BISTRO - General System Specifications

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1 Introduction

The *Berkeley Integrated System for Transportation Optimization* (BISTRO) framework harnesses advances in the machine learning and data science fields to enable data-driven transportation demand modeling and policy analysis at a resolution and scale that can empower and engage city officials, transportation system managers, the private sector, academics, and citizens to understand, analyze, and collaboratively plan for the rapidly evolving transportation realities shaping urban areas worldwide.

The *BISTRO platform* gives users an opportunity to envision a set of changes to existing transportation systems that bring about the greatest improvements across important indicators of transportation system performance in terms of system-wide *level of service* (LoS), congestion, and sustainability.

This document details the system specifications of BISTRO. First, Section 2 provides a brief overview of the current state of transportation planning, agent-based simulations and BISTRO. Then, Sections 4 and 5 gives a detailed mathematical description and analysis of the model behind BISTRO. Finally, the last two sections aim at giving users intuition about the meaning of the results. Section 6 shows how specific outputs are rewarded depending on the transportation policy; Section 7 explains how to use the visualization tool of BISTRO and how to interpret its outputs.

2 Background

2.1 Related work

As widely available transportation modes are proliferating and changing on a monthly basis or faster (*e.g.*, micromobility, shared mobility, automated mobility, etc.), understanding the behavioral responses of users and the subsequent transportation outcomes merit investigation. Forward-looking studies have begun to look at the possible transportation and environmental benefits offered by future and emerging shared modes, such as work conducted by the International Transport Forum[1] and the Lawrence Berkeley National Laboratory.[2]

In the U.S. context, many *metropolitan planning organizations* (MPOs) are equipped to analyze the long-range transportation effects of new modes in their regions, but just as many are not. The purpose of *BISTRO* is to provide a platform on which users can envision near-term implementable operational changes to a region's transportation system. These changes are intended to complement existing operational and infrastructure expenditure processes. Additionally, the outputs of the platform can provide a basis for discussions across many sets of stakeholders.

2.2 Agent-Based Simulation

Agent-based simulation (ABS) of travel demand, is a method by which to evaluate the network-wide effects of modifications to a transportation system. Agent-based travel demand microsimulation realizes the daily activity schedules and transportation choices of a socio-demographically heterogeneous population of citizens on a virtual representation of physical road networks.[3] This methodology enables an informative resolution of feedback loops and spatio-temporal constraints operating between travel purposes, road network congestion, household vehicle availability, and the levels of service provided by infrastructure and available transportation modes.

Person agents represent simulated individuals who make decisions about what transportation mode(s) to use to travel to and from their daily activities. During the simulation, person agents make one or more

[1] For more information, see: https://www.itf-oecd.org/sites/default/files/docs/shared-mobility-liveable-cities.pdf

[2] For more information, see https://www.nature.com/articles/nclimate2685

[3] While the population and its plans are synthetic, econometric modeling techniques using census data and travel surveys together with calibration against observed mode splits and network volumes ensure that the simulation represents typical daily traffic conditions.

tours of travel to sequential activities, starting and ending each tour at home. Each *trip* in a tour represents travel from one activity to the next. Trips may consist of one or more *legs* of travel, each using a particular *mode* of transportation. A *mode choice model* characterizes the transportation mode preferences of agents by accounting for the sensitivity of the agent to the attributes of each alternative, such as wait time, in-vehicle travel time, and trip cost.[4] The simulator uses a realistic representation of the transportation network and a *routing algorithm* to determine the generalized cost of routing vehicles on the network as a function of the expected travel-time on links taking into account congestion (*i.e.*, movement slower than the maximum allowable speed due to the number of vehicles on a link exceeding capacity).

The inputs to one instance of the simulation include a representative population of synthetic agents together with their typical daily activity plans. A virtual road network, transit schedule, and parking infrastructure define the transportation supply. The simulation proceeds iteratively: evaluating the plans on the physical network and then permitting agents to replan components of their schedule in response to the generalized costs of travel. Once agents have settled on a set of plans that collectively maximize the average utility of their set of evaluated plans, the simulation engine reaches a fixed point or equilibrium condition.

Each simulation run produces outputs of the actual paths and travel times realized by each person agent and each vehicle, as well as a host of other data, further detailed in Section 4. In practice, outputs of agent-based simulations may be used to communicate policy alternatives to stakeholders. For example, visualizations of congested roadways with millions of agents behaving independently can provide a concise method to communicate the effects of infrastructure interventions.

Agent-based simulation allows for the evaluation of counterfactual *scenarios*. A scenario is a simulation that implements a unique set of circumstances that differs in some way from a *base case*. The base case is calibrated using data representing the current state of the transportation system being simulated. Examples of scenarios include alteration of the population configuration representing population or employment growth, alteration of the transportation network such as unexpected road network restrictions due to sporting events, inclement weather or traffic accidents, as well as the introduction of new modes of transportation such as autonomous vehicles. Well-calibrated simulations of transportation systems, such as those just described, allow stakeholders to better understand the implications of policy proposals in hypothetical travel environments.

2.3 BISTRO

The *Berkeley Integrated System for TRansportation Optimization* (BISTRO) is an open-source *Collaborative Planning Support System* (CPSS) designed to assist stakeholders in addressing the increasingly complex problems arising in transportation systems worldwide. BISTRO includes an agent-based modeling and simulation (ABMS) framework—namely the *Behavior Energy Autonomy and Mobility* (BEAM) framework[5] developed at Lawrence Berkeley National Lab (LBNL)—and scenario development pipeline to build empirically-validated simulations of multimodal metropolitan transportation systems and algorithmically optimize system interventions that best align with policy and planning objectives. BISTRO was developed with the intent to leverage the distinct backgrounds of planners and computer scientists to facilitate a process to draw upon the strengths of two complementary areas of expertise to inform rather than direct public conversations about proposed transportation policy, investments, and regulations. In other words, it is the intent of the BISTRO developers to offer it as a tool to add complementary value to already existing transportation planning processes.

For an in-depth description of the BISTRO framework and all of its major components illustrated in Figure 1, refer to the BISTRO paper.

Add reference

[4]For more information about mode choice models, see: https://eml.berkeley.edu/books/choice2.html
[5]For more information about BEAM, see: http://beam.lbl.gov/

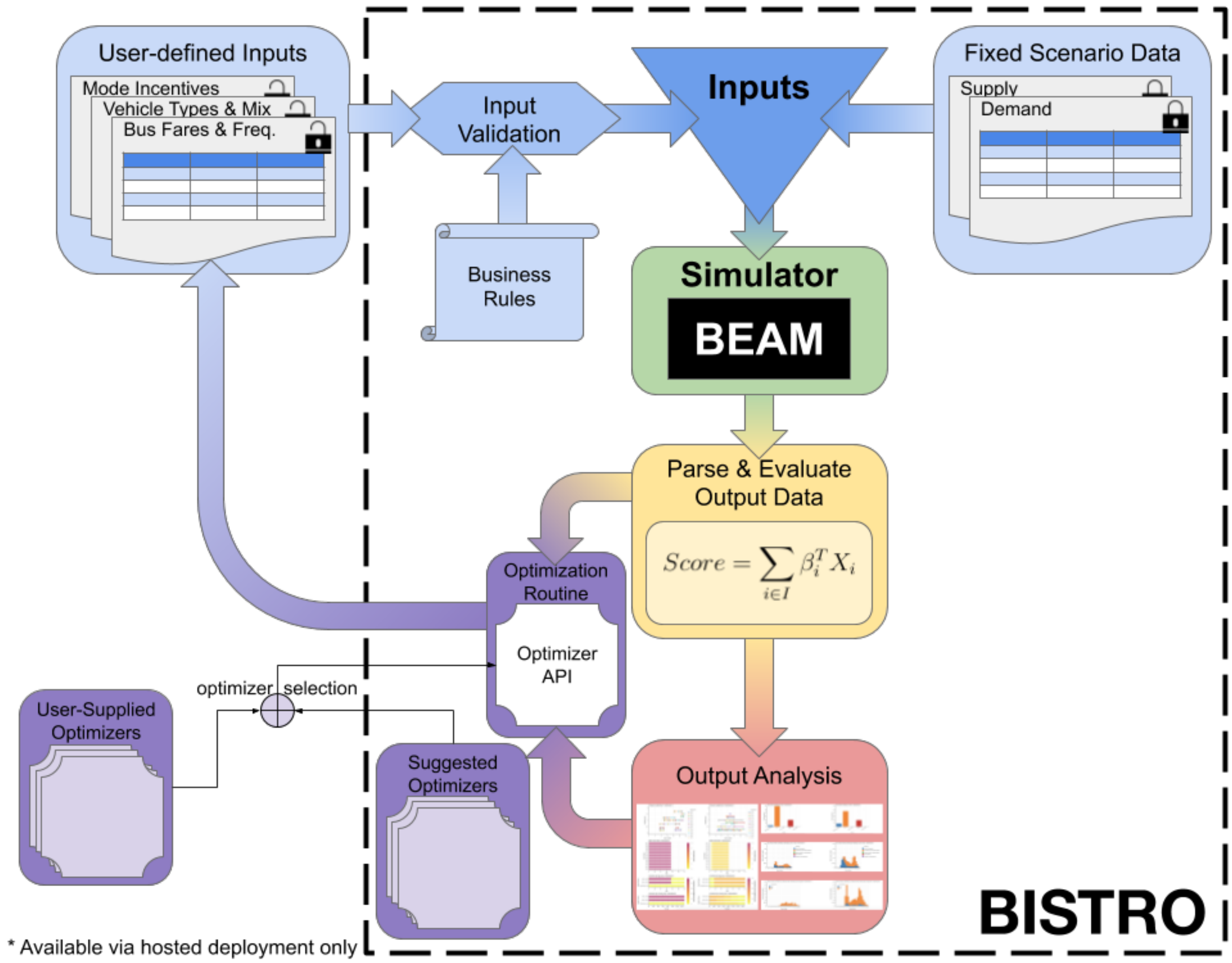


Figure 1: BISTRO framework flow diagram, outlining processes, user defined inputs, outputs and optimization.

3 Study Configuration

BISTRO enables the study of optimal interventions to a given transportation system that is modeled within the BISTRO run environment. A BISTRO run environment is configured using a set of fixed input data that define the required transportation system supply elements (*e.g.*, road network, transit schedule, on-demand ride fleet) and demand elements (*e.g.*, synthetic population, activity plans, and mode choice function parameters). Precisely which aspects of the virtual transportation system should be represented in the simulation model depends on the strategic goals and system objectives defined as part of the planning and analysis process motivating a particular BISTRO use case.

Each simulation run takes as input a set of configuration and user-defined input variables. The *configuration variables* (also called *fixed scenario data* in Figure 1) define the geographic and physical constraints of the transportation network, the characteristics of vehicles in the transit, private, and on-demand ride fleets, and the instantiation of each agent in the population, including their socio-demographic characteristics and activity plans. The configuration variables are not intended to be altered in any way during optimization, but may be altered through the scenario development pipeline to produce different scenarios across which the system interventions may be optimized.

The *user-defined inputs* (UDIs) represent the investment(*e.g.*, transit fleet mix modification, bus route modifications, parking supply, electric vehicle charge station locations, dynamic redistribution of e-bikes or on-demand vehicles), incentive (*e.g.*, incentives to specific socio-demographic groups for selected transportation modes, road pricing/toll roads, fuel tax), or policy/operational (*e.g.*, transit schedule adjustment, transit fare modification, parking pricing levers applicable to and available for the study at hand). The project owner may constrain the range of possible values upon which each UDI is valid by setting the corresponding input validation parameters and business rules.

In the following section, the specific scenario of Sioux Faux,

3.1 Scenario Configuration Inputs

System interventions may be optimized using one or more distinct representations of the supply and demand within the transportation system, each of which is called a *scenario*. The BISTRO scenario development pipeline enables project owners to generate multiple scenarios, each of which is defined by a unique set of configuration inputs that determine the physical transportation network and the dynamics of vehicles and person agents as well as the spatio-temporal and socio-demographic distribution and sensitivity of demand across the network.

Thus, the scenario configuration inputs include the following variables:

1. **Transportation Network Configuration**: inputs that specify the geography and physics of the transportation system as well as the operation of each transportation mode in the system.
    (a) **Transportation network(s)**: one or more directed graph composed of nodes and road links that define the access to and physics of vehicles that move throughout the transportation system. For example there may be separate networks for each of the following modes: pedestrians, cyclists, road transport, and rail.
    (b) **Facilities**: the locations of facilities in the network, each of which is located at a network node. Facilities include residences, places of work, transit stations, and additional locations at which agent activities may occur.
    (c) **Transportation modes**: each transportation mode is configured by inputs that define the number and type of vehicles in the fleet (if applicable), the method of distributing those vehicles at the start of a simulation run, the operational costs associated with the operation of the mode, and the fare, if any, charged for use of the mode. Transit mode configuration inputs also define the facilities and paths used for each transit route.
2. **Population Configuration**: inputs that specify the distribution and characteristics of the population, their activity plans, and modal preferences.
    (a) **Population synthesis**: the spatial distribution of households and the person agents that are in them, including the spatial distribution of socio-demographic variables. Concretely, the population synthesis inputs define the number and size of households to be randomly assigned to homes as well as the distribution of household- and individual-level socio-demographics in within each geographic zone.
    (b) **Daily activity schedules**: the spatio-temporal distribution of activity plans. For example, a scenario thta investigates a special event may be implemented in the scenario configuration by altering the activity plans of a portion of the population. Other examples include altering the scenario configuration to mimic changes in the employment rate or the telecommute mode share.
    (c) **Mode choice**: the mode choices of person gents are determined by a multinomial logit model, the coefficients of which can be altered by scenario configuration inputs. Doing so would allow for a sensitivity analysis across scenarios of varying demand sensitivities.

route_id	start_time	end_time	headway_secs	exact_times
1340	21600	79200	900	1
1341	21600	36000	300	1
1341	61200	72000	300	1

Table 1: Example of bus frequency adjustment input file.

3.2 User-Defined Inputs

A boundary separates external, exogenously defined inputs from the BISTRO simulation optimization pipeline. Outside of the boundary, the *user-defined inputs* (UDIs) represent the investment, incentive, and policy levers applicable to and available for the study at hand. Concretely, algorithm developers encode solutions as numeric values that represent vector-valued variables controlling aspects of the initialization and evolution of the simulation. For example, a UDI that alters frequency of buses on a route must specify a target transit agency, a route, a start time, an end time, and the desired headway.

BISTRO provides a library of possible inputs for scenario designers to adapt to specific use cases. The selection of UDIs is intended to be compatible with the system objective. UDIs may represent, for example, the investment (*e.g.*, transit fleet mix modification, bus route modifications, parking supply, electric vehicle charge station locations, dynamic redistribution of e-bikes or on-demand vehicles), incentive (*e.g.*, incentives to specific socio-demographic groups for selected transportation modes, road pricing/toll roads, fuel tax), or policy/operational (*e.g.*, transit schedule adjustment, transit fare modification, parking pricing) levers applicable to the study at hand. The project owner may constrain the range of possible values upon which each UDI is valid by setting the corresponding input validation parameters and business rules. The example input file for bus scheduling shown in Table 1 defines alteration of the headway of a particular bus route during a particular service period (defined by its start and end times). For discussion of the initially released BISTRO UDIs, refer to the BISTRO paper. An inventory and up-to-date descriptions of the UDIs may be found on the BISTRO website[6].

