CoAXs: A Collaborative Accessibility-based Stakeholder Engagement System for Communicating Transport Impacts

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ABSTRACT

When evaluating transport projects, locational accessibility measures, which connect land use and transport systems, provide insights into the potential for wider economic benefits. Emerging evidence also suggests that accessibility measures may effectively distill complex technical analyses into representations more easily understood and discussed by stakeholders with a range of expertise. A consolidated class of accessibility measures could thus potentially be the foundation for co-creative planning in which diverse stakeholders and experts work actively with transport planners to evaluate impacts of transport alternatives, especially wider impacts beyond individual travel time savings. This paper describes the development and initial testing of CoAXs (short for Collaborative Accessibility-based Stakeholder Engagement System), an open-source stakeholder engagement tool that seeks to support co-creative transport planning. Preliminary development and focus group testing using example bus rapid transit corridors in Boston, Massachusetts, suggest that interactive mapping tools can operationalize accessibility measures as a basis for engaging stakeholders in discussing the regional value and wider impacts of transport investment.

1. Introduction

This research aims to test the potential for interactive mapping of locational accessibility measures to inform collaborative stakeholder engagement and co-creative planning of transit corridors. More specifically, we hypothesize that interactively representing the spatial extent and associated catchment statistics of potential travel may encourage participants to consider wider impacts beyond their own journeys and individual travel time savings. This paper describes the functionality and preliminary testing of an open-source, web-based interactive mapping tool, called CoAXs (short for Collaborative Accessibility-based Stakeholder Engagement System), that can be used in co-creative planning workshops to evaluate and communicate accessibility benefits of public transit projects.[1]

Estimated benefits of public transit investments are often presented to community stakeholders and the public as static measures. Such measures tend to limit stakeholders to considering only pre-selected impacts of “pre-analyzed and pre-filtered choices” (Wigan 2012, p. 228). The complexity of public transit networks and their interactions with urban space imply significant analytical effort to compute relatively abstract estimates (e.g. aggregated travel time savings and related cost-benefit ratios). This likely discourages meaningful interaction in the planning process and the iterative evaluation of other wider benefits. It may also hamper exploratory analysis to identify potential project beneficiaries who may be spatially or temporally remote from the apparent locus of intervention.

Goodspeed (2014), however, asserts that such traditional “black box” models are “beginning to converge” with more open and understandable “planning support systems” (p. 65). Indeed, new digital data, network tools, and interactive software – combined with movement toward “open data” (e.g., Janssen, et al., 2012) – promise to transform stakeholder engagement, potentially expanding the project alternatives and scope of impacts considered in decision-making. This, in turn, could enhance the possibilities for co-creative transportation planning, involving a broader range of experts and stakeholders. Co-creation moves away from conventional logic “whereby transportation services are seen as a… good and customers act as passive consumers of that good” toward “a service-dominant logic” requiring “direct engagement and interactions with customers” (Gebauer et al., 2010, p. 512). Software tools for interactive mapping can help transit agencies meet this requirement. Such tools synthesize various sources and types of data, providing new ways of representing and evaluating transport projects in relation to land use, equity, and the environment.

Some of these software tools (see Páez et al., 2013; TfL, 2015; Papa et al., 2016) draw on urban accessibility measures to support collaboration with those who are not technical experts in transport. Accessibility measures go beyond traditional transport-focused mobility measures to encompass spatial and temporal dimensions related to mobility, land-use, and individual user components (Handy and Niemeier, 1997; Geurs and Van Wee, 2004; Sclar and Lönnroth, 2014). Such measures can reflect transport-enabled agglomeration economies, and the links between these measures and related wider economic benefits such as improved productivity are increasingly well established (Graham, 2007; Chatman

[1] For CoAXs source code and documentation, see https://github.com/mitTransportAnalyst/CoAXs

and Noland, 2013; Melo et al., 2016). Moreover, Metz (2008), Zegras (2011), and others have argued that improved accessibility not only enables wider economic benefits, but should itself be a fundamental aim of transport investment.

Regardless of whether improved accessibility is considered a fundamental benefit itself, accessibility-based project evaluation also has the potential advantage of being relatable to a wider set of stakeholders (Straatemeier and Bertolini, 2008), making it conducive to co-creative planning endeavors that involve diverse audiences. Moreover, policymakers and agencies have shown an increasing openness to adopting accessibility measures as evaluation metrics and performance indicators (e.g. USDOT, 2015; TfL, 2015).

Four sections follow this introduction. Section 2 defines accessibility, connects it with wider economic impacts such as agglomeration, discusses it as a benefit itself, and considers its role in co-creative transit planning processes. Section 3 offers an overview of emerging accessibility tools and policies, and describes the development and testing of one particular open-source accessibility tool, CoAXs. Section 4 details the results of initial development and testing, and discusses general lessons learned and future research directions. Section 5 briefly concludes.

2. Theory

2.1 Accessibility

Generally, urban accessibility reflects how easily people can reach destinations in an urban region. Hansen's (1959) seminal definition is a "measurement of the spatial distribution of activities about a point, adjusted for the ability and the desire of people or firms to overcome spatial separation" (p. 73). Geurs and Van Wee (2004) similarly define accessibility as "the extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" (p. 128). They identify four interacting components of accessibility: land use, transport, temporal, and individual. We modify their conceptualization by recognizing that the characteristics of places, flows, and individuals all vary over spatial and temporal dimensions (see Figure 1).

