Uber Prize: Sioux Faux Problem Statement

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Contents

1 Introduction **3**

2 Background **3**
2.1 Related work 3
2.1.1 Nomenclature 3
2.2 Agent-Based Simulation 4
2.3 BISTRO 4
2.4 Sioux Faux 5
2.4.1 Population synthesis 5
2.4.2 Daily Activity-Travel Plan Synthesis 5
2.4.3 Transportation network configuration 5
2.4.4 Vehicle routing 6
2.4.5 On-Demand ride service operations 6
2.4.6 Mode choice modeling 7

3 Task Description **9**
3.1 Mass transit operations 9
3.2 Transit and on-demand ride incentives 9

4 Evaluation and Scoring **10**
4.1 Vehicle movement output 10
4.2 Person trip output 10
4.3 Scoring criteria 11
4.3.1 Accessibility 11
4.3.2 Level of Service 12
4.3.3 Congestion 13
4.3.4 Costs and Benefits of Mass Transit Level of Service Intervention 13
4.3.5 Sustainability 13

5 Scoring Function Specification **14**
5.1 Input Variable Specification 14
5.1.1 Network and fleet configuration 14
5.1.2 Population configuration 15
5.1.3 Contestant-defined input 16
5.1.4 Person agent output 17
5.1.5 Vehicle output 18
5.2 Scoring Functions 19
5.2.1 Accessibility 19
5.2.2 Measures of Level of Service 19
5.2.3 Measures of Congestion 20
5.2.4 Costs and Benefits of Mass Transit Level of Service Intervention 21
5.2.5 Measures of Sustainability 21
5.3 Composite Score 22

6 Appendix A: Variable Specification **23**
6.1 Notation 23

7 Appendix B: Input Variable Values (WORK IN PROGRESS) **23**

1 Introduction

The inaugural *Uber Prize* 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.

Uber Prize contestants will 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, congestion, and sustainability.

The first round of the Uber Prize challenges contestants to optimize the transportation network of a benchmark city: Sioux Faux. The city's 157,000 citizens travel between activities using either their personal automobiles, buses provided vie a mass transit system, on-demand rides, walking, or a combination of multiple modes in accordance with their preferences. Considering the overall transportation system costs and revenues in Sioux Faux, contestants will compete to produce the best outcomes given the trade-offs between the metrics defined above.

2 Background

2.1 Related work

As the 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 agencies (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 the *Uber Prize* is to provide a platform on which contestants 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.

2.1.1 Nomenclature

To provide a usable working definition and to remain as consistent as possible with current academic[3] and industry[4] literature practices, for the purposes of the *Uber Prize*, on-demand for-hire automobility services are referred to in the following ways below:

- **On-demand rides** refer to the private use of a for-hire automobile (in which the user is being driven by a another individual), usually booked via an online platform or mobile app. While the number of riders and number of stops can vary, the trip is booked and controlled by one individual. Such modes have also been referred to as sequentially shared.

  To remain consistent with model configuration, technical documentation may refer to on-demand rides as **ridehailing**.

- **On-demand pooled rides** refer to the shared or pooled use of a for-hire automobile, usually booked via an online platform or mobile app. This is distinguished from on-demand rides as the trip is shared

[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] For more information see: https://escholarship.org/uc/item/68g2h1qv#main
https://www.nap.edu/catalog/25020/private-transit-existing-services-and-emerging-directions
http://onlinepubs.trb.org/onlinepubs/sr/sr319AppendixA.pdf
https://escholarship.org/uc/item/46p6n2sk
[4] For more information see: http://apalosangeles.org/sidewalk-wars-the-infrastructure-of-micro-mobility/
https://www.populus.ai/micro-mobility-2018-july

between multiple users who have each booked their own ride. Such modes have also been referred to as concurrently shared.

Other forms of shared automobility, such as carpooling, incidental pooling (or casual carpooling), and ridesharing (or vanpooling)–which typically do not involve the repeated use of an online platform or mobile app–are not included with on-demand rides.

2.2 Agent-Based Simulation

Agent-based simulation 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 sociodemographically heterogeneous population of citizens on a virtual representation of physical road networks.[5] 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 *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.[6] 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. Link travel data is gathered from repeated iterations of the simulation

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 the engine through which the *Uber Prize* will be run. BISTRO is an analysis and evaluation superlayer that works in concert with an

[5] While the population and its plans are synthetic, econometric modelling 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.