3.3 Input Validation and Business Rules

While BISTRO maintains a library of available interventions compatible with BEAM, scenario designers, policy makers, and other stakeholders will often want assurance that infeasible, regressive, or otherwise undesirable input combinations are prevented from being selected as "optimal." Together with syntactic and schematic validation of inputs, flexibly-defined *business rules* can effectively act as constraints on the search space—enhancing the interpretability and, thereby, the rhetorical and communicative value of BISTRO-derived solutions.

4 Evaluation and Scoring

The quality of a policy tested with BISTRO is judged based on a weighted combination of measurable outcomes from the simulation that emulate common operational and social goals considered by cities when evaluating the broader impacts of transportation policy and investment. The scoring components are derived from a discrete set of output variables produced for each simulation run.

The *outputs* of the simulation produced by users' solutions will determine the values of key performance metrics of the impact of the solutions on the accessibility, LoS, and congestion of the transportation network in the city of interest, as well as the resource constraints and environmental sustainability of the resulting network-wide travel equilibrium.

[6]https://sfwatergit.github.io/BISTRO-Website/

The following subsections detail the relevant person agent and vehicle movement outputs in the simulation as well as the scoring criteria used for evaluation.

4.1 Person output

For each trip taken by a person agent in the simulation, the following data is produced as output:

1. **Transportation mode(s):** for each trip, a person agent chooses one of the modes available to them. Person agents may use one or more modes to travel from their origin to their desired destination, as they may transfer between modes along the way.
   (a) **Mode(s) available:** the mode(s) available to person agents to use for each trip, including: walk, personal bicycle, personal car, on-demand ride, bus, rail, shared bicycle, shared scooter.
   (b) **Mode choice:** the mode chosen for each trip. Mode choices are made at the trip level, as the agent considers all available combinations of modes that may be used to travel from one activity to another. The use of a transit mode (bus or rail) involves the combination of that mode with one or more other modes used to access and egress the transit station. For example, a person agent may choose to drive to transit, which will result in a walking egress leg from the transit station to the agent's destination.
2. **Travel time:** the time spent by the person agent in the act of traveling during each leg of a trip. Travel time has several components, including:
   (a) **In-vehicle travel time:** the time spent in a vehicle by an agent while traveling to an activity.
   (b) **Wait time:** the time spent by an agent waiting for the arrival of a vehicle. Wait time may include time spent at a bus stop or time spent waiting for the arrival of an on-demand ride vehicle after the ride has been reserved.
   (c) **Transfer time:** time spent walking from one transportation mode to another while completing a trip. Transfer time may include walking from the bus stop of one bus route to a bus stop of another bus route.
3. **Travel expenditure:** the cost incurred by a person agent during a trip. The net cost of travel incurred may include:
   (a) Transit fares
   (b) On-demand ride fares
   (c) Gas consumption by a personal vehicle
   (d) Tolls paid (if applicable)
   (e) Applicable incentives
4. **Incentives:** the amount of monetary incentive available (based on the modes available) for a trip and the amount of incentive consumed by an agent during a trip. The amount of incentive consumed for a particular trip may not be more than the travel expenditure incurred for the trip.
5. **Trip purpose:** the nature of the primary activity to which a person agent is traveling during a trip. Trip purpose is segmented into two or more mutually exclusive categories. In the most simple case, there are two trip purpose categories: work trips and secondary trips. Additional trip purpose categories may be included in accordance with the availability of such categories in the activity plans used for the study at hand.

4.2 Vehicle output

Every vehicle movement during the simulation produces the following outputs:

1. **Origin-Destination-Time (ODT) record:** the origin location, destination location, time of departure, and time of arrival of a vehicle movement.
2. **Path:** an ordered list of the links traversed on the path from the origin to the destination of a vehicle movement.
3. **Fuel consumption:** the amount of fuel consumed by a vehicle during a movement.
4. **Vehicle occupancy:** the number of passengers in a vehicle during a movement.

4.3 Scoring criteria

Transportation system intervention alternatives are scored in BISTRO based on a function of score components evaluated using *key performance indicators* (KPIs) of the simulation. KPIs emulate common operational, environmental, and social goals considered by transportation planners and policymakers when evaluating the broader impacts of transportation policy and investment. BISTRO project planners may select KPIs to include in the scoring function from an existing library of options, or may choose to develop additional KPIs, as appropriate, for the goals and system objectives of the project. Additionally, the form of the scoring function may be designed by the analyst in consultation with the project planner.

These KPIs are all affected by the user-defined input variables, and care must be taken when optimizing to understand the interactions between metrics. There are two types of KPIs:

1. Those that measure the operational efficiency of the transportation system (*e.g.*, *vehicle miles traveled* [VMT], vehicle delay, operational costs, revenues)
2. Those that evaluate the experience of transportation system users (*e.g.*, generalized travel expenditure, bus crowding experienced, accessibility)

Both types of metrics are scored simultaneously by comparing the user-produced results to the *business-as-usual* (BAU) scenario.

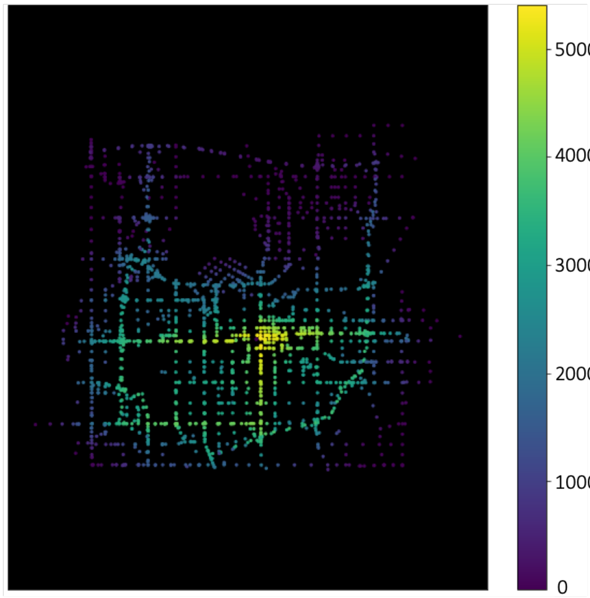
This section describes the six categories of KPIs that have been developed and implemented in BISTRO at the time of publication of this document.

4.3.1 Accessibility

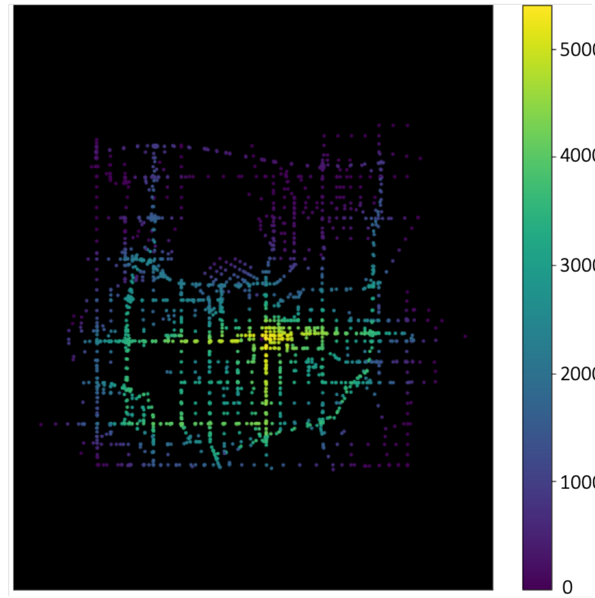
In an urban transportation planning setting, *accessibility* has often been defined as a measure of the ease and feasibility with which opportunities or points of interest can be reached via available modes of travel. Although there are many ways to measure accessibility, it is quantified herein as the average number of points of interest (of a specific type of activity) reachable within a given duration of time. More specifically, accessibility is measured as the sum of the average number of points of interest reachable from network nodes by car or using public transit, within a specified amount of time during specific time periods. Examples of the how the accessibility metric may be disaggregated by trip purpose, mode, and time periods are shown include:

1. **Accessibility to work-based trips by car**: The sum of the average number of work locations accessible from each node by car within 15 minutes during the AM peak (e.g., 7–10AM).
2. **Accessibility to work-based trips by public transit**: The sum of the average number of work locations accessible from each node using public transit within 15 minutes during the AM peak (e.g., 7–10AM).
3. **Accessibility to secondary trips by car**: The sum of the average number of secondary locations accessible from each node by car within 15 minutes during the AM peak (e.g., 7–10AM) and midday period (e.g., 10AM–5PM) periods.
4. **Accessibility to secondary trips by public transit**: The sum of the average number of secondary locations accessible from each node using public transit within 15 minutes during the AM peak (e.g., 7–10AM) and midday period (e.g., 10AM–5PM) periods.

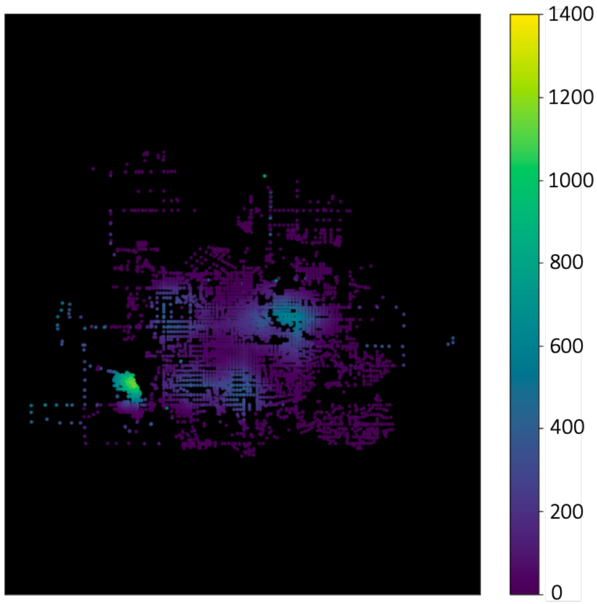
Figure 2 displays the accessibility for work-based and other trips, by car and by public transit, in a benchmark BISTRO scenario.



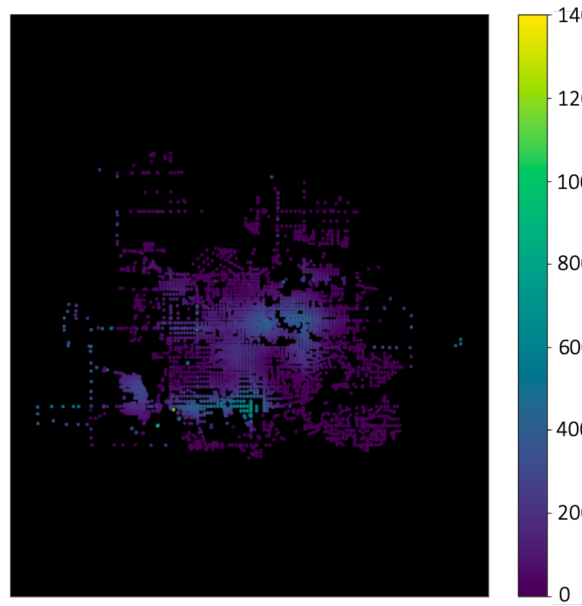
(a)



(b)



(c)



(d)

Figure 2: Points of interest accessible within 15 minutes in the *Business as Usual* (BAU) of a BISTRO benchmark scenario: (a) accessibility to work locations by car, (b) accessibility to secondary locations by car, (c) accessibility to work locations by public transit, (d) accessibility to secondary locations by public transit.

4.3.2 Equity

The socio-demographic and spatial heterogeneity of travel behavior within BISTRO enables a variety of equity-focused impact analyses. One such metric, which is applicable in scenarios for which there is limited intuition about both the composition of the population demographics and the spatial distribution of resources (*e.g.*, transit access, car ownership, etc.), is presented as such:

- **Average generalized transportation cost burden**: the generalized transportation cost for a particular trip is computed as the sum of the travel expenditures of the trip (costs of fuel, fares minus incentives, as applicable) and the duration of the trip multiplied by the average value of time of the population. The cost burden is computed by dividing the generalized cost burden by the household income of the agent completing the trip. The average generalized transportation cost burden is thus computed for all work trips and all secondary trips, separately.

Although this is an aggregate measure and does not examine the changes in outcomes for specific population groups, the means to pay of each household is accounted for.

4.3.3 Level of Service

The *level of service* (LoS) experienced by public transit passengers has a direct influence on short- and long-term demand for public transit service. In the short-term, passenger demand for a particular transit line is dependent on the time and cost of alternative travel options. Thus, the frequency and service period of transit service determines the availability, wait times, transfer times, and in-vehicle times of a prospective transit trip and thus the utility of that trip in comparison to the same trip completed with alternative transportation modes. In addition, the available capacity on a transit vehicle affects whether or not the passenger can board transit at the desired time. Furthermore, the comfort afforded by the available space on a transit vehicle has long-term effects on transit demand, as passengers internalize their experience during many transit trips over time and develop an additional aversion or affinity to transit based on their expectation of the LoS. Upon experiencing the discomfort of an overcrowded transit vehicle for the same 'trip' (*e.g.*, a traveler's 8AM home–work morning commute trip), a traveler will come to expect that LoS when considering whether to take transit for that trip in the future. Though the LoS may be measured in BISTRO by any one of the factors mentioned, here is an example of LoS in terms of passenger comfort:

1. **Average bus crowding experienced**: computed as the average over all transit legs of the total passenger-hours weighted by the value of time multipliers corresponding to the load factor (the ratio of total passengers to the seating capacity) of the bus during the leg.

4.3.4 Congestion

Congestion is measured in two primary ways: the total sum of miles traveled by all modes on the network, and by the delay incurred. Delay—calculated as the difference between actual and free flow time—is presented both as a sum across all vehicle movements in the simulation and as an average delay per agent trip. Using these three measures of congestion provides insight into the destination- or opportunity-independent level of mobility on a network, the overall network performance, and efficiency.

1. **Total Vehicle Miles Traveled (VMT)**: total miles traveled by all motorized vehicles of the system during the simulation.
2. **Average Vehicle Delay per Person Agent Trip**: the average across agent trips of vehicle hours of delay experienced by all vehicles while occupied by one or more passengers during the simulation.

4.3.5 Financial Sustainability

Financial Sustainability is considered on aggregate, as the sum of the operational costs of bus service and the total incentives used subtracted by the total bus revenue collected.

Vehicle type, $c \in C$	Fuel type	Fuel consumption rate ($Joule/meter$)	Operational cost ($\$/hour$)	Seating capacity	Standing capacity
CAR	gasoline	3655.98	n/a	4	0
BUS-DEFAULT	diesel	20048	89.88	37	20
BUS-SMALL-HD	diesel	18043.2	90.18	27	10
BUS-STD-HD	diesel	20048	90.18	35	20
BUS-STD-ART	diesel	26663.84	97.26	54	25

Table 2: Default Vehicle Types currently used in simulations. Note: other vehicle types can be chosen by users when configuring a new scenario.

