations. We achieve this through

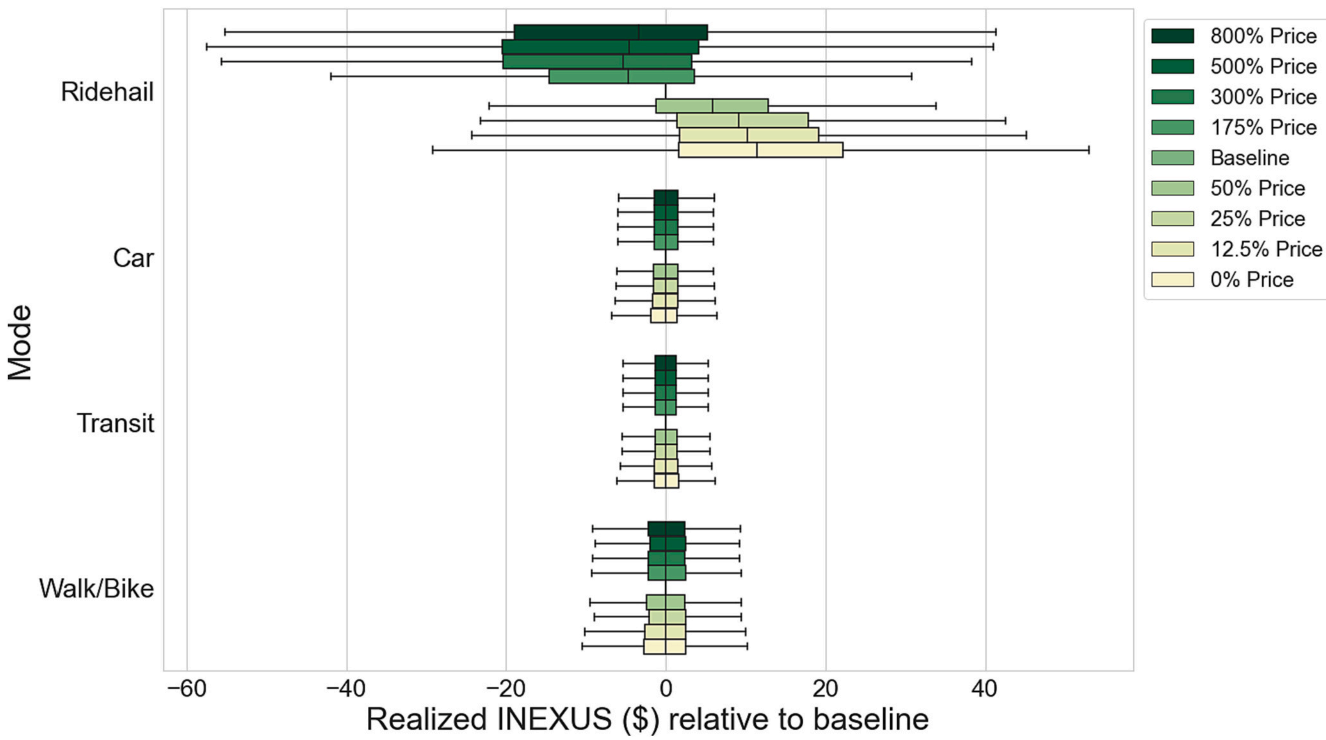

Fig. 7. Realized INEXUS for travelers who do not change their mode from the baseline.

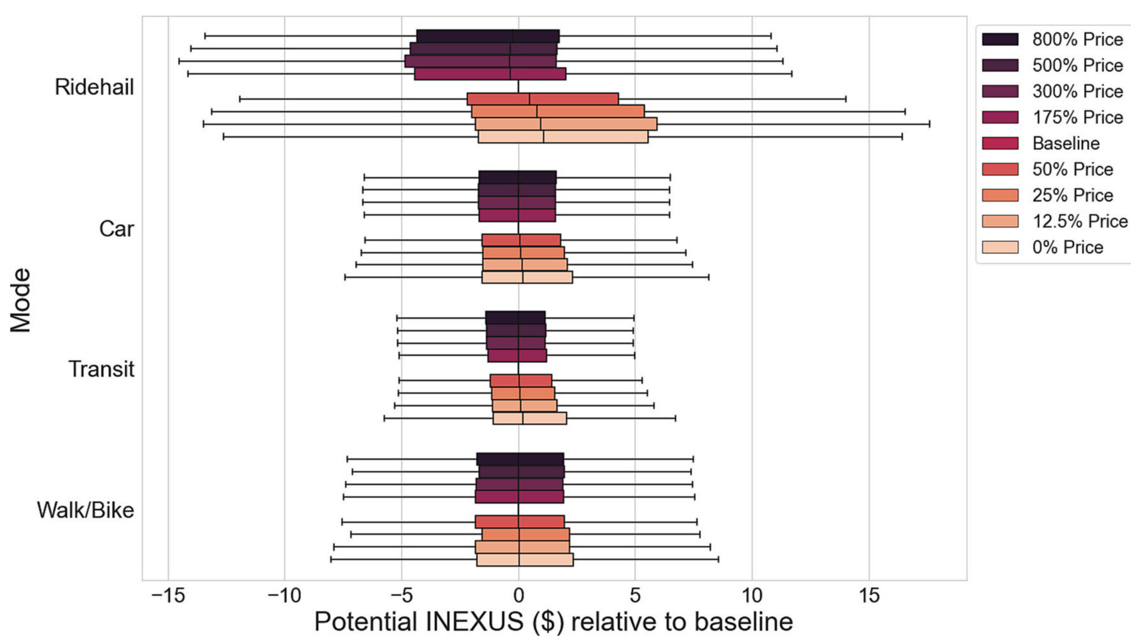

Fig. 8. Potential INEXUS for travelers who do not change their mode from the baseline.