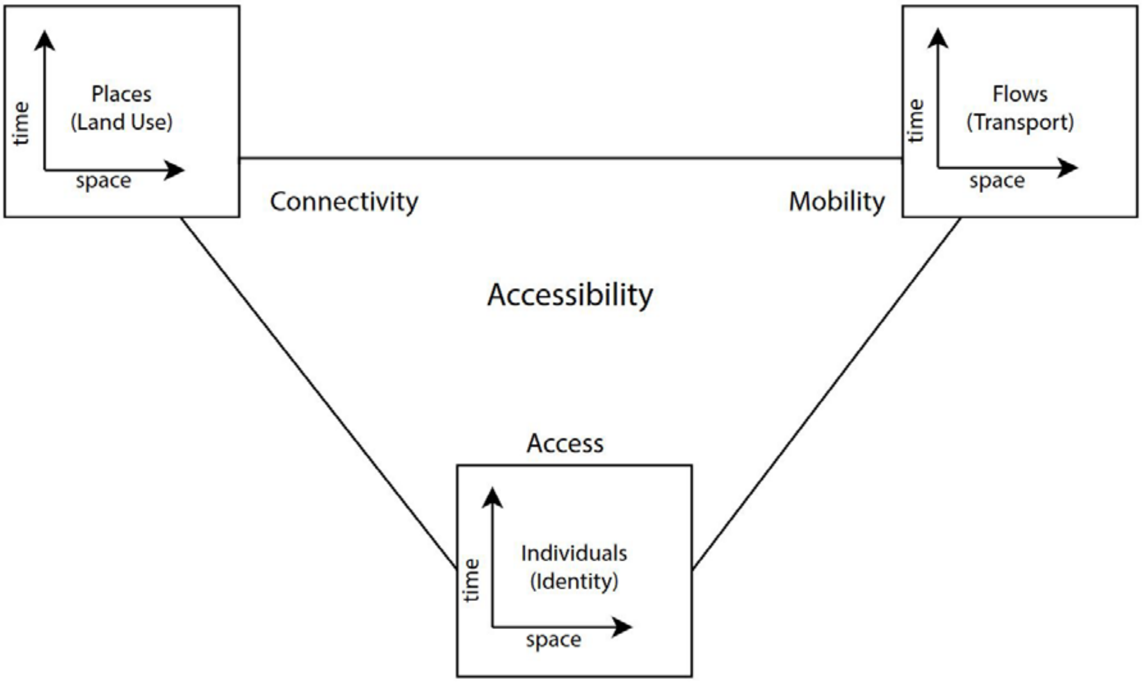

Figure 1 - Components of accessibility

Accessibility often means different things in different contexts. Geurs and Van Wee (2004) use "access" and "accessibility" to make explicit the distinction between individual and location-based perspectives, respectively. We follow that convention in this paper, referring to individual access and locational accessibility. To avoid confusion with accessibility in the sense of universal design (e.g. step-free access for wheelchair users), agencies such as Transport for London (TfL) use "connectivity" instead of accessibility to emphasize the land use and transport components of accessibility. We use regional connectivity to connote aggregated measures that do not require the specification of a single individual or location.

Different disciplinary perspectives, or purposes, tend to emphasize different perspectives on accessibility. Traditional transport modeling, for example, focuses primarily on the upper right vertex -- the transport system and the predicted mobility patterns of its users. Dominant project appraisal practice considers travel time savings within this system as the primary benefit (Rosewell, 2012). Researchers concerned with social inclusion and segregation consider the intersection between land use and identities (Preston and Rajé, 2007; Currie et al., 2010; Fol and Gallez, 2014; Lucas et al., 2015). Equity and environmental justice organizations advocate for improved access for constituencies disproportionately impacted along lines of race and class identity (e.g. Bullard, 2003). Sociologists and ethnographers consider how social and identity systems condition use of mobility systems (e.g. Sheller, 2004; Ghannam, 2011).

We situate accessibility at the nexus of the individual, land uses, and the transport system: accessibility's essence lies in its representation of the *potential* for interaction, even if this potential is not actually realized. Estimated travel time savings and induced demand, benefits typically included in transport appraisal, do not fully capture the wider benefits of improved connectivity, which may include option value and agglomeration benefits (as discussed in subsections 2.3 and 2.4).

2.2 Measuring accessibility

Numerous ways have been proposed to operationalize accessibility measures for project evaluation (e.g. Busby, 2004; Dong et al., 2005; El Geneidy and Levinson, 2006; Ducas, 2011; Bertaud, 2012; Peralta and Mehndiratta, 2015). Here we synthesize a relatively generalized accessibility measure, which can be customized for a given context, according to stakeholder needs, and data and analytical capabilities.

For a set of individuals or origin zones (*i* = 1…*n*) and a set of destination opportunities or zones (*j* = 1…*m*), an accessibility score a_i can be calculated for each origin as:

$$a_i(D, M, T, C) = \sum_{j=1}^{m} q_j\,(D) f(t_{ij}(M, T)) \tag{1}$$

Where:

D	is the selected destination opportunity/activity type (e.g. jobs, healthcare facilities, potential employees)
M	is the mode of travel (e.g. auto, transit)
T	is a time window for the trip (e.g. peak, off-peak), which implies a certain level of service offered, congestion delays, etc.
C	is the cutoff time if a binary cumulative opportunity measure is used (e.g. maximum allowable journey time), see below.
$q_j(D)$	is the attractiveness or number of opportunities of type *D* in zone *j*, and
$t_{ij}(M, T)$	is the typical time or generalized cost to travel from zone *i* to zone *j* by mode *M* at time *T*
$f(t_{ij}(M, T))$	is an attractiveness decay function, generally returning decreasing values as the time or generalized cost argument t increases.

Individual access measures can use individual-specific attractiveness, generalized cost, and attractiveness decay functions, while locational accessibility measures aggregated to origin zones use single versions of these functions.

For a binary cumulative-opportunity measure using a cutoff C,

$$f(t_{ij}) = \begin{cases} 0, t_{ij}(M, T) > C \\ 1, t_{ij}(M, T) \le C \end{cases} \tag{2}$$

That is, an opportunity's attractiveness is totally negated if the time or cost to reach it exceeds a threshold. The functional form of f can also be a typical gravity function, a gamma function, etc., or other means of representing individuals' non-linear "dislike" of travel. The binary cutoff form, however, is arguably the simplest to explain (e.g. the number of jobs reachable within a one-hour commute).