1. **Operational Costs**: total costs incurred by the public transit agency operations including the cost of fuel consumed, and hourly variable costs. Hourly variable costs include estimated labor, maintenance and operational costs. An example of the rates for each of these factors is specified in the vehicle fleet configuration variables (see Table 2).

Fuel type	Fuel cost ($\$/MJoule$)
Gasoline	0.03
Diesel	0.02
Electricity	0.01
Biodiesel	0.01

Table 3: Fuel Types currently used in simulations. Note: other fuel types can be chosen by users when configuring a new scenario.

2. **Incentives Used**: total incentives used by agents.
3. **Revenue**: sum of total bus fares collected.

4.3.6 Environmental Sustainability

Sustainability metrics provide a sense of the local externalities resulting from any transportation interventions.

1. **Total Particulate ($PM_{2.5}$) Emissions**: total $PM_{2.5}$ emissions produced by all motorized vehicles during the simulation. Using criteria pollutants, specifically particulate matter running exhaust emission factors, presents a mileage-based measure of local air quality impacts based upon vehicle type. This metric provides a complementary addition to fuel/energy consumption-based metrics, which are captured elsewhere[7].
2. **Total Greenhouse Gas (GHG) Emissions**: total well-to-wheels[8] emissions produced by all vehicles. The well-to-wheels emissions are calculated using estimates of fuel consumed calculated as a function of vehicle speeds. For more information on the methodology followed to estimate fuel consumption, please refer to the BEAM documentation https://beam.readthedocs.io/en/latest/index.html.

5 Variable and Scoring Function Specification

The scoring criteria are defined explicitly as functions of the input and output variables of a simulation run. For ease of understanding, the variable notation reflects the meaning of each category of variable in the

[7] For more information on the methodology followed to develop this metric, please refer to the California Air Resources Board documentation: https://www.arb.ca.gov/cc/capandtrade/auctionproceeds/cci_emissionfactordatabase_documentation.pdf?_ga=2.94247453.1690201828.1547860553-1364631033.1545190476

[8] Well-to-wheels analyses account for total life-cycle emissions, accounting for fuel or energy production, transport, and eventual consumption/burning in vehicles, among other aspects. More information can be found here: https://ec.europa.eu/jrc/en/jec/activities/wtw.

following manner: all network and vehicle configuration input variables are denoted with a Z, all population configuration input variables are denoted with a N, all user-defined input variables are denoted with a D, all person agent-level output variables are denoted with an X, and all vehicle movement output variables are denoted with a Y. The indices identifying the meaning of each variable will be defined in the following sections in addition to the corresponding units of measurement.

5.1 Input Variable Specification

5.1.1 Transportation network and fleet configuration

Network and fleet characteristic variables are defined during the configuration of a simulation, and remain static for each scenario. Tables 4 and 5 provide a summary of the network and fleet configuration input variables, respectively.

The road network is a directed graph, $\mathcal{G}(L, W)$, comprised of W nodes connected by L links. Road network configuration variables are indexed by the link identifier $l \in L$. A link instance is defined by the Boolean variable, $Z^l_{i,j}$, which indicates the origin and destination nodes connected by link l.

$$Z^l_{i,j} = \begin{cases} 1 \text{ if link } l \text{ connects node } i \text{ to node } j \\ 0 \text{ otherwise} \end{cases}$$

Each link is given a length (in miles), Z^l_{length}, capacity (in vehicles per hour), $Z^l_{capacity}$, and free-flow speed (in miles per hour), $Z^l_{speed-limit}$. These variables are input to the routing operator during the simulation to determine the travel time of vehicle movements as a function of the number of vehicles on a link at a particular time.

Every point of interest in a BISTRO simulation (e.g., residences, work locations, transit stations, etc.) is located at one and only one node in the network such that the set of all facilities, F is a subset of the set of nodes, W. The Boolean variable Z^K_w denotes that facility $f \in F$ is located at node $w \in W$. The sets of all points of interest of a particular type, such as the set of all transit stations $K_{transit}$ or the set of all residences $K_{residence}$, are each a subset of the set of all facilities, F.

$$Z^f_w = \begin{cases} 1 \text{ if facility } f \text{ is located at node } w \\ 0 \text{ otherwise} \end{cases}$$

The transit network configuration follows a *General Transit Feed Specification* (GTFS) format. Each transit agency, $t \in T$ in a BISTRO simulation environment has one or more transit routes. Thus, the transit network is a subgraph of the road network comprised of t set of all transit facilities $K_{transit} \subset W$ and a set of routes, R^t_{routes}, operated by each agency, $t \in T$. Each transit route is defined by an ordered list of $n^{t,r}_{stops}$ transit stations at which the route stops, $Z^{t,r}_{stops} = \{K_{t,r,i}\}_{i=1,\ldots,n^{t,r}_{stops}}$, and an ordered list of $n^{t,r}_{path}$ links along which the route travels, $Z^{t,r}_{path} = \{l_i\}_{i=1,\ldots n^{t,r}_{path}}$.

In the default BISTRO transit network configuration, the fare structure for transit is age-based and identical across all routes in an agency. The fares for each transit agency t are defined by the set $Z^t_{fare} = \{Z^t_{fare,a}\}_{a=0,1,\ldots,max\ age}$ such that $Z^t_{fare,a}$ denotes the fare for passengers of age $a \in \{0, 1, \ldots, max\ age\}$.

There are two available types of on-demand ride services, S. The *ride alone* service type allows passengers to reserve a ride on-demand directly from their origin to destination for themselves (and companion(s)). The *pool* service type allows passengers to reserve a ride on-demand from their origin to destination for themselves and up to one companion in which the ride may be shared with other passengers traveling along a similar route. A pooled on-demand ride may deviate from the shortest path for any particular passenger in order to pick up or drop off another passenger. Each service type $s \in S$ is instantiated with fare parameters, including the base fare $Z^{on-demand,s}_{fare,base}$, a distance-based fare $Z^{on-demand,s}_{fare,distance}$, and a duration-based fare $Z^{on-demand,s}_{fare,duration}$. The

Transportation Network		
Notation	Description	Specification
L	All links in the network	$l \in L$
W	All nodes in the network	$w \in W$
F	All facilities in the network	$f \in F \subset W$
M	All available transportation modes in the network	$m \in M$
$Z^l_{i,j}$	Link instance between nodes $i, j \in W$	$Z^l_{i,j} \in \{0, 1\}$
Z^l_{length}	Length of link $l \in L$ (meters)	$Z^l_{length} \in \mathbb{R},\ Z^l_{length} > 0$
$Z^l_{capacity}$	Capacity of link $l \in L$ (vehicles/hour)	$Z^l_{capacity} \in \mathbb{R},\ Z^l_{capacity} \geq 0$
$Z^l_{speed-limit}$	Free-flow speed of link $l \in L$ (meters/second)	$Z^l_{speed-limit} \in \mathbb{R},\ Z^l_{speed-limit} > 0$
Z^K_w	Facility instance at node $w \in W$	$Z^K_w \in \{0, 1\}$
Public Transit Network		
Notation	Description	Specification
T	All transit agencies in the network	$t \in T$
R^t_{routes}	All transit routes operated by agency $t \in T$	$r \in R^t_{routes}$
$K_{transit}$	All transit stations in the network	$f \in K_{transit} \subset F$
$n^{t,r}_{stops}$	Number of transit stations on transit route $r \in R^t_{routes}$ of transit agency $t \in T$	$n^{t,r}_{stops} \in \mathbb{R},\ n^{t,r}_{stops} > 0$
$Z^{t,r}_{stops}$	An ordered list of transit stations on route $r \in R^t_{routes}$ of transit agency $t \in T$	$Z^{t,r}_{stops} \subset K_{transit},\ Z^{t,r}_{stops} \in \mathbb{R}^{n^{t,r}_{path}}$
$n^{t,r}_{path}$	Number of links in the path for transit route $r \in R^t_{routes}$ of transit agency $t \in T$	$n^{t,r}_{path} \in \mathbb{R},\ n^{t,r}_{path} > 0$
$Z^{t,r}_{path}$	An ordered list of links on route $r \in R^t_{routes}$ of transit agency $t \in T$	$Z^{t,r}_{path} \subset K_{transit},\ Z^{t,r}_{path} \in \mathbb{R}^{n^{t,r}_{stops}}$
Z^t_{fare}	The set of fares per ride with transit agency t charged to riders of each age	$Z^t_{fare} \in \mathbb{R}^A,\ Z^t_{fare,a} \in \mathbb{R},\ Z^t_{fare,a} \geq 0$
$Z^{t,r}_{headway}$	The headway (i.e., frequency) of vehicles on transit route $t \in R^t_{routes}$ (seconds)	$Z^{t,r}_{headway} \in \mathbb{R},\ Z^{t,r}_{headway} > 0$
$n^{t,r}_{trips}$	Number of trips on route $r \in R^t_{routes}$ of transit agency $t \in T$	$n^{t,r}_{trips} \in \mathbb{R},\ n^{t,r}_{trips} \geq 0$
$Z^{t,r}_{trips}$	The set of all trips made on route $r \in R^t_{routes}$	$Z^{t,r}_{trips} \in \mathbb{R}^{n^{t,r}_{trips}}$
Z^v_{start}	Service start time of transit vehicle $v \in Z_{transit}$	$Z^v_{start} \in \mathbb{R},\ Z^v_{start} \geq 0$
Z^v_{end}	End start time of transit vehicle $v \in Z_{transit}$	$Z^v_{end} \in \mathbb{R},\ Z^v_{end} \geq 0$
On-Demand Ride Services		
Notation	Description	Specification
S	All types of on-demand ride services	$s \in S := \{ride\ alone, pool\}$
$Z^{on-demand,s}_{fare,base}$	The based fare charged for riding in an on-demand ride of service type $s \in S$ ($ / ride)	$Z^{on-demand,s}_{fare,base} \in \mathbb{R}, Z^{on-demand,s}_{fare,base} \geq 0$
$Z^{on-demand,s}_{fare,distance}$	The distance-based fare charged for riding in an on-demand ride of service type $s \in S$ ($ / meter)	$Z^{on-demand,s}_{fare,distance} \in \mathbb{R}, Z^{on-demand,s}_{fare,distance} \geq 0$
$Z^{on-demand,s}_{fare,duration}$	The duration-based fare charged for riding in an on-demand ride of service type $s \in S$ ($ / minute)	$Z^{on-demand,s}_{fare,duration} \in \mathbb{R}, Z^{on-demand,s}_{fare,duration} \geq 0$

Table 4: Transportation Network Configuration Input Notation

Vehicle Fleet Configuration		
Notation	Description	Specification
V	All vehicles in the transportation system	$v \in V := V_{transit} \cup V_{on-demand} \cup V_{private}$
$V_{transit}$	All transit vehicles	$v \in V_{transit} \subset V$
$V_{fleet}^{t,r}$	All transit vehicles in the fleet servicing route $r \in R_{routes}^{t}$ of transit agency $t \in T$	$v \in V_{fleet}^{t,r} \subset V_{transit}$
$V_{private}$	All privately owned vehicles	$v \in V_{private} \subset V$
$Z_{hhd,h}^{v}$	Vehicle ownership instance of vehicle $v \in V_{private}$ owned by household $h \in H$	$Z_{hhd,h}^{v} \in \{0,1\}$
C	All possible vehicle types in the transportation system	$c \in C$
C_m	All possible vehicle types in the vehicle fleet for mode $m \in M$	$c \in C_m \subset C$
$Z_{seating}^{c}$	The passenger seating capacity of vehicle type $c \in C$	$Z_{seating}^{c} \in \mathbb{R},\ Z_{seating}^{c} > 0$
$Z_{standing}^{c}$	The passenger standing capacity of vehicle type $c \in C$	$Z_{standing}^{c} \in \mathbb{R},\ Z_{standing}^{c} \geq 0$
$Z_{fuel-type}^{c}$	The fuel type used by vehicle type $c \in C$	$Z_{fuel-type}^{c} \in \{gasoline, diesel, electricity\}$
$Z_{fuel-consumption}^{c}$	The average fuel consumption rate of vehicle type $c \in C$ (mJ per meter)	$Z_{fuel-type}^{c} \in \mathbb{R},\ Z_{fuel-type}^{c} > 0$
$Z_{var-op-cost}^{c}$	The variable operational cost of vehicle type $c \in C$ ($ per hour)	$Z_{var-op-cost}^{c} \in \mathbb{R},\ Z_{var-op-cost}^{c} \geq 0$
$Z_{fuel-cost}^{f}$	The fuel cost of fuel type $f \in \{gasoline, diesel, electricity\}$ ($ per mJ)	$Z_{fuel-cost}^{f} \in \mathbb{R},\ Z_{fuel-cost}^{c} \geq 0$
$Z_{veh-type,c}^{v}$	Vehicle type assignment of vehicle $v \in V$	$Z_{veh-type,c}^{v} \in \{0,1\}$

Table 5: Vehicle Fleet Configuration Input Notation

total fare for on-demand rides is the sum of the base fare, the product of the total ride distance and the distance based fare, and the product of the total ride duration and the duration-based fare (see section 5.2.1).

The set of all vehicles, V, is comprised of the union of the set of personally owned vehicles, $V_{personal}$, the set of buses, V_{bus}, and the set of on-demand vehicles, $V_{on-demand}$. The number and type of vehicles in the private and on-demand fleets is defined during the configuration of the simulation and remains independent of user-defined input. However, the number of vehicles in the bus fleet is dependent on the service periods and headways (i.e., frequency) for each route, which can be altered by user-defined inputs (UDIs).

The schedules for each transit route are typically defined by GTFS input, which provides the headway, $Z_{headway}^{t,r}$, and the set of all trips, $Z_{trips}^{t,r} \in \mathbb{R}^{n_{trips}^{t,r}}$, to be completed for each route. Each trip on a particular transit route is assigned to a unique vehicle id. Thus, the set of all buses to be used on route $r \in R_{routes}^{t}$ is denoted as $V_{fleet}^{t,r} \in \mathbb{R}^{n_{trips}^{t,r}}$, and the set of all transit vehicles in the base case as $V_{transit} = \cup_{t \in T} \cup_{r \in R_{routes}^{t}} V_{fleet}^{t,r}$. Each transit vehicle, $v \in V_{transit}$, is given a start and end time (in seconds from the start of the simulation) for servicing the corresponding route, r, Z_{start}^{v} and Z_{end}^{v}, respectively. Thus, the configured service period for each route, t, is the tuple $(Z_{start}^{t}, Z_{end}^{t})$ where Z_{start}^{t} corresponds to the start time of the vehicle making the first trip on the route and Z_{end}^{t} corresponds to the end time of the vehicle making the last trip on the route.