our proposed Potential and Realized INEXUS metrics, which are person-trip specific, and therefore allow distributional estimates of accessibility changes. Examining INEXUS distributions, rather than average impacts, is particularly important when addressing equity for disadvantaged communities. In addition, valuable analyses can consist of a comparison between outcomes across these two metrics and the distinction between the Realized and the Potential INEXUS allows us to disentangle the mechanisms behind accessibility improvements, providing a comprehensive view of a given intervention's impact.

5.2. INEXUS case study insights

Case study insights fall into three broad areas. First, we can evaluate person-trip specific outcomes including the Potential INEXUS and the Realized INEXUS. We demonstrate the value of our rich data in examining outcomes and welfare impacts across groups. We also demonstrate the usefulness of monetizing INEXUS utility values to create metrics readily applied by policy-makers in planning and cost-benefit analysis.

Second, we showed that the INEXUS metrics can be used to assess distributional impacts, beyond simple average effects. We calculate

Table 2
Changes to consumer surplus under ride-hail scenarios.

Scenario	Change in Consumer Surplus relative to the baseline scenario ($)					
	Total for the total population (A)	Per person for the total population in one day (B)	Total for the lowest 10% income (C)	Per person for the lowest 10% income in one day (D)	Total for the highest 10% income (E)	Per person for the highest 10% income in one day (F)
Ridehail Price 0%	$874,109.22	$1.35	$135,334.37	$1.93	$51,138.28	$0.82
Ridehail Price 12.5%	$410,963.92	$0.64	$70,561.53	$1.00	$40,531.83	$0.64
Ridehail Price 25%	$380,346.88	$0.59	$52,800.53	$0.75	$24,386.43	$0.39
Ridehail Price 50%	$120,572.93	$0.19	$19,966.80	$0.28	$13,421.04	$0.21
Baseline	$0	$0	$0	$0	$0	$0
Ridehail Price 175%	-$365,187.83	-$0.57	-$22,378.67	-$0.32	-$45,804.34	-$0.73
Ridehail Price 300%	-$403,472.21	-$0.62	-$20,974.22	-$0.30	-$46,588.96	-$0.74
Ridehail Price 500%	-$427,651.78	-$0.66	-$27,945.06	-$0.40	-$55,213.79	-$0.88
Ridehail Price 800%	-$479,743.51	-$0.74	-$15,574.37	-$0.22	-$80,364.98	-$1.28