The formulation specified in Equation 1 can apply to different types of units (individuals, jobs, zones, etc.). To obtain an aggregated, regional, weighted average connectivity score (e.g. the number of jobs accessible to the average resident in the region) from disaggregate individual access measures, a sum suffices. When aggregated origin zones are used, a population-weighted average of zonal accessibility scores can be calculated:

$$A(O,D,M,T,C) = \frac{\sum_{i=1}^{n}(p_i(O)a_i(D,M,T,C))}{\sum_{i=1}^{n} p_i\,(O)} \tag{3}$$

Where:

$a_i(D,M,T,C)$	is as defined above in Equation (1).
O	is the selected origin class (e.g. residents, households, firms)
$p_i(O)$	is the population of the origin class O in zone *i*

Finally, these measures can be normalized by the total number of opportunities in the region (yielding, for example, the percentage of a region's jobs accessible to the average household):

$$A'(O,D,M,T,C) = \frac{\sum_{i=1}^{n}(p_i(O)a_i(D,M,T,C))}{\sum_{i=1}^{n} p_i\,(O)\sum_{j=1}^{m} q_j(D)} \tag{4}$$

Others (e.g. Handy and Niemeier, 1997; Kwan 1998) have discussed the formulation and relative merits of such indicators and have implemented analytical software to calculate the indicators. Our intended contribution is to refine the representation of these indicators, to support new understandings of public transit system benefits, and enable a co-creative planning process.

2.3 Accessibility and wider economic benefits

The benefits of transportation investments generally extend beyond individual travel time savings. The connectivity afforded by transport links enables higher effective densities, the clustering of firms within short distances or travel times of each other. For certain industries (e.g. business services), higher effective densities have been shown to translate into higher productivity (Graham, 2007). In addition, improved accessibility of a cluster can expand the size of a city's employment market, which also correlates positively with productivity (Venables, 2007). Emerging transport appraisal guidance (e.g. DfT 2013) now incorporates these agglomeration benefits, which are based on effective density and accessibility measures, as important positive and additional externalities (DfT 2013), though they may be less intuitive for stakeholders than straightforward time savings. Alstadt et al. (2012) emphasize the growing need to be able to "consider both industry detail and forms of accessibility in order to calculate accurately the relative impact of specific project proposals" (p. 154). Hensher et al. (2014) go beyond considering effective employment density and its attendant productivity benefits to incorporate effective social density, "a measure of the reduction in social exclusion consequent on increased potential accessibility to activities, which we refer to as social accessibility benefits" (p. 464).

2.4 Accessibility as a benefit

In addition to being a means toward wider economic benefit ends, accessibility can be framed as an end in itself. This framing relates to the idea of transport as a derived demand; rarely do we desire mobility for itself, rather we desire the ultimate access that mobility enables. Sclar and Lönnroth (2014) assert, “Few dispute the fact that the goal of expanding urban transport is to facilitate improved urban access” (p. 1). Metz (2008) explicitly calls for transport project appraisal to flip the travel time savings focus to an accessibility focus. Geurs (2006) establishes that even if residents’ travel patterns do not immediately take advantage of improved access, there may be an option value in having improved connectivity. With accessibility as the goal, project appraisal can shift away from the traditional travel time savings approach, which “abstracts from trip generation and economic impacts, and leaves it hard to incorporate environmental constraints” (Rosewell 2012 p. 663). Zegras (2011) argues that accessibility forms the core purpose of “sustainable mobility,” where individuals’ access (greater choices to different opportunities) represents basic human welfare and well-being.

2.5 Stakeholder involvement and equity

Locational accessibility metrics are inherently geographical, enabling association with specific (sub-) populations. As Miller (1991) writes, “The spatial distribution of accessibility, particularly *changes* in accessibility, can tell the planner or policy analyst directly who are the ‘winners’ and ‘losers’ in a given scenario” (p. 2). For new public transit projects in complex networks, beneficiaries may be distant from the project itself. Furthermore, the focus on potential for interaction, rather than speeding interactions that already occur, can better address issues of social exclusion for areas where current travel is limited because of poor transport options. Planning tools that show where accessibility gains occur can help planners identify stakeholders who stand to benefit, and engage them as allies early in the implementation process.

The ability to identify winners and losers, or the incidence of benefits and costs, is fundamental to equity analysis (Levinson, 2002; Litman, 2015). Accessibility measures have been proposed as the basis for equity evaluations using Gini indices (Welsh and Mishra, 2013; Lucas et al., 2015) and other equity indicators (Golub and Martens, 2014). These metrics are thus appealing both as informative tools for achieving more equitable outcomes, and – if formulated and applied transparently, engagingly, and widely – more equitable processes.

2.6 Co-creative transport planning

Rapidly proliferating information and communication technologies (ICTs) are shifting consumers “from being passive, isolated, and unaware to being active, connected, and informed” (Gebauer et al., 2010, p. 514). This shift has profound implications for transit agencies. For example, the provision of real-time information can increase transit ridership (Brakewood et al. 2015); e-hail apps (e.g., for taxis), on the other hand, may significantly disrupt traditional business models (Li and Zhao, 2015).

An orientation toward co-creation can help transit agencies navigate these new trends. Gebauer et al. (2010), drawing on experiences of the Swiss rail operator (SBB), recommend that "public-transport operators should facilitate the active participation of customers in designing and implementing their processes and systems." They base this recommendation on their assessment of five areas for personalizing the operator-customer relationship: customer engagement (e.g. promotions, communication channels), self-service (e.g. automated ticketing technology), customer experience (e.g. efforts to make service pleasant and instill loyalty), problem-solving (e.g. online trip planning and recovery of lost personal belongings), and co-design (e.g. coordinating service for special events, designing wheelchair accessibility). They judge that the last area, co-design, "has been rather under-utilized compared with the other four co-creation activities)." This underuse seems especially true for longer-term capital and corridor planning.