The type of vehicles in certain fleets may also be altered by UDIs. Across all vehicles, the set of possible vehicle types is the set C. In a BISTRO study that includes a user-defined input (UDI) that alters the fleet mix of one or modes, it is necessary to define the subset of vehicle types that are eligible to be included in the fleet mix for each mode. Some vehicle fleets may include only a subset of all vehicle types in a particular simulation run. For example, the vehicle types available for the transit fleet, $C_{transit}$ will typically be mutually exclusive from the set of vehicle types available for the private fleet, $C_{private}$.

Each vehicle type, $c \in C$, is defined by a seating and standing capacity (in number of person agents), $Z_{seating}^{c}$

Population Configuration		
Notation	Description	Specification
H	All households in a simulation scenario	$h \in H$
N	All person agents in a simulation scenario	$n \in N$
A	Maximum age for person agents in a simulation scenario	$A \in \mathbb{R},\ A \leq 120$
I	Maximum income for person agents in a simulation scenario	$I \in \mathbb{R},\ I < \infty$
P	Maximum number of activities completed by each agent in a simulation scenario	$P > 0$
$K_{residence}$	All residences in the network	$f \in K_{residence} \subset F$
$N^h_{residence}$	Residence location of household $h \in H$ at facility $f \in K_{residence}$	$N^h_{residence} \in K_{residence}$
$N^h_{hhd-income}$	The household income of household $h \in H$ (\$)	$N^h_{hhd-income}$
N^n_{hhd}	Household membership of person $n \in N$ in household $h \in H$	$N^n_{hhd,h} \in \mathbb{R},\ N^n_{hhd,h} \geq 0$
$N^h_{vehicles}$	The number of vehicles owned by household $h \in H$	$N^h_{vehicles} \geq 0$
N^n_{age}	The age of person agent $n \in N$	$N^n_{age} \in [0, A]$
N^n_{income}	The income of person agent $n \in N$ (\$)	$N^n_{income} \in [0, I]$
N^n_{gender}	The gender of person agent $n \in N$	$N^n_{gender} \in \{female,\ male\}$
N^n_{VOT}	The value of time (VOT) of person agent $n \in N$ (\$/hour)	$N^n_{VOT} \in \mathbb{R},\ N^n_{VOT} > 0$
$N_{avg-VOT}$	The average VOT of the population (\$/hour)	$N_{avg-VOT} \in \mathbb{R},\ N_{avg-VOT} > 0$
N^n_{plan}	An ordered list of facilities at which agent $n \in N$ complete planned activities $N^n_{activity,1}$ through $N^n_{activity,P}$	$N^n_{activity,i} \in F,\ i \in \{1, \ldots, P\}$
$N^{n,p}_{start}$	The desired start time of activity $p \in N^n_{plan}$	$N^{n,p}_{start} \in \mathbb{R},\ N^{n,p}_{start} \geq 0$
$N^{n,p}_{end}$	The end time of activity $p \in N^n_{plan}$	$N^{n,p}_{end} \in \mathbb{R},\ N^{n,p}_{end} \geq 0$

Table 6: Population Configuration Input Notation

and $Z^c_{standing}$, a fuel type, $Z^c_{fuel-type}$, average fuel consumption rate (in units of fuel consumed per meter), $Z^c_{fuel-consumption}$, and a variable operational cost (in dollars per hour traveled), $Z^c_{var-op-cost}$. For each fuel type, $Z^K_{fuel-cost}$ defines the cost of fuel consumption (in dollars per mJ of fuel consumed).

The default set of fuel types available in BISTRO includes gasoline, diesel, and electricity. While the average fuel consumption rate for each vehicle type is provided, the actual fuel consumed by each vehicle movement is calculated in BEAM based on the speed profile on each link traversed. Therefore, the actual fuel consumed by a vehicle in a simulation run may not be equal to the product of the average fuel consumption rate and the total miles driven by that vehicle.

At the start of a simulation run, each vehicle is instantiated with an identifier, $v \in V$, and a Boolean identifier, $Z^v_{veh-type,c}$, that denotes the vehicle type of the vehicle such that

$$Z^v_{veh-type,c} = \begin{cases} 1 \text{ if vehicle } v \text{ is of vehicle type } c \\ 0 \text{ otherwise} \end{cases}$$

Additionally, all vehicles in the private vehicle fleet are identified by the household to which they belong using the Boolean identifier $Z^v_{hhd,h}$, defined in the following subsection.

5.1.2 Population configuration

Prior to the simulation, a synthetic population is generated. The population consists of a set of households, H. Each household $h \in H$ owns a number of vehicles, $N^h_{vehicles} \geq 0$. The Boolean identifier, $Z^v_{hhd,h}$ denotes whether vehicle $v \in V_{private}$ is owned by household h such that

$$Z^v_{hhd,h} = \begin{cases} 1 \text{ if vehicle } v \text{ is owned by household } h \in H \\ 0 \text{ otherwise} \end{cases}$$

Each person agent in the population, $n \in N$, is a member of one household, denoted by the variable $N^n_{hhd} \in H$, with home location denoted by $N^h_{residence} \in K_{residence}$.

Additionally, each person agent is assigned fixed socio-demographic attributes. These include variables identifying age, N^n_{age}, gender, N^n_{gender}, and income, N^n_{income}. The maximum age and income, A and I, respectively, are configurable input variables. Additionally, the input $N^h_{hhd-income}$ denotes the household income of household h.

Finally, each person is instantiated with an activity plan, $N^n_{plan} = \{N^n_{plan,i}\}_{i=1,...,P}$, which is an ordered list of facilities at which agents will complete their planned activities, starting and ending at home. The maximum number of activities in each plan is a configurable input variable, P. For simplified plans with just one activity outside of the home ($P = 3$), agents have plans of the form

$$N^n_{plan} = \{N^{N^n_{hhd}}_{residence}, N^n_{activity,2}, N^{N^n_{hhd}}_{residence}\}$$

where $N^n_{activity,2}$ may be a work facility or other, *secondary activity*, or point of interest. Each activity in a person's plan, $p \in N^n_{plan}$, has a desired start and end time, denoted (in seconds from the start of the simulation) by $N^{n,p}_{start}$ and $N^{n,p}_{end}$, respectively.

5.1.3 User-defined input

As mentioned in Section 4, users may alter aspects of the transportation system by, for example, redefining the transit vehicle fleet composition, bus service schedules, and fares, and/or incentive amounts for particular demographic groups to use bus and/or on-demand ride services. Example specifications for these four UDIs mentioned are provided below. In a base case scenario, the transit fleet may be homogeneous, with all vehicles in the fleet configured with the same vehicle type:

$$Z^v_{veh-type,c} = Z^{v'}_{veh-type,c} \ \forall v, v' \in V_{transit}, c \in C$$

Users may choose to alter the vehicle type servicing each transit route, $t \in \{1, 2, \ldots, T\}$, by changing the value of the variable $D^t_{veh-type,c}$, which denotes the vehicle type for route $r \in R^t_{routes}$. Thus

$$D^{t,r}_{veh-type,c} = D^v_{veh-type,c} = D^{v'}_{veh-type,c} \ \forall v, v' \in V^{r,t}_{fleet}, c \in C_{transit}$$

Users may redefine the service period of a transit route by appending one or more tuples to the mutable, ordered array of tuples, $D^{t,r}_{schedule}$, corresponding to the bus route t. Thus, a bus route with $n^{t,r}_{periods}$ user-defined service periods has the form:

$$D^{t,r}_{schedule} = \{(D^{t,r}_{start,1}, D^{t,r}_{end,1}), (D^{t,r}_{start,2}, D^{t,r}_{end,2}), \ldots (D^{t,r}_{start,n^{t,r}_{periods}}, D^{t,r}_{end,n^{t,r}_{periods}})\}$$

where

$$D^{r,t}_{start,i} < D^{r,t}_{end,i} \ \forall i \in \{1, 2, \ldots n^{t,r}_{periods}\}$$

and

$$D^{r,t}_{end,i} \leq D^{r,t}_{start,i+1} \ \forall i \in \{1, 2, \ldots n^{t,r}_{periods} - 1\}$$

A business rule that constrains the maximum number of service periods that can be defined during optimization, $n_{max-periods}$ is recommended.

Users may redefine the headway of a route using the ordered array of $n^{t,r}_{periods}$ variables, $D^{t,r}_{headway} = \{D^{t,r}_{headway,i}\}_{i=1,...,n^{t,r}_{periods}}$, corresponding to each service period. An additional set of business

Example User-Defined Input: Transit Vehicle Fleet Configuration		
Notation	Description	Specification
$D^{t,r}_{veh-type}$	Vehicle type assignment for route $r \in R^t_{routes}$ of transit agency $t \in T$	$D^{t,r}_{veh-type,c} \in C_{transit}$
Example User-Defined Input: Transit Route Rescheduling		
Notation	Description	Specification
$n_{max-periods}$	The maximum number of allowable user-defined service periods	$n_{max-periods} \in \mathbb{Z},\ n_{max-periods} \geq 0$
$n^{t,r}_{periods}$	The number of user-defined service periods for route $r \in R^t_{routes}$ of transit agency $t \in T$	$n^{t,r}_{periods} \in \mathbb{Z},\ n^{t,r}_{periods} \in [0, n_{max-periods}]$
$D^{t,r}_{start,i}$	The start time of user-defined service period i for route $r \in R^t_{routes}$ of transit agency $t \in T$	$D^{t,r}_{start,i} \in \mathbb{Z},\ D^{t,r}_{start,i} \geq 0$
$D^{t,r}_{end,i}$	The end time of user-defined service period i for route $r \in R^t_{routes}$ of transit agency $t \in T$	$D^{t,r}_{end,i} \in \mathbb{Z},\ D^{t,r}_{start,i} < D^{t,r}_{end,i} \leq D^{t,r}_{start,i+1}$
$D^{t,r}_{schedule}$	A vector of $n^{t,r}_{periods}$ service period tuples for transit route $r \in R^t_{routes}$ of transit agency $t \in T$	$D^{t,r}_{schedule} \in \mathbb{Z}^{n^{t,r}_{periods},2}$
$n_{min-headway}$	Minimum allowable user-defined headway (seconds)	$n_{min-headway} \in \mathbb{Z},\ n_{min-headway} \geq 0$
$n_{max-headway}$	Maximum allowable user-defined headway (seconds)	$n_{max-headway} \in \mathbb{Z},\ n_{max-headway} \geq 0$
$D^{t,r}_{headway}$	User-defined headway for route $r \in R^t_{routes}$ of transit agency $t \in T$	$D^{t,r}_{headway} \in \mathbb{Z}^{n^{t,r}_{periods}},\ D^{t,r}_{headway} \in [n_{min-headway}, n_{max-headway}]$
Example User-Defined Input: Transit Pricing		
Notation	Description	Specification
D^t_{fare}	A vector of user-defined fares charged to transit riders of each age for using transit agency $t \in T$	$D^t_{fare} \in \mathbb{R}^A,\ D^t_{fare,a} \in \mathbb{R}, D^t_{fare,a} \geq 0$
Example User-Defined Input: Multi-modal Incentives		
Notation	Description	Specification
$D^m_{incentive}$	A matrix of user-defined incentive amount for agents of age a and income group i to use mode $m \in M$	$D^m_{incentive} \in \mathbb{R}^{A,I},\ D^m_{incentive,a,i} \in \mathbb{R},\ D^m_{incentive,a,i} \geq 0$

Table 7: Example User-Defined Input Notation

rules that constrain the range of possible user-defined headway values, $n_{min-headway}$ and $n_{max-headway}$, are recommended.

The fare for riding with transit agency $t \in T$ can be redefined by the set of user-defined variables, $D^t_{fare} = \{D^t_{fare,a}\}_{a=0,1,\dots,A}$. All fares must be nonnegative.

Finally, the last example UDI demonstrate how users may choose to allocate multi-modal incentives. An incentive for mode $m \in M$ may be defined based on any number of parameters. Here, an age- and income-based incentive is shown:

$$D^m_{incentive} = \{D^m_{incentive,a,i}\}_{a=0,1,\dots,A;i\in I}$$

where the indices a, i correspond to the age and income group of riders, respectively. All incentive values must be nonnegative.

5.2 Output Variable Specification

Each BEAM simulation run outputs records of all person and vehicle agent events that occur during the run. In this subsection, specification is provided only for output variables that are directly used in the default KPIs provided in the BISTRO KPI library. Additional details of all outputs that may be accessed via the BISTRO output analysis suite are provided in section 7.

5.2.1 Person output

The person agent output reports the choices, movements, and expenditures of each person agent in the population during a simulation run. Each person agent, $n \in N$ takes $R^n_{trips} = X^n_{activities} - 1$ trips during the simulation, where $X^n_{activities}$ is the number of activities in the agent plans for a given scenario.

The mode(s) available to person agent n for trip $r \in \{1, \dots, R^n_{trips}\}$ are output as a set of modes, $X^{n,r}_{available}$.

The mode ultimately chosen by a person agent for trip $r \in \{1, \dots, R^n_{trips}\}$ is output as the variable, $X^{n,r}_{choice} \in X^{n,r}_{available}$. where

$$X^{n,r}_{choice,m} = \begin{cases} 1 \text{ if mode } m \text{ is chosen by person } n \text{ for trip } r \in \{1, \dots, R^n_{trips}\} \\ 0 \text{ otherwise} \end{cases}$$

Trips may include multiple legs. Thus, the number of legs, $G_{n,r}$, included in trip $r \in \{1, \dots, R^n_{trips}\}$ of agent $n \in N$, is

$$G_{n,r} \begin{cases} = 1 \text{ if } X^{n,r}_{choice,walk} = 1 \text{ or } X^{n,r}_{choice,on-demand} = 1 \text{ or } X^{n,r}_{choice,bicycle} = 1, \text{ etc.} \\ >= 2 \text{ otherwise} \end{cases}$$

Transit trips include an access and egress leg as well as one or more transit legs, depending on the use of one or more transit routes during the trip. The mode used during each leg is denoted by the variable $X^{n,r,g}_{mode}$.

$$X^{n,r,g}_{mode} = \begin{cases} 1 \text{ if mode } m \text{ is used by person } n \text{ for leg } g \text{ of trip } r \\ 0 \text{ otherwise} \end{cases}$$

Each trip leg is made using a vehicle, recorded by the output variable, $X^{n,r,g}_{vehicle} \in V$. The output variable $X^{n,r,g}_{route} = \{X^{n,r,g}_{route,1}, X^{n,r,g}_{route,2}\}$ records the transit agency, $X^{n,r,g}_{route,1}$, and route, $X^{n,r,g}_{route,2}$ used by agent n during leg g of trip r such that $X^{n,r,g}_{route} = \{\emptyset, \emptyset\}$ if the agent did not use transit during leg g.