[6] For more information about mode choice models, see: https://eml.berkeley.edu/books/choice2.html

agent-based simulation (BEAM) to enable the open-sourced development and evaluation of transportation optimization methods in response to given policy priorities.

2.4 Sioux Faux

This round of the *Uber Prize* challenges contestants to use ABS to optimize the transportation network of the benchmark city Sioux Faux. Like many cities around the world, Sioux Faux is urbanizing rapidly. All of this growth has led to a precipitous rise in congestion. Roads that were once pathways to jobs and opportunity are now clogged with idling vehicles polluting the air. Fauxians are in need of improved mobility– particularly given the population expansion predicted to take place over the next two decades. The city has put out a call for support, and is engaging the foremost minds in the fields of transportation and data science to help them understand the problem, explore solutions, and set this booming metropolis back on the path to sustainable growth!

2.4.1 Population synthesis

In order to simulate the activity and travel behavior of the citizens of Sioux Faux, a population of virtual agents and households was generated such that the sociodemographic attributes of these virtual entities are spatially distributed in accordance with real-world census data. In order to provide realistic distributions of household and individual attributes for Sioux Faux, we expanded publicly-available survey data for the city of Sioux Falls, South Dakota[7].

In practice, we use the Doppelganger library[8], a state-of-the-art population synthesis framework developed in Python. Specific inputs to Doppelganger used to generate the Sioux Faux population included household and individual Public Use Microdata Sample (PUMS) data for South Dakota from the 2012-2016 (5-year) American Community Survey (ACS), which is conducted annually by the US Census [9]. The Public Use Microdata Area (PUMA) for Sioux Falls constrains the state-wide survey data to our general area of interest. The PUMS data as well as a set of configurable parameters are used to train a set of Bayesian networks, which are structured such that drawing samples from these networks reproduces empirically-observed relationships between attributes that define household and individuals. The population-level characteristics of synthetic agents and households are further constrained using convex optimization to match summary statistics (also known as *marginals*) from other census data aggregates for the Sioux Falls PUMA. Household attributes that acted as controls in the allocation optimization algorithm included size of household (number of residents), number of vehicles per households, and household income. Similarly, individual marginals included age, gender, and income.

2.4.2 Daily Activity-Travel Plan Synthesis

An existing set of agent plans for Sioux Falls developed for MATSim simulations was used as the basis for our expanded Sioux Faux population For more information on the Sioux Falls scenario, see `https://www.ethz.ch/content/dam/ethz/special-interest/baug/ivt/ivt-dam/vpl/reports/901-1000/ab978.pdf`. After initial pilot runs and evaluations to determine trade-offs between population size, behavioral realism, and computational complexity, we took a 15% sub-sample of the full synthetic population (approximately 15,000 agents). We used a spatially-constrained sampling mechanism in order to allocate plans to agents in accordance with household locations and census tract household and individual attribute distributions. The subsampling mechanism also enforces logical assumptions such as "agents under the age of 18 should not have a work activity" and "agents under the age of 16 should not be allowed to drive".

2.4.3 Transportation network configuration

The transportation network for Sioux Faux is derived from the Open Street Maps (OSM) data regarding the street network of Sioux Falls, North Dakota. The data provides the configuration of the road network in

[7]The so-called "Sioux Falls" scenario has often been used as a benchmark in agent-based simulation research, hence its use in the initial phase of the *Uber Prize*, see `https://github.com/bstabler/TransportationNetworks/tree/master/SiouxFalls`

[8] For more information about the Doppelganger library, see `https://github.com/sidewalklabs/doppelganger`

[9]The 5-year PUMS comprises a 5% sample of the US population. It is computed as an aggregate of 1-year samples, which themselves aim to survey 1% of the US population

the form of links (road segments) and nodes, which are encoded as a directed graph in BEAM. The physical dynamics of each link are determined based on the road type classification provided by the OSM data (see Table 1). These include the length (in meters), the number of lanes per direction, the free-flow travel speed, and capacity of each lane for every link [10].