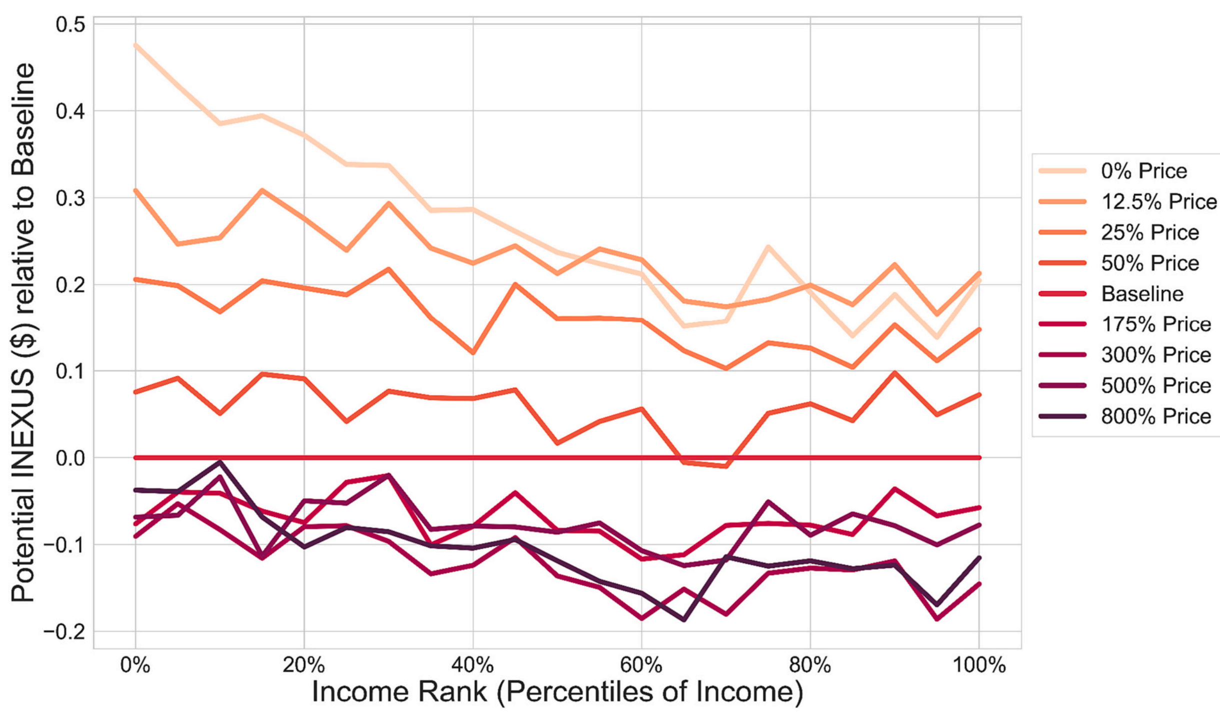

Fig. 9. Change in Potential INEXUS relative to baseline (i.e., change in consumer surplus) by income ranks reveals accessibility inequity.

detailed person-trip specific utility, allowing for rich, person-specific estimation of metrics that can be looked at with a fine lens in terms of equity across income, mode choice, etc. This specificity, in data and metrics, is critical to identifying impacted subpopulations and effectively targeting policies.

Third, we identify interesting equity-related results that may have policy relevance. We find that an average traveler in the lowest income decile received approximately 1.9 times the benefit from quartering ridehail prices as compared to the average traveler in the highest income decile (Table 2, columns C and E). In particular, while all income groups benefited, the free ridehail scenario resulted in an increase in per-person consumer surplus for the lowest income decile that is over 2.3 times that of the highest income decile.

5.3. Limitations and future research

5.3.1. Further examination of welfare and distributional impacts

While we have here discussed distributional impacts across income deciles, there are additional ways to consider welfare, distributional impacts, and equity using INEXUS. As mentioned above, INEXUS is a building block metric, but its value to grapple with questions pertaining to equity, justice, policy evaluation, planning, or any other application depends critically on the way the building block INEXUS values are formulated into specific metrics and insights. The formulation of various types of metrics, specifically with respect to equity (such as equality, proportionality, or Rawlsian justice (Bills, 2022)), have to be driven by the priorities of the policy-maker or researcher, and can have important implications for takeaways from a study. Careful consideration of INEXUS applications with an equity focus must take into account the underlying definitions of equity being employed. For example, making everyone's experience the same versus disproportionately benefiting those that have been historically disenfranchised are two different definitions of "equitable" outcomes with very different implications for different subpopulations. This is something that needs to be taken into account in any future work with INEXUS.

5.3.2. Other heterogeneity aspects

It will be informative to explore equity in accessibility across other characteristics, e.g., race, gender, vehicle ownership, presence of children in household, and disability status. In addition to income, race, and other demographics, future work could include examining differences in INEXUS across different geographies (e.g., census tracts), and how these values change under various policy scenarios.

5.3.3. Additional transportation policy and market changes

In addition to ridehail price changes, there are numerous potential policy, technology, and system design scenarios to investigate, spanning various transportation modes: 1) mass transit (e.g., expanding or improving bus service), 2) ridehail (e.g., fleet size, wheelchair accessibility), and 3) private vehicles (e.g., ownership rates, vehicle technology changes, regulations and mandates, connectivity and automation, micromobility use). Across modes, system-wide changes such as increased reliance on electrification and automation also have implications for traveler outcomes. Explorations of the impacts, including changes to INEXUS distributions for various population groups, are forthcoming for the specific topics of: ridehail fleet size and number of competing ridehail fleets in a region, wheelchair accessibility of ridehail vehicles, availability and use of telecommuting as a work mode, completed and planned Bay Area public transit improvement projects, and entry pricing for heavily traveled traffic cordons.

5.3.4. Exploration of different regions

While we have used the San Francisco Bay Area in this study, BEAM CORE can be used to model many different U.S. geographies; thus, INEXUS can be adapted to examine accessibility impacts of local and regional transportation changes across the country. Other parts of the world could also potentially be examined using INEXUS as well. The models we use are open-source, but feasibility will be conditional on the availability of appropriately detailed data. The necessary data to calibrate mode choices within the models, e.g., population demographics, household characteristics, and travel behaviors, are more likely to be available in open-source format for major cities. A comparison between model performance and outcomes between our SF Bay Area work and additional geographies both inside and outside the U.S. is of great interest for future exploration.

CRediT authorship contribution statement

Nazanin Rezaei: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Data curation. **Annika Todd-Blick:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing, Validation. **K. Sydny Fujita:** Writing – original draft, Writing – review & editing, Conceptualization, Methodology. **Natalie Popovich:** Conceptualization, Methodology. **Zachary Needell:** Software, Validation. **Cristian Poliziani:** Software, Validation. **Juan David Caicedo:** Software, Validation. **Carlos Guirado:** Writing – review & editing, Writing – original draft. **C. Anna Spurlock:** Conceptualization, Funding acquisition, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Formal analysis.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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