Person Output		
Notation	Description	Specification
N	All person agents in a simulation scenario	$n \in N$
P	Maximum number of activities completed by each agent in a simulation scenario	$P > 0$
$X^n_{activities}$	The number of activities in the activity plan of person agent $n \in N$	$m^n_{activities} \in \mathbb{Z},\ m^n_{activities} > 0$
R^n_{trips}	The number of trips made by agent $n \in N$ during a simulation run	$R^n_{trips} = X^n_{activities} - 1$
$G_{n,r}$	The number of legs in trip $r \in \{1, \ldots, R^n_{trips}\}$ of person agent $n \in N$	$G_{n,r} \geq 1$
$X^{n,r}_{available}$	Set of mode(s) available to person agent $n \in N$ for trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r}_{available,i} \in M \ \forall \ X^{n,r}_{available,i} \in X^{n,r}_{available}$
$X^{n,r}_{choice}$	The mode chosen by person agent $n \in N$ for trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r}_{choice} \in X^{n,r}_{available}$
$X^{n,r,g}_{choice}$	The mode chosen by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r,g}_{choice} \in M$
$X^{n,r,g}_{vehicle}$	The vehicle in which person agent $n \in N$ completed leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r,g}_{vehicle} \in V$
$X^{n,r,g}_{route}$	The transit agency and route chosen by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r,g}_{route,1} \in T \cup \emptyset,\ X^{n,r,g}_{route,2} \in R^{X^{n,r,g}_{route,1}}_{routes} \cup \emptyset$
$p_{n,r,g}$	The number of links traversed by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$	$p_{n,r,g} \in \mathbb{Z},\ p_{n,r,g} > 0$
$X^{n,r,g}_{path}$	The ordered set of links traversed by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r,g}_{path} := \{X^{n,r,g}_{path,i}\}_{i=1,\ldots,p_{n,r,g}},\ X^{n,r,g}_{path,i} \in L$
$X^{n,r,g}_{distance}$	The total distance traveled by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$ (meters)	$X^{n,r,g}_{distance} \in \mathbb{R},\ X^{n,r,g}_{distance} > 0$
$X^{n,r,g}_{duration}$	The total duration traveled by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$ (seconds)	$X^{n,r,g}_{duration} \in \mathbb{Z},\ X^{n,r,g}_{duration} > 0$
$X^{n,r,g}_{fare,m}$	The fare paid by person agent $n \in N$ for the use of mode $m = X^{n,r,g}_{choice}$ during leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r,g}_{fare,m} \in \mathbb{R},\ X^{n,r,g}_{fare,m} \geq 0$
$X^{n,r,g}_{fuel-consumed}$	The total fuel consumed by person agent $n \in N$ by driving a personal vehicle during leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$ (mJ)	$X^{n,r,g}_{fuel-consumed} \in \mathbb{R},\ X^{n,r,g}_{fuel-consumed} \geq 0$
$X^{n,r,g}_{fuel-cost}$	The total fuel cost to person agent $n \in N$ of driving a personal vehicle during leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$ (\$)	$X^{n,r,g}_{fuel-cost} \in \mathbb{R},\ X^{n,r,g}_{fuel-cost} \geq 0$
$X^{n,r}_{incentive}$	The total incentive amount available to person agent $n \in N$ for trip $r \in \{1, \ldots, R^n_{trips}\}$ (\$)	$X^{n,r}_{incentive} \in \mathbb{R},\ X^{n,r}_{incentive} \geq 0$
$X^{n,r}_{exp}$	The total (net) expenditure incurred by person agent $n \in N$ for trip $r \in \{1, \ldots, R^n_{trips}\}$ (\$)	$X^{n,r}_{exp} \in \mathbb{R},\ X^{n,r}_{exp} \geq 0$

Table 8: Person Output Notation

Each leg of a trip traverses a path, recorded as an ordered list of $p_{n,r,g}$ links traversed,

$$X^{n,r,g}_{path} = \{X^{n,r,g}_{path,i}\}_{l\in\{1,\ldots,p_{n,r,g}\}}$$

where $X^{n,r,g}_{path,i} \in L$ is a link in the transportation network.

The distance traveled (in miles) by agent n during leg g of trip r is

$$X^{n,r,g}_{distance} = \sum_{l\in X^{n,r,g,}_{path}} Z^{X^{n,r,g}_{path,l}}_{length}$$

The duration (in seconds) of each leg is a result of the traffic dynamics of the simulation and is recorded by the ouput variable $X^{n,r,g}_{duration} \geq 0$. The expenditure (in dollars \$) incurred by a person agent during a trip is the sum of all fare(s) paid for the legs of the trip, if any, plus additional expenditures from driving a personal vehicle, if applicable.

The applicable fare for person agent $n \in N$ to use mode $m \in M$ for leg $g \in G_{n,r}$ of trip $r \in \{1,\ldots,R^n_{trips}\}$ is given by the mode-specific fare output, $X^{n,r,g}_{fare,m}$. The default mode-specific fares for transit and on-demand rides are defined below. If additional fare-charging modes are included in the simulation, such as bikesharing, carsharing, or other shared mobility, additional mode-specific fares may be defined.

By default, the transit fare incurred by agent n during a trip leg is defined either by the corresponding configuration input variable, or by the user-defined transit fare input variable, in the case that the transit fare UDI is used for a particular simulation run:

$$X^{n,r,g}_{fare,transit} = \begin{cases} Z^{X^{n,r,g}_{route,1}}_{fare,N^n_{age,a}} \; if \;\; D^t_{fare} = \emptyset \\ D^{X^{n,r,g}_{route,1}}_{fare,N^n_{age,a}} \; otherwise \end{cases}$$

The on-demand ride fare for service type $s \in S$ incurred by agent n during any trip leg is

$$X^{n,r,g}_{fare,on-demand,s} = Z^{on-demand,s}_{fare,base} + X^{n,r,g}_{distance} Z^{on-demand,s}_{fare,distance} + \frac{1}{60} X^{n,r,g}_{duration} Z^{on-demand,s}_{fare,duration}$$

The cost of fuel consumed by agent n during any trip leg is the product of the total amount of fuel consumed by driving during that leg, $X^{n,r,g}_{fuel-consumed}$, and the corresponding fuel cost of the vehicle used during the leg, as follows:

$$X^{n,r,g}_{fuel-cost} = X^{n,r,g}_{choice,drive} X^{n,r,g}_{fuel-consumed} \sum_{c\in C_{personal}} Z^{X^{n,r,g}_{vehicle}}_{veh-type,c} Z^{Z^c_{fuel-type}}_{fuel-cost}$$

Where $Z^v_{veh-type,c}$ is a Boolean indicator denoting which vehicle type $c \in C_{private}$ corresponds to the vehicle $X^{n,r,g}_{vehicle} \in V_{personal}$ that was used during the trip leg, $Z^c_{fuel-type}$ denotes the fuel type used by that vehicle type, and $Z^K_{fuel-cost}$ is the cost per mJ consumed of that fuel type.

The incentive available to agent n during trip r is given by the output variable:

$$X^{n,r}_{incentive} = D^{X^{n,r}_{choice}}_{incentive,N^n_{age},N^n_{income}}$$

Where $D^m_{incentive,a,i}$ denotes the user-defined incentive amount available for a person agent of age a and income i, N^n_{age} and N^n_{income} are the age and income, respectively, of agent n.

The total expenditure incurred per person agent trip is captured by the output variable,

$$X^{n,r}_{exp} = \left(\sum_{g=1}^{G_{r,n}} \left(X^{n,r,g}_{fare,X^{n,r,g}_{choice}} + X^{n,r,g}_{fuel-cost} \right) - X^{n,r}_{incentive} \right)_+$$

Vehicle Output		
Notation	Description	Specification
V	All vehicles in the transportation system	$v \in V := V_{transit} \cup V_{on-demand} \cup V_{private}$
Q_v	The total number of movements made by vehicle $v \in V$	$Q_v \in \mathbb{Z},\ Q_v \geq 0$
$p_{v,q}$	The number of links traversed by vehicle $v \in V$ during movement $q \in [1, Q_v]$	$p_{v,q} \in \mathbb{Z},\ p_{v,q} > 0$
$Y^{v,q}_{path}$	The ordered set of links traversed by vehicle $v \in V$ during movement $q \in [1, Q_v]$	$Y^{v,q}_{path} := \{Y^{v,q}_{path,i}\}_{i=1,...,p_{v,q}},\ Y^{v,q}_{path,l} \in L$
$Y^{v,q}_{distance}$	The total distance traveled by vehicle $v \in V$ during movement $q \in [1, Q_v]$ (meters)	$Y^{v,q}_{distance} \in \mathbb{R},\ Y^{v,q}_{distance} > 0$
$Y^{v,q}_{duration}$	The total duration of movement $q \in [1, Q_v]$ of vehicle $v \in V$ (seconds)	$Y^{v,q}_{duration} \in \mathbb{Z},\ Y^{v,q}_{duration} > 0$
$Y^{v,q}_{fuel-consumed}$	The total fuel consumed by vehicle $v \in V$ during movement $q \in [1, Q_v]$ (mJ)	$Y^{v,q}_{fuel-consumed} \in \mathbb{R},\ Y^{v,q}_{fuel-consumed} > 0$
$Y^{v,q}_{fuel-cost}$	The total cost of fuel consumed by vehicle $v \in V$ during movement $q \in [1, Q_v]$ (\$)	$Y^{v,q}_{fuel-cost} \in \mathbb{R},\ Y^{v,q}_{fuel-cost} \geq 0$
$Y^{v,q}_{op-cost}$	The total operational cost of movement $q \in [1, Q_v]$ by vehicle $v \in V$ (\$)	$Y^{v,q}_{op-cost} \in \mathbb{R},\ Y^{v,q}_{op-cost} \geq 0$
$Y^{v,q}_{pax}$	The number of passengers on board vehicle $v \in V$ during movement $q \in [1, Q_v]$ (\$)	$Y^{v,q}_{pax} \in \mathbb{Z},\ Y^{v,q}_{pax} \geq 0$

Table 9: Vehicle Output Notation

where

$$(x)_+ = \begin{cases} x \text{ if } x \geq 0 \\ 0 \text{ otherwise} \end{cases}$$

In the event that the incentive amount available to an agent for a particular trip exceeds the total fare and/or fuel cost of the trip, the agent receives an incentive amount equal to the total fare and fuel cost incurred during the trip.

5.2.2 Vehicle output

The vehicle output reports the movements of all vehicles during a simulation run. Each vehicle, $v \in V$, makes $Q_v \geq 0$ movements. For buses, a movement consists of travel between two bus stops. For personal vehicles, a movement consists of travel between two parking facilities. Finally, for on-demand ride vehicles, a movement consists of the travel from origin to destination during any one of the three phases of service: empty, fetch, and fare.

The path, fuel consumption, and occupancy of each vehicle v is recorded upon every vehicle movement. Similar to paths for person agent legs, the path traversed by vehicle v during a movement, $q = \{1, 2, ..., Q_v\}$, is recorded as an ordered list of $p_{v,q}$ links traversed,

$$Y^{v,q}_{path} = \{Y^{v,q}_{path,l}\}_{l \in \{1,...,p_{v,q}\}}$$

where $Y^{v,q}_{path,l} \in L$ is a link in the network.

Thus, the distance traveled by vehicle $v \in V$ during movement $q \in Q_v$ is given by:

$$Y^{v,q}_{distance} = \sum_{l \in Y^{v,q}_{path}} Z^l_{length}$$

Where Z^l_{length} is the length of link $l \in L$ in the transportation network. The duration of the movement (in seconds) is recorded by the output variable $Y^{v,q}_{duration} > 0$, and the fuel consumed by the variable, $Y^{v,q}_{fuel-consumed}$.

Thus the cost of fuel consumed by vehicle v during movement q is the product of the fuel consumed during the movement and the fuel cost of the corresponding vehicle type:

$$Y^{v,q}_{fuel-cost} = Y^{v,q}_{fuel-consumed} \sum_{c \in C} Z^{v}_{veh-type,c} Z^{Z^{c}_{fuel-type}}_{fuel-cost}$$

The total operational cost, if applicable, for vehicle v during movement q is the product of the duration of the movement and the variable operational cost for the corresponding vehicle type, as follows:

$$Y^{v,q}_{op-cost} = \frac{1}{3600} Y^{v,q}_{duration} \sum_{c \in C} Z^{v}_{veh-type,c} Z^{c}_{var-op-cost}$$

The number of passengers in vehicle v during movement q is recorded by the output variable $Y^{v,q}_{pax} \geq 0$.

5.3 KPI Specification

All score components are assessed as the ratio of the value of the corresponding KPI in a simulation run to the corresponding KPI value in the business as usual simulation run; that is, the scenario run without any inputs. The following sections detail each of the KPI functions included in the composite score, which is explained in Section 5.4.

5.3.1 Accessibility

Accessibility measurements utilize the network characteristics resulting for any given submission (*i.e.*, links $l \in L$ are weighted with average travel-times, and average bus headways are assigned to routes during $n_{periods}$ periods of interest). Accessibility is then calculated as the sum of the average number of points of interest (work or secondary) reachable from all nodes $w \in W$ by a specified road network mode (car or transit) within a specified amount of time. Separate calculations are made for car (incorporating drive alone and a lower-bound estimate for on-demand rides) and transit trips to compare the changes in accessibility across network users. For the purposes of calculating the accessibility KPI, the output variable $Y^{m,e,u,w}_{shortest}$ reports the set of links that correspond to the *shortest path directed network distance* (in units of time) for mode $m \in M$ to travel from node $u \in W$ to node $w \in W$ during time period $e \in \{1, \ldots, n_{periods}$. Thus, $Y^{m,e,u,w}_{shortest} = \{Y^{m,e,u,w}_{s-p,i}\}_{i=1 \ldots n^{m,e,u,w}_{sp}}$, where each element, of $Y^{m,e,u,w}_{s-p,i} \in Y^{m,e,u,w}_{shortest}$ is a link in the network ($Y^{m,e,u,w}_{shortest} \in L$). The average travel time for mode $m \in M$ on link $l \in L$ during time period e is recorded by the output variable $Y^{m,l,e}_{avg-tt}$. Thus, the accessibility KPI for trip purpose *purpose* (identified by the facility type of the point of interest) and mode m is calculated as follows:

$$K_{accessibility,purpose,m} = \frac{1}{n_{periods} \sum_{w \in W} 1} \sum_{e=1}^{n_{periods}} \sum_{u \in W} \sum_{w \in W} \sum_{f \in K_{purpose}} Z^{f}_{w} I_{\tau \geq \sum_{l \in Y^{m,e,u,w}_{shortest}} Y^{m,l,e}_{avg-tt}}$$

where Z^{K}_{w} is a Boolean indicator of whether facility $f \in K_{purpose}$ of type *purpose* is located at node $w \in W$ and the term $I_{\tau \geq \sum_{l \in Y^{m,e,u,w}_{shortest}} Y^{m,l,e}_{avg-tt}}$ indicates whether the total average travel time on the shortest path for mode m from node u to node w is less than or equal to the threshold travel time of τ as follows:

$$I_{\tau \geq \sum_{l \in Y^{m,e,u,w}_{shortest}} Y^{m,l,e}_{avg-tt}} = \begin{cases} 1 \; if \;\; \tau \geq \sum_{l \in Y^{m,e,u,w}_{shortest}} Y^{m,l,e}_{avg-tt} \\ 0 \; otherwise \end{cases}$$