In the United States, longer term transportation infrastructure planning has lacked true co-design. Even basic public involvement "has been, and in many cases continues to be, highly problematic" (Bailey and Grossardt, 2010). Gaps between different types of stakeholder knowledge (e.g., "experts" and "non-experts"; Fischer, 2000) are a major reason such engagement has been so problematic. Describing a participatory transport planning exercise in Ghana, Jones et al. (2004, p. 21) distinguish and seek to integrate, "tacit knowledge, which is personal and experiential," and "explicit knowledge…gained through data-driven experimentation, empirical analysis, development of theoretical understanding, etc." Te Brömmelstroet and Bertolini (2012) also use this distinction in differentiating between the expertise of different professional planners.

Ideally co-creative planning would extend beyond merely integrating different types of knowledge, to generate new knowledge through a process of mutual learning. Innes and Booher (2004, p. 428) describe such possibilities: "When an inclusive set of citizens can engage in authentic dialogue where all are equally empowered and informed… everyone is changed … They can work through issues and create shared meanings as well as the possibility of joint action. They can learn new heuristics."

In short, public transport agencies and service providers almost certainly must move toward a co-creation-based paradigm of creating value for their users. Supporting a true co-design process, which productively generates new knowledge, requires new evaluative tools – tools with rapid feedback to enable a tighter cycle of iterative design in which professional planners and community stakeholders can communicate with each other more clearly.

3 Methodology: Software Design and Evaluation

3.1 Software Overview

GIS-based transport modeling tools have long had the capability to generate isochrones and accessibility measures (e.g. Caliper TransCAD, CitiLabs Voyager and Accession). These tools generally have user interfaces with a wide range of options designed for expert analysis. Other public-facing visualization tools (e.g. Caliper Web-based Accessibility Toolkit, TfL WebCAT, Páez, 2013) allow for more rapid computation, mapping, and online communication to broader audiences, but they generally require pre-compiled scenarios with limited options for modifications. We seek a middle ground – an online (web browser-based) tool that allows on-the-fly modifications of transport scenarios, with a user interface simple enough for use by groups of non-experts.

Conveyal Analyst is an open software project that builds analysis capabilities on top of widely used journey planning software. Stewart (2014) evaluated an early prototype (called OpenTripPlanner Analyst) with focus groups of professional planners and community stakeholders in Santiago de Chile and Boston, Massachusetts. The lessons learned from these sessions guided the development of a new front-end interface for collaboratively creating, modifying, and evaluating public transport scenarios, called CoAXs.

Our design of the overall CoAXs tool aims to provide a responsive, intuitive front-end interface that facilitates iterative evaluation of alternatives, collaboration among stakeholders, and improved public confidence regarding estimates of project impacts. As shown in Figure 2, baseline data are uploaded and managed in Conveyal Analyst[2], which has API endpoints for sending requests to a multi-modal routing engine, transmitting processed travel time and accessibility results to client browsers, and receiving modifications of the baseline data from clients. The CoAXs interface itself has two windows (see Figure 3).

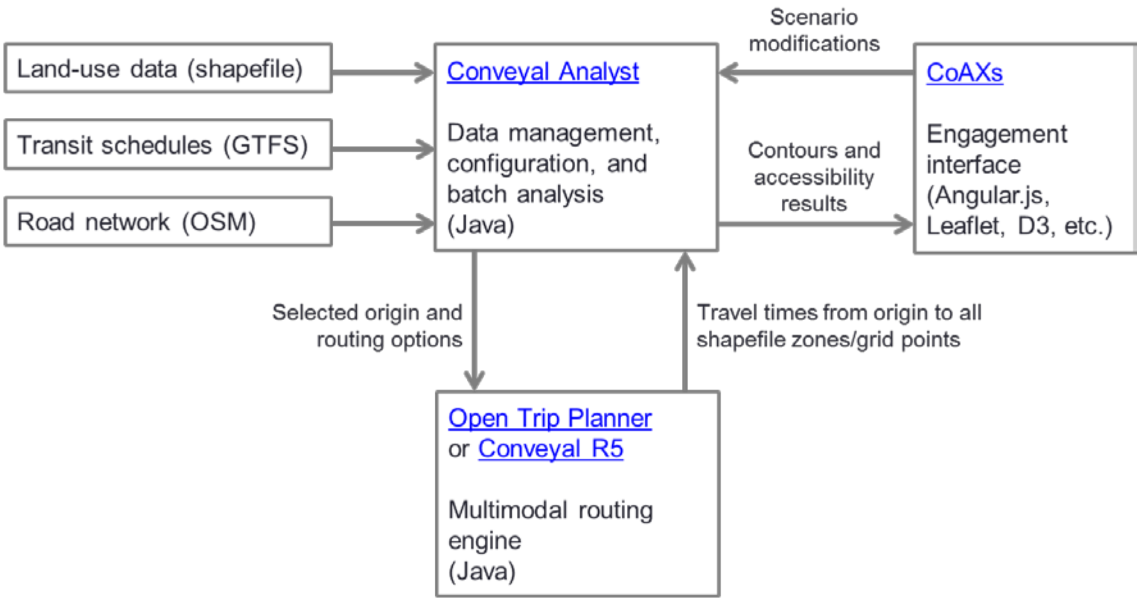

Figure 2 - CoAXs input data and software modules

3.2 Functionality

CoAXs' first module includes a suite of map-based accessibility visualizations that synthesize data about transit service, pedestrian and cycling networks, land use, and socio-economics. This module intends to help users examine access to opportunities through multi-scale personal and regional lenses and thereby develop a better understanding of the links between them. Section 4, below, provides details, using the example of the MBTA in Boston and a proposed scenario including four new BRT corridors. Note that open data (specifically an Open Street Map extract, the United States EPA's Smart Location Database,

[2] For Conveyal Analyst's source code and documentation, see https://github.com/conveyal/analyst-server/

and General Transit Feed Specification [GTFS]-based feeds) and open source software underlie the interface shown below, making it easily adaptable to other settings.