The information regarding the bus routes in Sioux Faux is presented in the Generalized Transit Feed Specification (GTFS) format. GTFS characterizes scheduled transit movements (as visible riders) in a standardized fashion, using linked text files to encode agency operation characteristics such as transit stops, routes, trips, fares, and other schedule data. GTFS can also accommodate frequency-based dispatching as opposed to scheduled arrival and departure times from stops; for more information on this type of dispatching, refer to Section 3 of the Starter Kit Input Schema.

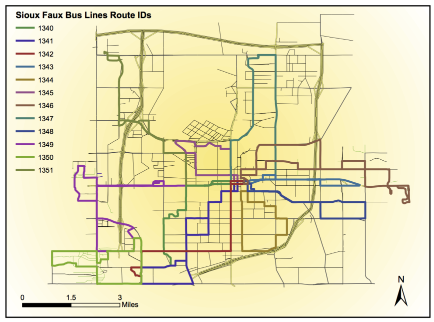

Figure 1: Map of the Sioux Faux Bus Lines (SFBL) Routes

2.4.4 Vehicle routing

BEAM uses the R5 routing engine to accomplish multimodal routing. Agents' trip requests are input to the router, which computes the shortest path for the corresponding mode(s) available to the agent for the trip [11]. The results of the routing calculation are then transformed into objects that are used as inputs to the mode choice model, described in the following subsection.

2.4.5 On-Demand ride service operations

On-demand ride service is delivered by a population of on-demand ride vehicles that are randomly distributed at the start of a simulation run. On-demand ride vehicles undergo three phases of service:

1. empty: the vehicle is not carrying a passenger and is available to be reserved for service; if moving, the vehicle is repositioning to a location of anticipated demand;

2. fetch: the vehicle is reserved and is en-route to pickup a passenger;

3. fare: a passenger is in the vehicle traveling to its requested destination.

The price of on-demand rides is fixed, consisting of a distance-based and a duration-based component. On-demand rides cannot be shared across multiple trips in the Sioux Faux scenario.

[10] The values of the parameters used for each link classification type can be found in the MATSim documentation, see `https://github.com/matsim-org/matsim/blob/0.10.x/matsim/src/main/java/org/matsim/core/utils/io/OsmNetworkReader.java`

[11] For detailed information about the R5 router, see `https://github.com/conveyal/r5` and `https://doi.org/10.3141/2653-06`

2.4.6 Mode choice modeling

Discrete choice modeling is a probabilistic technique to predict the choices of users between a finite number of two or more orthogonal (or mutually exclusive) alternatives, among other applications. Discrete choice has its roots in utility theory, and in general, discrete choice models can vary based upon functional form, the ways in which individual and alternative characteristics are modeled, and the ways in which stochasticity is handled.

In transportation, discrete choice models are often used to explain, predict, and analyze user decisions regarding what mode of transportation to utilize, hence the name mode choice model.[12] One prevalent example is multinomial logit modeling (MNL), which models the decision of individuals between a set of greater than two mode choice alternatives, assuming that the alternatives are not correlated. In MNL, each individual $n \in N$ is assigned a probability of choosing a mode $i \in J$ between an exhaustive set of alternatives $j \in J$ (i.e., an individual cannot choose something outside the set). The probability is represented as follows:

$$P_{ni} \equiv \Pr(\text{Person n chooses alternative i}) = G(x_{ni}, x_{nj,j\neq i}, s_n, \beta)$$

where:

- x_{ni} is a vector of attributes of alternative i
- $x_{nj,j\neq i}$ is a vector of attributes of all other alternatives
- s_n is a vector of characteristics (e.g., demographics, value of time, etc.) of person n
- β is a set of parameters delineating the effects of the attributes on choice probabilities, which are estimated statistically

Each individual has a utility function which characterizes the welfare resulting from making a mode choice decision. Individuals are assumed to be utility maximizing–they will choose the alternative with the highest expected utility, given their attributes and the attributes of each alternative. The utility functions have the form:

$$U_{ni} = \beta z_{ni} + \epsilon_{ni}$$

where:

- U_{ni} is the utility associated with choosing alternative i
- β is a vector of coefficients corresponding to observed variables related to alternative i and person n
- z_{ni} is a vector of observed variables for alternative i and person n that may depend on x_{ni}, and/or s_n
- ϵ_{ni} is an error term that captures the influence of unobserved factors that affect person n's utility from choosing alternative i. For the purposes of MNL, ϵ_{ni} is assumed to be independently and identically distributed (iid) following the extreme value distribution.