KPI: Accessibility		
Notation	Description	Specification
$n_{periods}$	The number of time periods of interest for the accessibility KPI	$n_{periods} \in \mathbb{Z},\ n_{periods} > 0$
K_{work}	All work facilities in the network	$f \in K_{work} \subset F$
$K_{secondary}$	All secondary facilities in the network	$f \in K_{secondary} \subset F$
Z_w^K	Facility instance at node $w \in W$	$Z_w^K \in \{0,1\}$
$Y_{shortest}^{m,e,u,w}$	The set of links in the shortest path from node $u \in W$ to node $w \in W$ using mode $m \in M$ during time period $e = 1 \ldots n_{periods}$	$Y_{shortest}^{m,e,u,w} := \{Y_{shortest,i}^{m,e,u,w}\}_{i=1,\ldots,n_{periods}},\ Y_{shortest,i}^{m,e,u,w} \in L$
$Y_{avg-tt}^{m,l,e}$	The average travel time for mode $m \in M$ on link $l \in L$ during time period e	$Y_{avg-tt}^{m,l,e} \in \mathbb{R},\ Y_{avg-tt}^{m,l,e} \geq 0$
τ	The travel time within which points of interest must be accessible in order to be counted for the the accessibility KPI (minutes)	$\tau \in \mathbb{R},\ \tau > 0$

Table 10: Accessibility KPI Notation

1. **Work-based trips:**

$$K_{accessibility,work,m} = \frac{1}{n_{periods} \sum_{w \in W} 1} \sum_{e=1}^{n_{periods}} \sum_{u \in W} \sum_{w \in W} \sum_{f \in K_{work}} Z_w^f I_{\tau \geq \sum_{l \in Y_{shortest}^{m,e,u,w}} Y_{avg-tt}^{m,l,e}}$$

2. **Secondary trips:**

$$K_{accessibility,secondary,m} = \frac{1}{n_{periods} \sum_{w \in W} 1} \sum_{e=1}^{n_{periods}} \sum_{u \in W} \sum_{w \in W} \sum_{f \in K_{secondary}} Z_w^f I_{\tau \geq \sum_{l \in Y_{shortest}^{m,e,u,w}} Y_{avg-tt}^{m,l,e}}$$

5.3.2 Measures of Level of Service

The LoS of the transportation system are evaluated on average, across person trips. Each person, $n \in N$ completes R_{trips}^n trips from one activity to another throughout a simulation run. Each trip, $r \in \{1, \ldots, R_{trips}^n\}$ includes $G_{n,r}$ legs, each using a single mode of transportation.

1. **Average Generalized Transportation Cost Burden**: As detailed in Section 4.1:3, the total travel expenditure, $X_{exp}^{n,r}$, for a person agent, $n \in N$, during any trip, $r \in \{1, \ldots, R_{trips}^n\}$, may include bus and/or on-demand ride fares, and the cost of fuel consumed less any applicable incentives.

   The average transportation cost burden is considered by trip purpose: for example, by work trips and secondary activity trips. Thus the average transportation cost burden for work trips is

$$K_{cost-burden,work} =$$

$$\frac{1}{\sum_{n \in N} \sum_{r=1}^{R_{trips}^n} I_{N_{plan,r+1}^n \in K_{work}}} \sum_{n \in N} \sum_{r=1}^{R_{trips}^n} I_{N_{plan,r+1}^n \in K_{work}} \frac{X_{exp}^{n,r} + X_{duration}^{n,r} \cdot N_{avg-VOT}}{\hat{N}_{hhd-income}^{N_{hhd}^n}}$$

$$\hat{N}_{hhd-income}^h = max(1, N_{hhd-income}^h)$$

$$I_{N_{plan,r+1}^n \in K_{work}} = \begin{cases} 1 \ \textit{if } N_{plan,r+1}^n \in K_{work} \\ 0 \ \textit{otherwise} \end{cases}$$

KPI: LoS- Average Transportation Cost Burden		
Notation	Description	Specification
N	All person agents in a simulation scenario	$n \in N$
R^{n}_{trips}	The number of trips made by agent $n \in N$ during a simulation run	$0 < R^{n}_{trips} \leq P - 1$
$G_{n,r}$	The number of legs in trip $r \in \{1, \ldots, R^{n}_{trips}\}$ of person agent $n \in N$	$G_{n,r} \geq 1$
$X^{n,r}_{exp}$	The total (net) expenditure incurred by person agent $n \in N$ for trip $r \in \{1, \ldots, R^{n}_{trips}\}$ (\$)	$X^{n,r}_{exp} \in \mathbb{R},\ X^{n,r}_{exp} \geq 0$
$X^{n,r}_{duration}$	The total duration traveled by person agent $n \in N$ during trip $r \in \{1, \ldots, R^{n}_{trips}\}$ (seconds)	$X^{n,r}_{duration} \in \mathbb{R},\ X^{n,r}_{duration} > 0$
$N^{h}_{hhd-income}$	The household income of household $h \in H$ (\$)	$N^{h}_{hhd-income}$
$N_{avg-VOT}$	The average VOT of the population (\$/hour)	$N_{avg-VOT} \in \mathbb{R},\ N_{avg-VOT} > 0$
KPI: LoS- Average Bus Crowding Experienced		
Notation	Description	Specification
$X^{n,r,g}_{choice}$	The mode chosen by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^{n}_{trips}\}$	$X^{n,r,g}_{choice} \in M$
G_{bus}	The total number of bus trip legs made by all person agents	$G_{bus} \in \mathbb{Z},\ G_{bus} \geq 0$
V_{bus}	The set of all vehicles in the bus fleet	$v \in V_{bus} \subset V$
$Y^{v,q}_{duration}$	The total duration of movement $q \in [1, Q_v]$ of vehicle $v \in V$ (seconds)	$Y^{v,q}_{duration} \in \mathbb{Z},\ Y^{v,q}_{duration} > 0$
$Z^{v}_{veh-type,c}$	Vehicle type assignment of vehicle $v \in V$	$Z^{v}_{veh-type,c} \in \{0, 1\}$
$Z^{c}_{seating}$	The passenger seating capacity of vehicle type $c \in C$	$Z^{c}_{seating} \in \mathbb{Z},\ Z^{c}_{seating} > 0$
$Z^{c}_{standing}$	The passenger standing capacity of vehicle type $c \in C$	$Z^{c}_{standing} \in \mathbb{Z},\ Z^{c}_{standing} \geq 0$
$Y^{v,q}_{pax}$	The number of passengers on board vehicle $v \in V$ during movement $q \in [1, Q_v]$	$Y^{v,q}_{pax} \in \mathbb{R},\ Y^{v,q}_{pax} \geq 0$
$Tm^{v,q}_{seated}$	The value of time multiplier for seated passengers on board vehicle $v \in V$ during movement $q \in [1, Q_v]$	$Tm^{v,q}_{seated} \in \mathbb{R},\ Tm^{v,q}_{seated} \geq 0$
$Tm^{v,q}_{standing}$	The value of time multiplier for standing passengers on board vehicle $v \in V$ during movement $q \in [1, Q_v]$	$Tm^{v,q}_{standing} \in \mathbb{R},\ Tm^{v,q}_{standing} \geq 0$

Table 11: Level of Service (LoS) KPI Notation

where $N^{N^n_{hhd}}_{hhd-income}$ is the income of household $N^n_{hhd} \in H$ of which individual $n \in N$ is a member, and $N_{avg-VOT}$ is the population-wide average value of time (VOT).

Similarly, the average transportation cost burden for secondary trips is

$$K_{cost-burden,secondary} =$$

$$\frac{1}{\sum_{n\in N}\sum_{r=1}^{R^n_{trips}} I_{N^n_{plan,r+1}\in K_{secondary}}}\sum_{n\in N}\sum_{r=1}^{R^n_{trips}} I_{N^n_{plan,r+1}\in K_{secondary}} \frac{X^{n,r}_{exp} + X^{n,r}_{duration}\cdot N_{avg-VOT}}{N'^{N^n_{hhd}}_{hhd-income}}$$

2. **Average Bus Crowding Experienced**: The average bus crowding KPI is by default calibrated with time multipliers corresponding to the perceived value of time (VOT) in buses. However, a similar KPI may be implemented for crowding on other types of transit services, such as rail, using mode-specific functions for the VOT multipliers. The average bus crowding KPI is computed from simulation output as follows (using the fleet configuration UDI):

$$K_{bus-crowding} =$$

$$\frac{1}{G_{bus}}\sum_{v\in V_{bus}}\sum_{q=1}^{Q_v}\left(Y^{v,q}_{duration}\sum_{c=1}^{C} D^v_{veh-type,c}(Tm^{v,q}_{seating} min(Z^c_{seating}, Y^{v,q}_{pax}) + Tm^{v,q}_{standing}(Y^{v,q}_{pax} - Z^c_{seating}))\right)$$

where G_{bus} is the total number of trip legs in which a bus was used such that

$$G_{bus} = \sum_{n\in N}\sum_{r=1}^{R^n_{trips}}\sum_{g=1}^{G_{n,r}} I_{X^{n,r,g}_{choice}=bus}$$

$Tm^{v,q}_{seated}$ and $Tm^{v,q}_{standing}$ are the time multipliers for seating and standing passengers to account for the relative disutility of time spent in buses that are filled over seating capacity, respectively such that

$$Tm^{v,q}_{seated} = \begin{cases} 1.1 + log(\frac{Y^{v,q}_{pax}}{Z^c_{seating}}) \text{ if } Y^{v,q}_{pax} \geq Z^c_{seating} \\ 0 \text{ otherwise} \end{cases}$$

$$Tm^{v,q}_{standing} = \begin{cases} 1.1 + 2.5log(\frac{Y^{v,q}_{pax}}{Z^c_{seating}}) \text{ if } Y^{v,q}_{pax} > Z^c_{seating} \\ 0 \text{ otherwise} \end{cases}$$

5.3.3 Measures of congestion

The first two measures of congestion, total vehicle miles traveled (VMT) and total vehicle hours of delay, are assessed on aggregate across all vehicle movements in a simulation run.

1. **Total VMT**:

$$K_{vmt} = \sum_{v\in V}\sum_{q=1}^{Q_v} Y^{v,q}_{distance}$$

where $Y^{v,q}_{distance}$ is the total distance (in miles) traveled by vehicle v during movement q.

2. **Average Vehicle Delay per Passenger Trip**:

$$K_{pax-trip-delay} = \frac{1}{\sum_{n\in N} R^n_{trips,motorized}}\sum_{n\in N}\sum_{r\in\{1,\ldots,R^n_{trips}\}}\left(\sum_{g=1}^{G_{n,r}} X^{n,r,g}_{duration} - \sum_{l\in X^{n,r,g,}_{path}} \frac{Z^l_{length}}{Z^l_{speed-limit}}\right)$$

KPI: Congestion- Total Vehicle Miles Traveled (VMT)		
Notation	Description	Specification
V	All vehicles in the transportation system	$v \in V := V_{transit} \cup V_{on-demand} \cup V_{private}$
Q_v	The total number of movements made by vehicle $v \in V$	$Q_v \in \mathbb{Z},\ Q_v \geq 0$
$Y^{v,q}_{distance}$	The total distance traveled by vehicle $v \in V$ during movement $q \in [1, Q_v]$ (meters)	$Y^{v,q}_{distance} \in \mathbb{R},\ Y^{v,q}_{distance} > 0$
KPI: Congestion- Average Vehicle Delay per Passenger Trip		
Notation	Description	Specification
$R^n_{trips,motorized}$	The number of trips taken by agent $n \in N$ using a motorized mode $m \in \{drive, on-demand, walk-transit, drive-transit\}$	$R^n_{trips,motorized} \in \mathbb{Z},\ R^n_{trips,motorized} \geq 0$
$X^{n,r}_{choice}$	The mode chosen by person agent $n \in N$ for trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r}_{choice} \in M$
$X^{n,r,g}_{duration}$	The total duration traveled by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$ (seconds)	$X^{n,r,g}_{duration} \in \mathbb{Z},\ X^{n,r,g}_{duration} > 0$
$X^{n,r,g}_{path}$	The ordered set of links traversed by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^n_{trips}\}$	$X^{n,r,g}_{path} \in \mathbb{R}^{p_{n,r,g}},\ X^{n,r,g}_{path,l} \in L$
Z^l_{length}	Length of link $l \in L$ (meters)	$Z^l_{length} \in \mathbb{R},\ Z^l_{length} > 0$
$Z^l_{speed-limit}$	Free-flow speed of link $l \in L$ (meters/second)	$Z^l_{speed-limit} \in \mathbb{R},\ Z^l_{speed-limit} > 0$

Table 12: Measures of Congestion KPI Notation

where $R^n_{trips,motorized}$ is the number of trips taken by agent n using a motorized mode during the simulation run:

$$R^n_{trips,motorized} = \sum_{r=1}^{R^n_{trips}} I_{X^{n,r}_{choice} \in \{drive, on-demand, walk-transit, drive-transit\}}$$

5.3.4 Financial Sustainability

Any intervention on the transportation system is likely to result in costs and benefits for the operation of mass transit in the city of interest. The financial sustainability component is computed as the difference between the total revenue collected through transit fares $K_{revenue}$ and the net cost of transit operations $K_{op-cost}$ and multi-modal incentives used to manage demand $K_{incentives-used}$:

$$K_{financial-sust} = K_{revenue} - (K_{op-cost} + K_{incentives-used})$$

1. **Operational costs**: Operational costs include fixed costs, variable hourly costs, and fuel costs for transit operations.

$$K_{op-cost} = \sum_{v \in V_{transit}} \sum_{q \in Q_v} Y^{v,q}_{fuel-cost} + Y^{v,q}_{op-cost}$$

   where $Y^{v,q}_{fuel-cost}$ and $Y^{v,q}_{op-cost}$ are the total fuel and operational costs produced during movement q of vehicle v in the transit fleet during the simulation run.