CoAXs' second module is a sketch-planning corridor editor that allows users to modify the service parameters of bus corridors and create different scenarios of corridor combinations. Co-creative transit planning requires building credibility, not only by allowing stakeholders to specify the specific form of the accessibility benefits considered, but also by giving users the ability to edit and modify the underlying transport scenarios being assessed. The corridor editor module allows users to activate/deactivate routes and modify frequency, dwell time, and other service parameters. The selected accessibility measures, and estimated capital and operating costs of the corridor characteristics chosen, update dynamically in response to these modifications. This process, in effect, offers a way for users to "test new heuristics," the participatory ideal outlined by Innes and Booher (2004), in examining tradeoffs between project costs and accessibility benefits, at both the regional and personal levels.

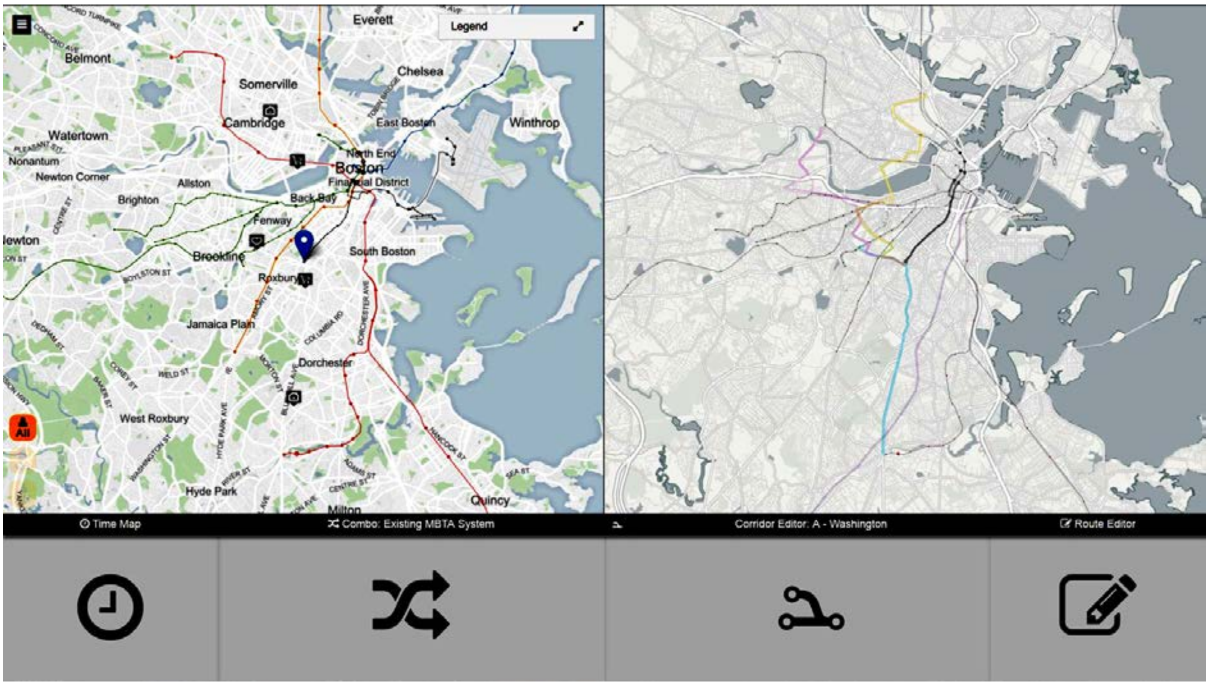

Figure 3 - CoAXs windows: accessibility module on left (showing home and destination locations for sample users), and corridor editor module on right (showing existing lines in grayscale, and potential new lines in color)

In both of these modules, points of interest and itineraries pre-identified by participating stakeholders can be displayed and filtered. This might help participants orient themselves on the maps and make the illustrated impacts more relevant to their own travel routines.

3.3 Development and Evaluation

In June, 2015, we conducted a focus group at the Massachusetts Institute of Technology (MIT) to solicit input on the design and deployment of CoAXs and related co-creative transit planning tools. The twelve participants included representatives from the Massachusetts State Department of Transportation, local municipalities, transportation advocacy groups, business interests, nonprofits, and others invited by a local civic philanthropy advocating for Bus Rapid Transit (BRT). The specific application context was the Boston Metropolitan Area and its public transportation system, operated by the MBTA. The following section summarizes the focus group results.

Figure 4 – Focus group testing of the CoAXs touchscreen interface

4. Results and Discussion

4.1 Functionality

This section discusses the accessibility module of the CoAXs interface, using the notation of equations (1)-(4), above. Specific features of the corridor editor module are not detailed here, though in a full co-creation session users would iteratively evaluate scenarios created in the corridor editor using the accessibility results described below.

4.1.1 Personal travel diagnostic

On an interactive touchscreen, users can move a marker to any location on the map (with the pre-loaded points of interest shown as suggestions). Once the browser loads the isochrones (requiring approximately six seconds to calculate and download for the Boston network during the AM peak), users can move a "slider" on the touchscreen to vary the travel time threshold (C). In response, the visualization dynamically highlights areas reachable within that threshold by a selected mode (M) during a selected time period (T) (see Figure 3). This feature allows users to compare the tool's representation of transit system performance relative to their own personal perceptions of that performance.