The probability the person n chooses alternative i, in this case, can be calculated in the following way:

$$P_{ni} = \frac{\exp(\beta z_{ni})}{\sum_{j=1}^{J} \exp(\beta z_{nj})}$$

This type of formulation is sometimes referred to as the Softmax function. The probabilities for every alternative $i, j \in J$ must sum to 1, and it is assumed that every person n chooses the alternative with the highest associated probability.

The parameters used for the MNL model within BEAM, and thus BISTRO, are shown below in Table 1.

[12] Pioneering work in the field of mode choice modeling has been done by Kenneth Train, Daniel McFadden, and Moshe Ben-Akiva, among others.

Description	Variable Type	Value
Value of Time	$s_{n_{VOT}}$	18 [$/hr]
Transfer Coefficient	$\beta_{transfer}$	-0.6
Car Coefficient	β_{car}	10.562
Walk to Transit Coefficient	$\beta_{walk-transit}$	-10.0
Drive to Transit Coefficient	$\beta_{drive-transit}$	0
On-demand Ride to Transit Coefficient	$\beta_{on-demand-ride-transit}$	-0.124
On-demand Ride Coefficient	$\beta_{on-demand-ride}$	0.00
Walk Coefficient	β_{walk}	-11.0

Table 1: Mode Choice Parameters

Figure 2 displays the mode share in the business as usual scenario of Sioux Faux.

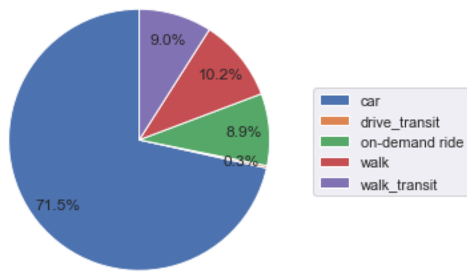

Figure 2: Mode Share for the Sioux Faux BAU Scenario

3 Task Description

In Phase 1, contestants are tasked with assisting the *Sioux Faux Department of Transportation* (SFDOT) to reduce congestion and improve overall mobility in Sioux Faux using an agent-based simulation of the city's transportation demand. The suite of inputs under contestants' control represent possible city-wide policies regarding transportation: policies that control *operational* and *financial* aspects of mass transit as well as *incentives* that influence the use of mass transit and on-demand ride services. Representatives from SFDOT have provided *guidelines* and *evaluation metrics* for the policies under consideration.

A fully specified transportation policy consists of a set of *contestant-defined input variables*: mass transit vehicle fleet composition, mass transit service frequency, and the details of a newly agreed upon partnership between Sioux Faux Bus Lines and on-demand ride service providers operating within the city boundaries that provides incentives for on-demand ride and transit trips.

Solutions will be evaluated based on a scoring function that weights performance measures computed from the simulation outputs, including measures of accessibility and the level of service of the transportation network, congestion, and the net costs to the SFDOT. The scoring and evaluation criteria are detailed in 4.

3.1 Mass transit operations

SFDOT is exploring the possibility of providing *Sioux Faux Bus Lines* (SFBL) with additional funding to improve the operations of existing bus services. As the highest-capacity transportation option available in Sioux Faux, mass transit offers an efficient means by which to service travel along corridors under high demand. Unfortunately, the *mode share* of mass transit in Sioux Faux is rather low, at about four percent. According to a user survey, travelers avoid mass transit due to a perceived lack of control over departure timing (both in frequency and variability), habit or inertia that induces automobile dependency, as well as indicators of comfort such as crowding.

Currently, SFBL operates a small fleet of buses on 12 routes in Sioux Faux. Contestants may impact the level of service provided by the bus system by modifying the transit vehicle fleet composition, altering the bus route headways (service frequencies), and impacting the fares of existing bus routes by altering the fares and/or providing incentives for transit use by particular demographic groups.

Contestants will tune the parameters listed below:

1. **Vehicle fleet composition:** originally purchased as a group, each bus currently in the SFBL fleet possesses identical attributes of seating capacity, fuel consumption, operations and maintenance cost, etc. SFBL is considering optimizing bus type in order to improve the level of bus service by better matching the specific demand characteristics of each route. Four types of buses are available from its supplier, each of them with different technical properties and cost characteristics. Contestants may choose to purchase additional vehicles to include in the bus fleet for any of the existing bus routes, specifying which vehicle types are to be used for each route.