2. **Incentives used**

$$K_{incentives-used} = \sum_{n \in N} \sum_{r=1}^{R^n_{trips}} X^{n,r}_{incentive} - X^{n,r}_{exp}$$

KPI: Financial Sustainability		
Notation	Description	Specification
$V_{transit}$	All transit vehicles	$v \in V_{transit} \subset V$
Q_v	The total number of movements made by vehicle $v \in V$	$Q_v \in \mathbb{Z},\ Q_v \geq 0$
$Y^{v,q}_{op-cost}$	The total operational cost of movement $q \in [1, Q_v]$ by vehicle $v \in V$ (\$)	$Y^{v,q}_{op-cost} \in \mathbb{R},\ Y^{v,q}_{op-cost} \geq 0$
$Y^{v,q}_{fuel-cost}$	The total cost of fuel consumed by vehicle $v \in V$ during movement $q \in [1, Q_v]$ (\$)	$Y^{v,q}_{fuel-cost} \in \mathbb{R},\ Y^{v,q}_{fuel-cost} > 0$
N	All person agents in a simulation scenario	$n \in N$
$X^{n}_{activities}$	The number of activities in the activity plan of person agent $n \in N$	$m^{n}_{activities} \in \mathbb{Z},\ m^{n}_{activities} > 0$
R^{n}_{trips}	The number of trips made by agent $n \in N$ during a simulation run	$R^{n}_{trips} = X^{n}_{activities} - 1$
$G_{n,r}$	The number of legs in trip $r \in \{1, \ldots, R^{n}_{trips}\}$ of person agent $n \in N$	$G_{n,r} \geq 1$
$X^{n,r}_{incentive}$	The total incentive amount available to person agent $n \in N$ for trip $r \in \{1, \ldots, R^{n}_{trips}\}$ (\$)	$X^{n,r}_{incentive} \in \mathbb{R},\ X^{n,r}_{incentive} \geq 0$
$X^{n,r}_{exp}$	The total (net) expenditure incurred by person agent $n \in N$ for trip $r \in \{1, \ldots, R^{n}_{trips}\}$ (\$)	$X^{n,r}_{exp} \in \mathbb{R},\ X^{n,r}_{exp} \geq 0$
$X^{n,r,g}_{choice}$	The mode chosen by person agent $n \in N$ for leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^{n}_{trips}\}$	$X^{n,r,g}_{choice} \in M$
$X^{n,r,g}_{fare,m}$	The fare paid by person agent $n \in N$ for the use of mode $m = X^{n,r,g}_{choice}$ during leg $g \in G_{n,r}$ of trip $r \in \{1, \ldots, R^{n}_{trips}\}$	$X^{n,r,g}_{fare,m} \in \mathbb{R},\ X^{n,r,g}_{fare,m} \geq 0$
KPI: Environmental Sustainability		
Notation	Description	Specification
$Y^{v,q}_{distance}$	The total distance traveled by vehicle $v \in V$ during movement $q \in [1, Q_v]$ (meters)	$Y^{v,q}_{distance} \in \mathbb{R},\ Y^{v,q}_{distance} > 0$
$Z^{c}_{fuel-type}$	The fuel type used by vehicle type $c \in C$	$Z^{c}_{fuel-type} \in \{gasoline, diesel, electricity\}$
$Z^{v}_{veh-type,c}$	Vehicle type assignment of vehicle $v \in V$	$Z^{v}_{veh-type,c} \in \{0, 1\}$
$PM^{c,f}_{2.5}$	The $PM_{2.5}$ emission factor for vehicle type $c \in C$ using fuel type $f \in \{gasoline, diesel, electricity\}$	$PM^{c,f}_{2.5} \in \mathbb{R},\ PM^{c,f}_{2.5} \geq 0$

Table 13: Financial and Environmental Sustainability KPI Notation

where $X_{exp}^{n,r}$ and $X_{incentive}^{n,r}$ are the expenditure and incentives used, respectively, by agent n during trip r. Both the trip expenditure and incentives must be nonnegative, as defined in section 5.2.1. Incentives may only be used by qualifying agents, as defined by user-defined inputs.

3. **Revenue**:

$$K_{revenue} = \sum_{n \in N} \sum_{r=1}^{R_{trips}^{n}} \Big(\sum_{g \in G_{n,r}} I_{X_{choice}^{n,r,g}=transit} X_{fare,transit}^{n,r,g} \Big) - X_{incentive}^{n,r}$$

where $X_{choice}^{n,r,g}$ indicates the mode that agent n chose to use for leg g of trip r. The variable $X_{fare,transit}^{n,r,g}$ is the transit fare paid, and $X_{incentive}^{n,r}$ is the incentive amount received by agent n for trip r.

5.3.5 Measures of environmental sustainability

Environmental sustainability will be assessed as the total particulate matter emitted from $PM_{2.5}$ running exhaust (RUNEX) and the GHG emissions from all vehicle movements in a simulation run. $PM_{2.5}$ emissions vary by mode and by fuel type; for Sioux Faux, there are only two possible vehicle-fuel type combinations: gasoline auto and diesel bus, simplifying the summation to:

1. **Total $PM_{2.5}$ Emissions**:

$$K_{PM_{2.5}} = \sum_{v \in V} \sum_{q=1}^{Q_v} Y_{distance}^{v,q} \sum_{c \in C} Z_{veh-type,c}^{v} \sum_{f \in F} PM_{2.5}^{c, Z_{fuel-type}^{c}}$$

where $Y_{distance}^{v,q}$ is the total distance (in miles) traveled by vehicle v during movement q, $Z_{veh-type,c}^{v}$ is a Boolean indicator that vehicle v is of type c, $Z_{fuel-type}^{c}$ is the fuel type used by vehicle type c, and $PM_{2.5}^{c,f}$ is defined as follows:

$$PM_{2.5}^{c,diesel} = \begin{cases} 0.259366648 \; grams/mile \text{ if the vehicle is a bus} \\ 0.018403666 \; grams/mile \text{ if the vehicle is a car} \\ 0 \text{ otherwise} \end{cases}$$

$$PM_{2.5}^{c,gasoline} = \begin{cases} 0.002517723 \; grams/mile \text{ if the vehicle is a bus} \\ 0.001716086 \; grams/mile \text{ if the vehicle is a car} \\ 0 \text{ otherwise} \end{cases}$$

2. **Total *GHG* Emissions**: BEAM uses a high resolution data-driven vehicle energy consumption model based on a similar model[9]. Consequently, similarly detailed vehicle emissions statistics can be backed out of BEAM energy usage outputs.

5.4 Composite Score

The BISTRO scoring function serves as the objective function by which the UDIs are optimized. The selection and/or definition of the objective function is left to the decision of the project owner, according to project directives; herein, a general structure is defined to facilitate users in the creation of custom objective functions. Multiple project objectives (referred here specifically as *score components*) may be included in the scoring function, either as individual elements within a vector of scalar-valued score components to be minimized or as parameters to a function that aggregates the objectives into a one-dimensional scalar score. The score components are computed as the normalized ratio of the value of the corresponding KPI in the given simulation run to the value of the same KPI in the *business-as-usual* (BAU) run.[10] The improvement ratios

[9] To find the description of this model, read: https://www.nrel.gov/docs/fy17osti/69121.pdf

[10] In the BAU of a given scenario, the simulation is run without alteration from the initial configuration of that scenario.

Composite Score Parameters		
Notation	Description	Specification
$\vec{C}_s$	A vector of all simulation inputs for alternative solution, s	See specifications in Section5.3
$\vec{K}$	A vector of all KPIs evaluated for solution s, $K_i(C_s)$	$K_i(C_s) \in \mathbb{R}, \forall i$
$\vec{\sigma}$	A vector of standard deviations of each KPI produced by random search	$\sigma_i \in \mathbb{R}, \forall i$
$\vec{\mu}$	A vector of means of each KPI produced by random search	$\mu_i \in \mathbb{R}, \forall i$
$\vec{\alpha}$	A vector of user-defined parameters for each score component	n/a
$\vec{z}$	A vector of normalized KPIs	$\vec{z}_i \in \mathbb{R}, \forall i$

Table 14: Composite Score Function Notation

are normalized using KPI values produced by a randomized sample of the UDI space, the size of which can be defined by the BISTRO project owner. This normalization accounts for differences in variance across KPIs, thus allowing the score components to provide meaningful feedback on the improvement achieved for each KPI relative to the distribution of the ratios of KPI to BAU produced by the random search. The composite score is thus a function of the normalized relative improvements of the candidate input to the BAU in each metric, as follows:

$$F\left(\vec{C}_a, \vec{K}, \vec{\sigma}, \vec{\mu}, \vec{\alpha}\right) = f\left(\vec{z}, \vec{\alpha}\right), \tag{1}$$

where $\vec{K}$ is the vector of all KPIs evaluated for a given set of inputs (see Table 15 for example specified in Section 5.3), $\vec{C}_s$; $\vec{\mu}$ and $\vec{\sigma}$ are the vectors of normalization parameters; and $\vec{z}$ is a vector of each KPI's z-scores, *i.e.*,

$$z_i = \frac{\frac{K_i(C_s)}{K_i(C_{BAU})} - \mu_i}{\sigma_i}, \tag{2}$$

for the i-th KPI. The value of the i-th score component in the BAU case is simply $K_i(C_{BAU})$.

The default objective is to minimize the composite score function, since an increase in many of the score components actually represents a scenario that is worse than the *status quo* (*e.g.*, decreasing VMT over BAU results in a lower unscaled score than increasing VMT). To maintain consistency in this regard, the scoring function may include an additional parameter $\vec{\alpha}$ to allow for transformation of score components that are positively related to desirable outcomes (*e.g.*, improvements in accessibility). For example, if the scoring function takes the form of a sum over all score components, the parameter $\vec{\alpha}$ may be used as a coefficient of each score component that determines whether the component will be summed or subtracted, as follows:

$$\alpha_i = \begin{cases} -1 \text{ if it is desirable for score component } i \text{ to increase} \\ 1 \text{ otherwise} \end{cases} \tag{3}$$

6 Policy Weights and Scaled Scores

In order to explore the interpretation of score components in a broader decision support and enhanced planning context, as often happens during long-range planning exercises, the BISTRO team developed a preliminary set of generalized policy focus areas. Five distinct policy objectives were chosen to emphasize the importance of alternative simulation outcomes from the perspective of a metropolitan or regional planning organization. In this way, the performance of each of four sets of inputs–designed to demonstrate different objectives or intentions (VMT Reduction and Cost Inefficient Transit in Figure 3, Minimum Transit Service

Example KPIs		
Notation	Description	Specification
K_i	The scoring function for KPI i	$K_i \in \mathbb{R}$
$K_{accessibility,purpose,m}$	Accessibility by mode $m \in M$ to POIs for $purpose \in \{work, secondary\}$ (number of POIs)	$K_{accessibility,purpose,m} \geq 0$
$K_{cost-burden,purpose}$	The average generalized transportation cost burden for trips of $purpose \in \{work, secondary\}$ (\$)	$K_{generalized\ cost-burden,purpose} \geq 0$
$K_{bus-crowding}$	The average bus crowding experienced (seconds)	$K_{bus-crowding} \geq 0$
K_{vmt}	The total vehicle miles traveled (VMT) across all vehicle in a simulation run (miles)	$K_{vmt} > 0$
$K_{pax-trip-delay}$	The average vehicle delay per passenger trip (seconds)	$K_{pax-trip-delay} \geq 0$
$K_{financial-sust}$	The net revenue of total transit operational costs, transit revenue and multi-modal incentives distributed (\$)	
$K_{PM_{2.5}}$	The total $PM_2.5$ emissions from all vehicle movements in the simulation run (g)	$K_{PM_{2.5}} \geq 0$

Table 15: Example KPI Notation

and the redistribution of transportation costs via incentives in Figure 5, respectively) when designing the solution–can be examined with respect to five different policy areas, as detailed below.

Table 16 illustrates how score components can be re-weighted in accordance with these objectives via assignment of an integer indicator of relative priority.

1. The System Efficiency alternative prioritizes congestion and financial sustainability metrics primarily, with a secondary preference for accessibility improvements.
2. The main foci of the Sustainability alternative are total $PM_{2.5}$ Emissions, GHG Emissions, and congestion (vehicle miles traveled).
3. Accessibility improvements as well as LoS indicators are emphasized under the Personal Mobility alternative.
4. Transit Operations weight settings allocate greater importance to outcomes that reduce bus crowding and reduce the costs of operation compared to the benefits (with respect to random search normalization).
5. A Policy Agnostic alternative (all weights are normalized and then set to contribute to the total score equally) is also included to facilitate comparison with the scenario wherein all components are treated equally (Figure 6, top). The sum of the indicators across each policy focus alternative is then used to normalize the respective weights for the alternative to sum to 1.0.

We should add a weight on GHGs here

Figure 3 illustrates how the weighting alternatives impact the relative importance of the individual score components. In order to compute the final submission score, each of these weighted scoring components is summed for each policy alternative. Finally, Figure 5 demonstrates how the various alternatives can have quite a significant impact on the final evaluation of users. It is interesting to note that the percent difference in final score between the two sets of inputs can change significantly when using the different criteria. Thus, different policy objectives will influence the ranking of scores. This observation makes it clear that a principled approach to setting the weights is an important consideration prior to using the BISTRO platform.

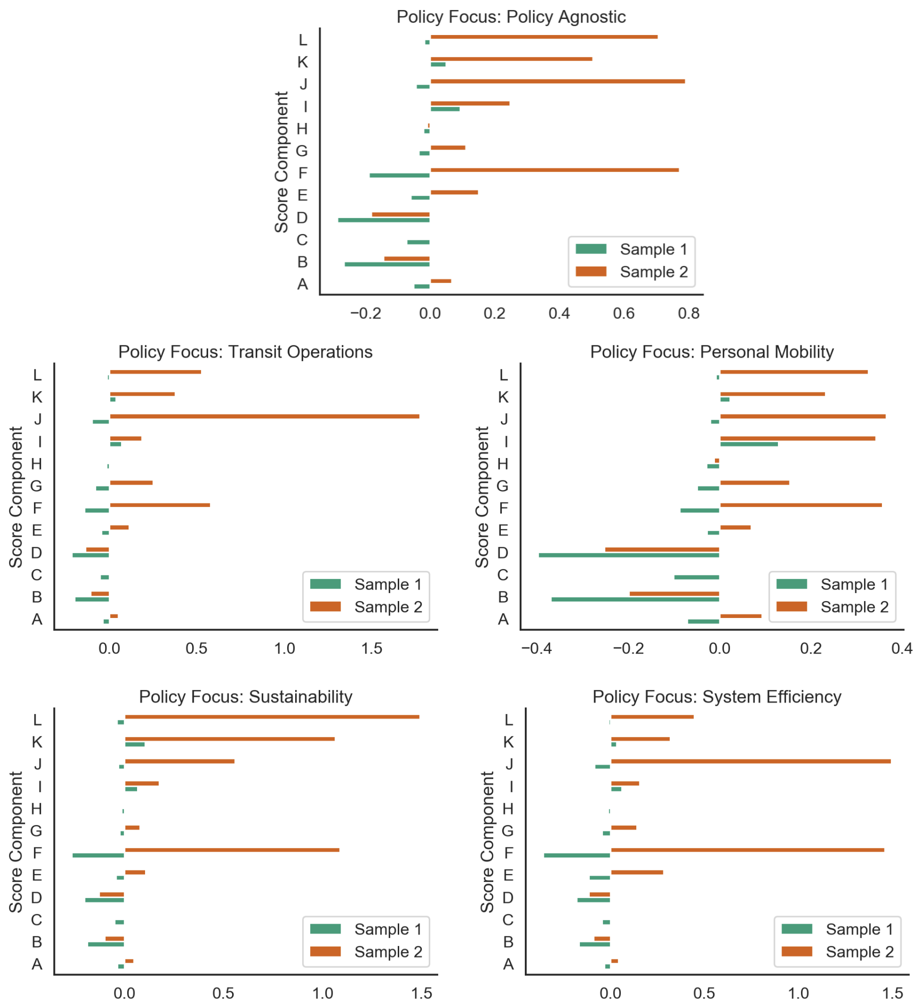
Score Component / Policy Focus	Accessibility: Number of secondary locations accessible within 15 minutes by car	Accessibility: Number of secondary locations accessible within 15 minutes by transit	Accessibility: Number of work locations accessible within 15 minutes by car	Accessibility: Number of work locations accessible within 15 minutes by transit	Congestion: average vehicle delay per passenger trip	Congestion: total vehicle miles traveled	Equity: average travel cost burden - secondary	Equity: average travel cost burden - work	Level of service: average bus crowding experienced	Level of service: costs and benefits	Sustainability: Total grams $GHGe$ Emissions	Sustainability: Total grams $PM_{2.5}$ Emitted
1. System efficiency	1.0	1.0	1.0	1.0	3.0	3.0	1.0	1.0	3.0	3.0	1.0	1.0
2. Sustainability	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0	3.0	3.0
3. Personal Mobility	3.0	3.0	3.0	3.0	1.0	1.0	3.0	3.0	1.0	1.0	1.0	1.0
4. Transit Operations	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.0	3.0	1.0	1.0
5. Policy Agnostic	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 16: Policy focus and associated levels of importance (weights) for scoring components.