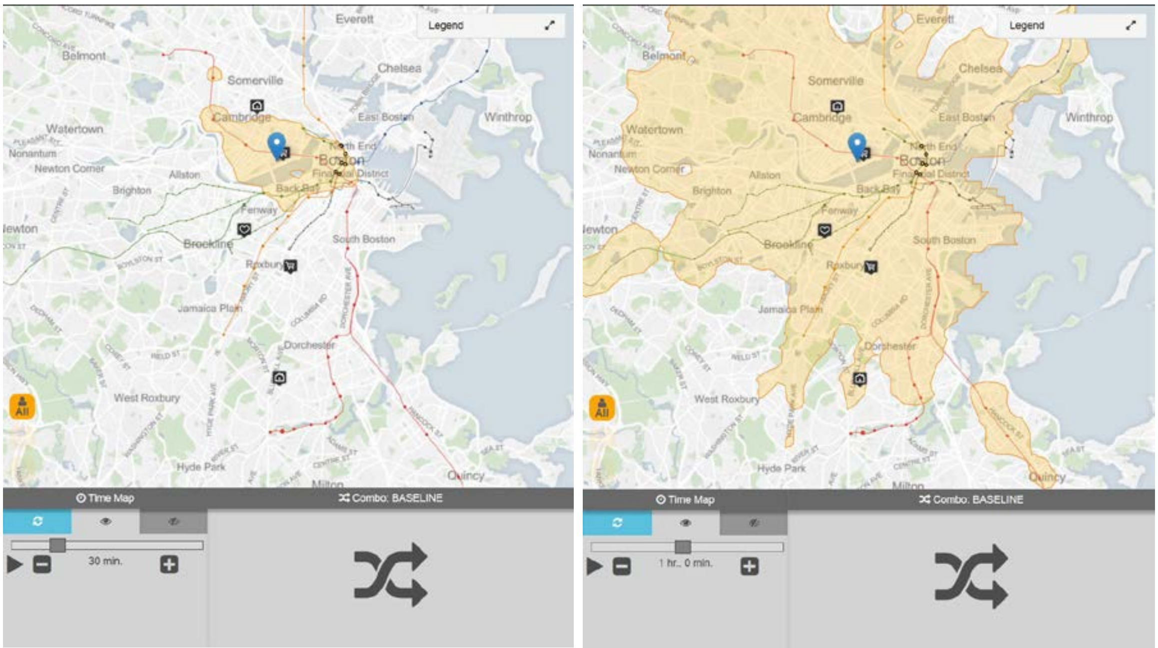

Figure 5 - Accessibility analyst isochrone view, showing contours for 30 minutes (left) and 60 minutes (right) of travel time on transit from the blue marker during the morning peak

Based on the selected location, the user can also opt to display a cumulative plot of accessible opportunities (See Figure 6). A drop-down menu allows users to modify *D* (for example, to see accessibility to total jobs, jobs in a specific sector, or car-free households). This plot can display a_i for all values of C up to 120 minutes. Given an impedance function, these data could be used to calculate a decay-weighted form of a_i (that is, a single summary value independent of C).

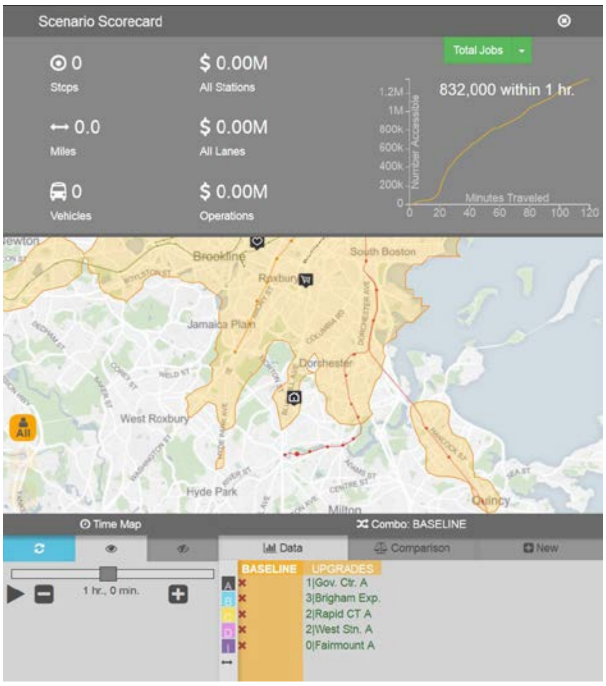

Figure 6 - Accessibility module cumulative opportunity view, showing a plot of cumulative jobs accessible by travel time cutoff

4.1.2 Testing new corridors

Figures 5 and 6 show examples assuming one transit service scenario has been selected. Users also have the option to display a comparison of two transit service scenarios. For example, Figure 7 shows estimated changes by activating new transit services in five corridors; the light purple indicates areas that are faster to reach with the new services, while the yellow indicates areas to which travel times remain unchanged.

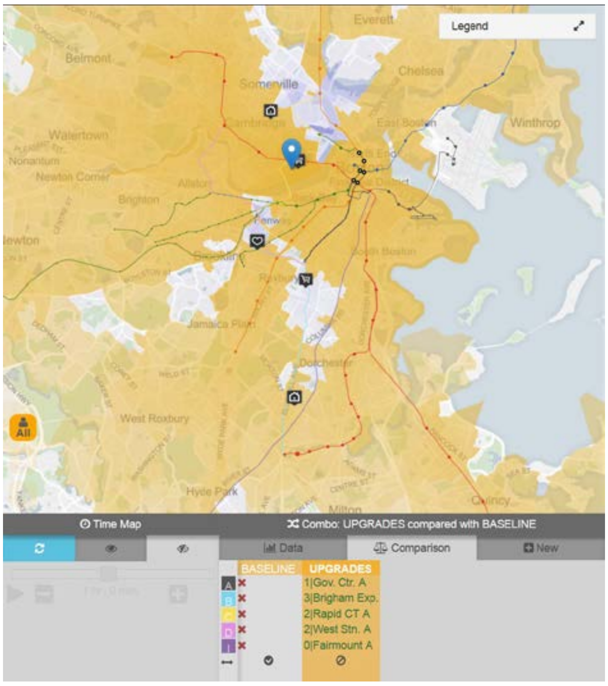

Figure 7 - Comparison view

4.1.3 Regional Connectivity

While choosing a single point for analysis can help users develop intuition about the tool and trust in its results, project evaluations would require a_i be calculated for all origin zones. Conveyal Analyst provides this functionality (see Conway, Byrd, and van der Linden, under review), but we have not yet implemented it in CoAXs. Using the notation from equation 1, Figure 8 shows, for each Census block group in the Boston metropolitan area, a_i (to jobs, by existing transit service, between 7 and 9 AM, within 30 minutes).