2. **Route schedules:** a bus route schedule is determined by the hours of service, or the *service period*, and the *headway*, or time between vehicles traveling along the route. At the start of a service period of a route, a bus is dispatched from the route origin to travel a predefined route between stops. An additional bus departs from the origin after each interval of time defined by the route headway. Contestants may choose to define multiple service periods for each route, each with varying headways. The number of buses used to service a route will be dependent on the headways across all service periods, thus requiring contestants to co-optimize the vehicle fleet compositio with route scheduling.

3. **Transit fares:** contestants may alter the *fare*, or cost to a passenger of traveling on a particular transit route. Passengers pay one flat fare each time they board a bus. Contestants may choose to alter the fare for any of the SFBL routes and may choose to segment the fares based on passenger age groups.

3.2 Transit and on-demand ride incentives

In an effort to provide a viable alternative to private automobiles for as wide a population as possible, SFBL is considering providing incentives to promote mass transit in Sioux Faux. SFBL is exploring options for citizens lacking access to quality transit or means to pay fares, including defraying the cost of certain qualified transit trips and/or on-demand rides. While the exact details of the incentives are yet to be determined, SFBL staff are keenly interested in seeing the trade-offs between service provision, operational costs, Fauxian mobility, and sustainability.

In order to specify the incentive policy, contestants will use a structure that provides reimbursement to qualifying individuals based on age and income. Contestants may choose to defray the cost of on-demand rides and/or transit based on either age group, income group, or both. To do so, the range of qualifying socio-demographic characteristics and value of the incentive provided to each group must be defined for passengers using each of the following modes of transportation to complete a trip: on-demand rides, walk to/from transit, or drive to/from transit.

4 Evaluation and Scoring

Solutions will be 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 judging criteria are derived from a discrete set of output variables produced for each simulation run.

Each simulation run takes as input a set of configuration and contestant-defined input variables. The configuration variables 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 may not be altered in any way by the challenge contestants.

The contestant-defined inputs specify the type of vehicles to be added to the bus fleet, the assignment of vehicle types to specific routes in the SFBL service, the headway, service periods, and fare of each route, and finally, transit and on-demand ride incentive policies.

The outputs of the simulation produced by contestants' solutions will determine the values of key performance metrics of the impact of the solutions on the accessibility, level of service, and congestion of the transportation network in Sioux Faux, as well as the resource constraints and environmental sustainability of the resulting network-wide travel equilibrium.

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

4.1 Vehicle movement 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.

4.2 Person trip 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 car, on-demand ride, bus, walk to/from transit, drive to/from bus, and walk to/from bus.
   (b) **mode choice:** the mode chosen for each trip, as determined by the process described in **??**

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) Mass transit fares
   (b) On-demand ride fares
   (c) applicable incentives
4. **Incentives:** the amount of monetary incentive available (based on the modes available) for each leg of a trip and the amount of incentive consumed by an agent during each leg of a 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 mutually exclusive categories: work trips and secondary trips.

4.3 Scoring criteria

The overall scoring function will appropriately weigh multiple aggregate measures of the the simulation outputs that evaluate system-wide accessibility, level of service, congestion, resource constraints, and sustainability. These five categories of criteria are all affected by the user-defined input variables, and care must be taken when optimizing to understand the interactions between metrics.

- There are three types of metrics: 1) those that involve system users only (e.g., incentives used, average travel expenditure), 2) those that involve users and the system (e.g., accessibility, delay), and 3) those that involve only the system (e.g. operational costs, revenue)
- We are treating these three types of metrics simultaneously and comparing the user-produced results to the BAU scenario
- This can be thought of similarly to a costs and benefits approach, however it differs from many transportation implementations as user and agency-specific scores can both be thought of as benefits, or costs, depending upon the metric.

4.3.1 Accessibility

While the term *accessibility* takes on a variety of meanings in different contexts, 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 will be quantified as the average number of points of interest (of a specific type of activity) reachable within a given duration of time. More specifically, during Phase 1 accessibility will be measured as the sum of the average number of points of interest reachable from network nodes by driving within a specified amount of time during the peak hour as shown below. During Phase 2, accessibility metrics will be calculated using a wider variety of modes.