The final score to be weighted under each policy focus is the sum of the standardized scores for each metric (the ratio of the corresponding score component from the user submission to that of the business as usual case). The composite scoring function is as follows:

$$\Phi_{policy,n}\left(C_s, \mathbb{P}_n = \left(\vec{z}, \vec{\beta_n}\right)\right) = \frac{\sum_{\{z_i,\beta_{n,i}\}\in\mathbb{P}_n} \beta_{n,i} \cdot z_i}{\sum_{\{\beta_{n,i}\}\in\mathbb{P}_n} \beta_{n,i}} \tag{4}$$

where $\vec{z}$ is the vector parameter of z-scores for score components (computed as defined in Equation (1)), while $\vec{\beta_n}$ is the vector of weight values under policy focus n for each of the score components i.



A: Accessibility: number of secondary locations accessible by car within 15 minutes
B: Accessibility: number of secondary locations accessible by transit within 15 minutes
C: Accessibility: number of work locations accessible by car within 15 minutes
D: Accessibility: number of work locations accessible by transit within 15 minutes
E: Congestion: average vehicle delay per passenger trip
F: Congestion: total vehicle miles traveled
G: Equity: average travel cost burden - secondary
H: Equity: average travel cost burden - work
I: Level of service: average bus crowding experienced
J: Level of service: costs and benefits
K: Sustainability: Total grams GHGe Emissions
L: Sustainability: Total grams PM 2.5 Emitted

Figure 3: Score components for "VMT Reducing" scenario (4) and "Transit Operating Cost Inefficient" scenario (5) reweighted per policy alternatives in Table 16.

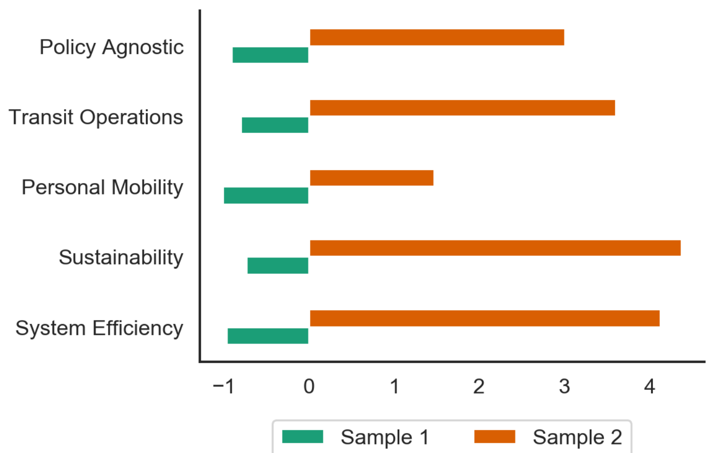


Figure 4: Total submission scores for all policies for "VMT Reducing" scenario (4) and "Transit Operating Cost Inefficient" scenario (5).

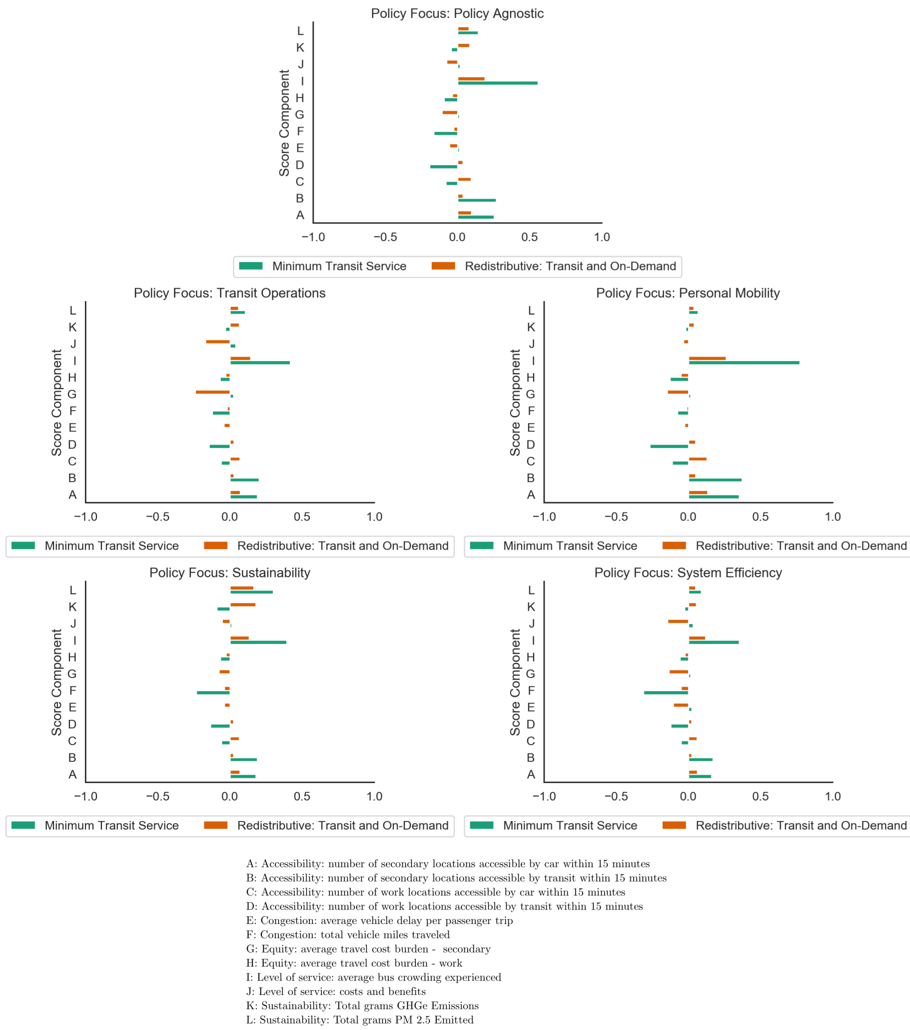


Figure 5: Score components for the Minimum Transit Service and Redistributive Incentives scenarios re-weighted per policy alternatives in Table 16.

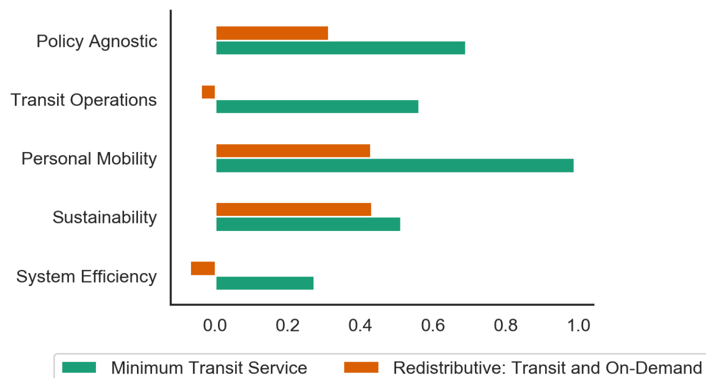


Figure 6: Total submission scores for all policies for Minimum Transit Service and Redistributive Incentives scenarios.

7 Output analysis

The outputs of calibrated simulations of transportation systems allow stakeholders of BISTRO to better understand the implications of proposals identified using optimization algorithms. For example, visualizations of congested roadways with millions of agents behaving independently can provide a concise method to communicate the effects of infrastructure interventions. To help users with the interpretation of these outputs, the BISTRO platform provides a suite of tools that parse the raw output from BEAM simulation runs and facilitate multi-variate analysis and visualization.

7.1 Data Generation for visualization

The *parser* processes the raw outputs of a BEAM simulation run into a collection of tables in the structure of a relational database. An easy-to-use Jupyter notebook template is provided that imports six primary table that can be used for complete analysis of the results of any simulation run: `Household`, `Person`, `Activity`, `Trip`, `Leg`, `PathTraversal` (see 7). All tables can be linked together by one of two common variables: the `personID` or the `vehicleID`. The `Person` table includes the personal attributes of each agent (*e.g.*, her `householdId`, age, sex and income), identified by her unique `personId`. Similarly, the `Household` table defines the household attributes as well as the home location of the household. The `Activity` table defines the characteristics of each planned activity (*e.g.*, its location, desired start time, duration, desired end time). While the `Person`, `Household`, and `Activity` tables are fixed for a particular scenario, the following three tables (the `Trip`, `Leg`, and `PathTraversal` tables) are generated after each simulation run and thus are identified uniquely by a combination of the simulation run and other key attributes. The `Trip` and `Leg` tables describe agent movements. During the simulation, person agents make one or more `tours` of travel to sequential activities, starting and ending each tour at home. Each `trip` in a tour represents travel from one activity to the next. Trips may consist of one or more `legs` of travel, each using a particular `mode` of transportation. Finally, the `PathTraversal` table describes the vehicle movements and their features (*e.g.*, `driverId`, number of passengers, distance, fuel consumed, etc.).

7.2 Content of the visualization notebook

The *visualization notebook* helps users to understand the concrete impacts of a set of policy inputs on the transportation network. To visualize the inputs, the outputs and the KPIs of their simulation, as well as understand their impact on their final scores, a visualization tool (`visualization.py`) was made available in the `/utilities` folder of the `BISTRO-Starter-Kit GitHub` repository. Via the `Visualization.ipynb` notebook

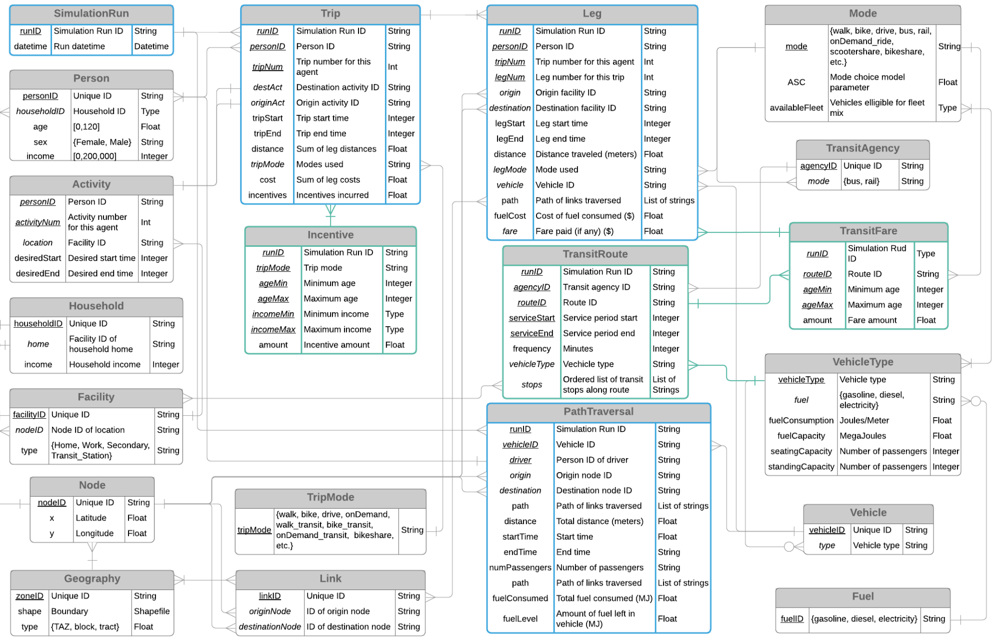


Figure 7: BISTRO output database entity-relationship diagram. Each entity is identified by a unique primary key (underlined) made up of one or more attributes. Primary keys may include foreign keys (italicized), or attributes that uniquely identify another entity. All entities shown in grey are fixed across simulation runs for a given scenario. Entities highlighted in green are example BISTRO inputs. Entities highlighted in blue are simulation outputs. Thus, the physical entities (`Geography`, `Node`, `Link`, and `Facility`), transportation mode-defining entities (`VehicleType`, `Fuel`, `TransitAgency`, `Mode`, and `TripMode`), and population-defining entities (`Household`, `Person`, and their `Activity`) do not change across simulation runs. Each `SimulationRun` produces unique travel behaviors (`Trip`, `Leg`, and `PathTraversals`). The inputs defined for each `SimulationRun` may influence travel behavior through the pathways highlighted in green.

located in the `/examples` folder, users can generate a list of graphs describing metrics in the following fields:

1. Inputs
   (a) Vehicle fleet mix

    (b) Mass transit fare
    (c) Mode incentives
    (d) Mass Transit Frequency Adjustment

2. Scores
    (a) Weighted subscores and submission score

3. Mode choice (= modal split)
    (a) Overall mode choice - Agent's preferences (initial agent's plan when leaving from his origin)
    (b) Overall mode choice - Level of service (realized agent's plan to go from his origin to his destination)
    (c) Mode Choice by hour of the day
    (d) Mode Choice per income group
    (e) Mode Choice per age group
    (f) Mode Choice by Trip Distance

4. Accessibility
    (a) Number of work activity facilities reachable from each network node within 15 minutes
    (b) Number of secondary activity facilities reachable from each network node within 15 minutes

5. Level of service
    (a) Average agent's travel expenditure per trip (per mode and by hour of the day)
    (b) Average Hours of Bus crowding per bus route (by period of the day)

6. Congestion
    (a) Average trip travel time per mode over the day
    (b) Average trip travel time per mode by hour of the day
    (c) Total miles traveled per mode over the day
    (d) Bus vehicle miles traveled per bus occupancy state by hour of the day
    (e) On-demand ride vehicle miles traveled per occupancy state by hour of the day
    (f) Average travel speed per passenger trip per mode by hours of the day

7. Financial sustainability
   (a) Distribution of costs and benefits of Mass Transit Agencies by bus route
   (b) Total incentives distributed per mode by hours of the day
8. Environmental Sustainability
   (a) Daily PM2.5 emissions by mode

Explanations on how to interpret each of the graphs mentioned above can be found in the `Cheat Sheet - Interpretation of the visualization` document located in the GitHub repository.