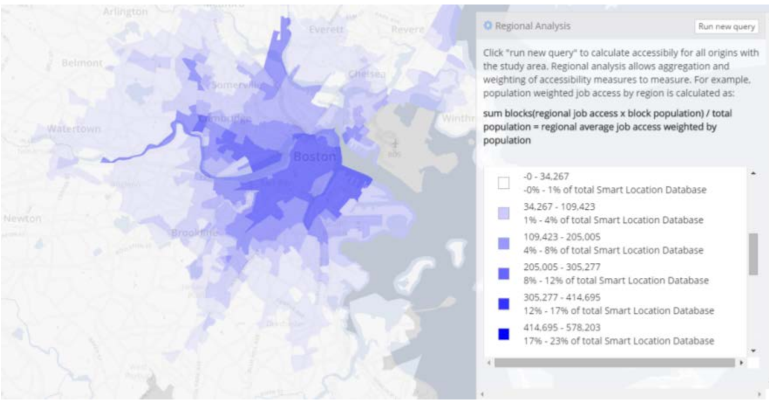

Figure 8 - Regional connectivity view

This regional view also has a comparative function. For example, the choropleth map of Figure 9 shows estimated impacts for each Census block group of introducing a new BRT service: $a_i^{new} - a_i^{base}$, where a_i^{new} is accessibility to jobs by existing transit and new BRT service, between 7 and 9 AM, within 30 minutes; and a_i^{base} is accessibility to jobs, by existing transit service, between 7 and 9 AM, within 30 minutes.

Drop-down menus and sliders enable modifications of *D, T,* and *C*, allowing for nearly instantaneous evaluation of how different types of workers in different areas of the city might benefit. Because of the inter-connectedness of public transit services, a new project in one area of the city may benefit more distant users, making this tool useful for quickly identifying potential project allies who may not otherwise realize that they stand to benefit from a change (or, in the case of service reductions, potential opponents who may not otherwise realize they stand to lose).

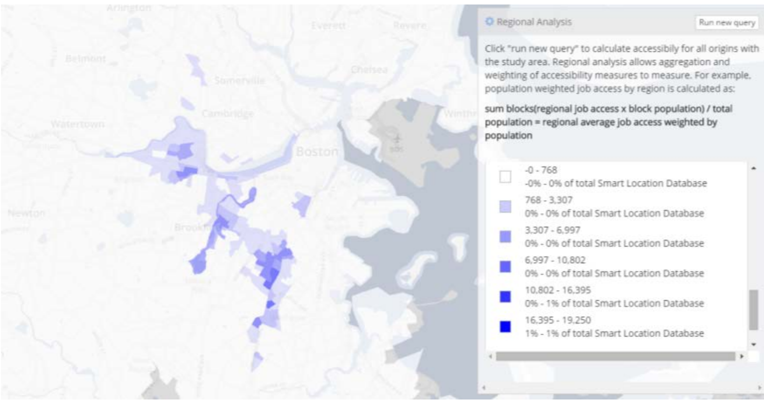

Figure 9 - Regional accessibility comparison view

The results underlying these maps can also be used to perform other analyses and calculations. For example, each calculated a_i could be plotted against $p_i(O)$ (or, alternatively, the origin population density), to identify, for example, priority areas with high population (density) and low accessibility.

The aggregate regional connectivity indices A_i and A'_i can also be calculated from these views. In Table 1: *O* = {all residents, car-free households}; *D* = all jobs; *M* = {baseline scenario of existing transit service, or BRT scenario of existing transit augmented with proposed BRT}; *T* = 7 to 9 AM; *C* = {30 minutes, or 60 minutes}.

Table 1: Regional Accessibility Indices – Transit to All Jobs

		Baseline		BRT Scenario		Percent Change	
		30 min	60 min	30 min	60 min	30 min	60 min
Average Resident	Number	24,787	157,632	25,047	158,112	1.1%	0.3%
	% of Regional Total	1.1%	6.8%	1.1%	6.9%		
Average Car-Free Household	Number	83,111	368,890	83,975	369,963	1.4%	0.3%
	% of Regional Total	3.6%	16.0%	3.64%	16.1%		

Table 2 shows the same, except with *D* = healthcare jobs.

Table 2: Regional Accessibility Indices – Transit to Healthcare Jobs

Morning Transit Accessibility to Healthcare Jobs		Baseline		BRT Scenario		Percent Change	
		30 min	60 min	30 min	60 min	30 min	60 min
Average Resident	Number	2,552	16,372	2,658	16,482	4.2%	0.7%
	% of Regional Total	0.9%	5.8%	0.9%	5.8%		
Average Car-Free Household	Number	7,758	39,697	8,121	39,905	4.7%	0.5%
	% of Regional Total	2.7%	14.0%	2.86%	14.1%		

These tables indicate, for example, that the proposed BRT scenario would increase by about 1.1% the number of jobs accessible within 30 minutes to the average Boston area resident and would increase by about 4.2% the corresponding number of healthcare jobs accessible. Given the importance of the healthcare sector for the Boston and Massachusetts economies, such indices, combined with interactive maps of accessibility to important healthcare clusters, could help provide a more meaningful understanding of the proposed scenario.

Other measures, not reliant on specifying a cutoff value (C), could be calculated using the data underlying the cumulative plot shown in Figure 6 and an appropriate attractiveness decay function, $f(t_{ij}(M,T))$. These results then could be used with elasticities of productivity with respect to effective density (as recommended in DfT 2013) to quantify wider impacts, with CoAXs providing a transparent, understandable view of how the transport inputs to these calculations are derived.

Stakeholders concerned with equity might choose to focus not on all residents, but instead on low-income residents, car-free households, or other sub-groups of special concern (i.e., varying *O*). In the specific context of Boston, car-free households tend to be located in more central areas, as do major healthcare facilities. Accordingly, the average car-free household has higher accessibility by transit to healthcare jobs than the average resident.

Industry- and demographic-specific indices like those discussed above respond to the need identified by Aldstadt (2012) for incorporating more forms of accessibility into analyses of wider economic benefits. Moreover, depending on interests and contexts, stakeholders can openly and easily select and test different origin, destination, mode, and time parameters, using the online interface. This potential is an important part of the co-creation process.

4.2 Focus group feedback

Participant feedback about CoAXs helped illuminate the tool's limitations, challenges, and promise. Participants agreed that the constraints and goals of the co-creative exercise must be clearly specified up front to attain credibility with community stakeholders. Without this clear framing, users did not have a sufficient shared foundation on which to discuss the accessibility measures. Another limitation was the reliance on digital, interactive, maps, which some stakeholders may be less comfortable with compared to traditional media. Many individuals may orient themselves more easily on paper maps or 3-D models of urban space. A compromise solution may be selecting basemaps that better depict building footprints and heights. Further research along these lines would be relevant for projects that loaded different land use scenarios into Conveyal Analyst.

The main promise of CoAXs revealed in the focus group seemed to lie in its potential to use the general accessibility framing to connect participants' everyday "spatial practices" -- and how they imagine these spatial practices -- with cartographic and quantitative "representations of space" (using the terminology of Lefebvre, 1991). Much of the participants' feedback centered on ways to expand this functionality – linking the maps and accessibility indices with various common travel patterns people deem important.

One participant expressed the concern that, for some opportunities like jobs, access to a large number of potential opportunities within a large commute time is important, while for other opportunities like grocery stores, access to one or two destinations within a short travel time is important. While the focus group conversation focused mostly on accessibility to jobs, the functions used are easily adapted to other accessibility measures decided upon by stakeholders. With input data on grocery store locations, for example, the general forms of accessibility (Equations 1 and 3) could be specified to calculate the number of grocery stores available to the average household in a region using *O* = {all households}; *D* = grocery stores; *M* = {walking, biking, or transit}; *T* = weekend mid-day; *C* = {10 minutes}. Conversely, the time required to reach a certain number of opportunities (say the closest two grocery stores), could be read from a revised version of Figure 6.

Similarly, focus group participants wanted more of the experiential and emotional aspects of travel represented through the tool. In the accessibility framework, aspects like crowding, poor reliability, and transfers could be represented in a generalized cost reformulation of $t_{ij}(M,T)$ that assigns user-specified penalty weights to unpleasant (e.g. crowded) conditions. CoAXs could be extended to allow stakeholders to test different weights (e.g. a slider for a crowding penalty) for such a reformulation and use them in evaluation.

4.3 Discussion

These examples illustrate the promise of a general form of accessibility measures, and CoAXs' presentation of them, for supporting co-creation of transport. With some refinements to the interface, stakeholders in a public workshop should be able to successfully weigh the tradeoffs between individual, neighborhood, and interest group accessibility changes (a_i for specific locations or A_i for specific sub-populations) on the one hand, against regional connectivity changes (A_i or A'_i for the entire population) and costs. Community stakeholders and professional planners could then have a common platform, for generating project alternatives as well as a shared understanding of how the impact of those alternatives should be measured and weighed.

4.4 Future Research

With the support of a local civic philanthropy, follow-on public workshop tests of an improved version of CoAXs and other integrated modeling tools were conducted with stakeholder groups in Boston in October 2015. Ongoing analysis of this round of testing will eventually allow for the quantification of performance along a number of dimensions, including user-friendliness, relevance, and effectiveness in fostering mutual learning.

Various opportunities for improving and testing the transferability CoAXs exist. For example, one improvement could be through acquiring and displaying participants' itineraries and travel experiences, rather than merely destinations, using a tool like Flocktracker (see Zegras et al., 2015). Integration of such data would enhance CoAXs' usefulness as a way to generate and catalogue new knowledge about users' travel behavior. In data sparse settings, where for example, GTFS feeds on public transit services do not yet exist, Flocktracker or a similar tool could also be deployed to generate the necessary data for inclusion in CoAXs. In more data rich settings, richer measures of effective capacity, reflecting system congestion and crowding, could be incorporated into the route choice models used in CoAXs. Recent research into capacity-constrained accessibility, which extends traditional models with queuing theory and detailed simulation, has shown that ignoring capacity constraints in accessibility analysis can have distortionary effects (Shen and Zhao, 2015). Further extensions could focus on integrating CoAXs into more traditional transportation planning tools (e.g., the four step forecasting model and/or microscopic traffic models) and processes.

5. Conclusions

Accessibility measures have the potential to clarify how investments in the transport system may trigger wider impacts, such as potential agglomeration effects and employment opportunity expansion, and to connect complex network representations backed by explicit technical knowledge to more readily understandable everyday forms of knowledge. With a consistent yet customizable measure of accessibility at its core, CoAXs seeks to enable co-creative transit planning. Accessibility measures themselves are not new. Our intended contribution aims to operationalize these measures within an interactive planning tool that can serve as the foundation for a co-creative transportation planning process. In co-creative planning, community stakeholders, whether focused on specific development parcels, industry clusters, or user groups, can meaningfully engage in the design of projects themselves as well as the measures by which projects are evaluated. An open-source tool, and a well-designed public involvement process built around it, accordingly has potential to generate important new insights into evolving travel preferences, emerging land use trends, the value placed on accessibility by different types of stakeholders and firms, and how stakeholders value and make tradeoffs regarding accessibility.

If accessibility is viewed as an input to other, well-documented economic impacts of transportation, the process we describe can be a rapid and relatively transparent way of calculating these crucial inputs. And if accessibility is viewed as a benefit itself, the co-creative process we describe and have begun to test could be the basis for fundamentally new approaches to urban transport planning.

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