1. **Work-based trips** The sum of the average number of work locations accessible from each node by automotive modes within 15 minutes during the AM peak (7-10 am) and PM peak (5-8 pm) periods.

2. **All other trips** The sum of the average number of secondary locations accessible from each node by automotive modes within 15 minutes during the AM peak (7-10 am) and PM peak (5-8 pm) periods.

Figures 3 and 4 display the accessibility for work-based and other trips, respectively, in the Sioux Faux BAU scenario.

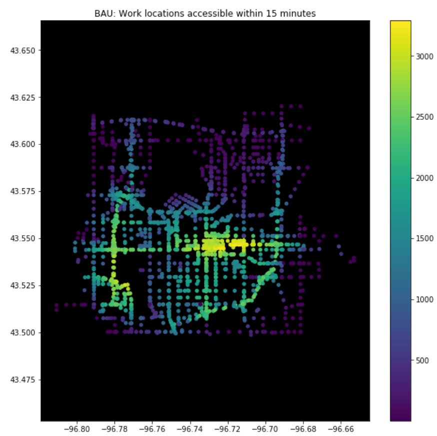

Figure 3: Accessibility to work locations in the Sioux Faux BAU scenario

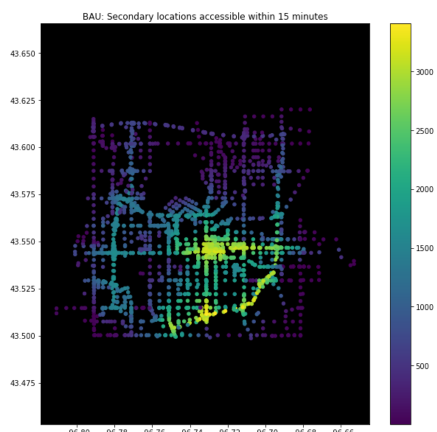

Figure 4: Accessibility to secondary locations in the Sioux Faux BAU scenario

4.3.2 Level of Service

The level of service provided by the transportation network will be evaluated by assessing the travel cost, wait times, and comfort - measured as crowding on transit vehicles. The level of service scoring criteria will be assessed on average, across all agent trips.

1. **Average Travel Expenditure**: the average over all trips of the total cost of travel incurred by all person agents during the simulation. Travel expenditures for a person agent trip are calculated as the sum of all bus fares, on-demand ride fares, and the cost of gas consumed subtracted by the total incentives received during the trip. Average travel expenditure will be assessed for work trips and secondary trips separately.

2. **Average Bus Crowding Experienced**: measured in agent hours, this is the average time spent per agent trip in buses occupied above their seating capacity.

4.3.3 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. **Total Vehicle Hours of Delay**: total hours of delay experienced by all motorized vehicles of the system during the simulation. Delay is measured as the difference between the free-flow travel time over the path of a vehicle movement and the actual duration of the movement in the simulation.

3. **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.

4.3.4 Costs and Benefits of Mass Transit Level of Service Intervention

The costs and benefits of mass transit interventions will be 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.

1. **Operational Costs**: total costs incurred by SFBL operations including the cost of fuel consumed, and hourly variable costs. The rates for each of these factors is specified in the vehicle configuration and will be known by contestants.

2. **Incentives Used**: total incentives used by agents.

3. **Revenue**: sum of total bus fares collected.

4.3.5 Sustainability

Sustainability metrics provide a sense of the local externalities resulting from any transportation interventions. Using criteria pollutants, specifically particulate matter running exhaust emission factors, presents a mileage-based measure of local air quality impacts based upon vehicle type. For more information on the methodology followed to develop this metric, please refer to the California Air Resources Board documentation [13].

1. **Particulate ($PM_{2.5}$) Emissions**: total $PM_{2.5}$ emissions produced by all motorized vehicles during the simulation.

[13] https://www.arb.ca.gov/cc/capandtrade/auctionproceeds/cci$_{e}mission factor database_{d}ocumentation.pdf?_{g}a$ $=$ $2.94247453.1690201828.1547860553 - 1364631033.1545190476$

5 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 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 contestant-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 Network and fleet configuration

Network and fleet characteristic variables are defined during the configuration of a simulation, and remain static for each scenario.

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.

The transit network configuration follows a General Transit Feed Specification (GTFS) format. The transit network is a subgraph of the road network comprised of a set of transit facilities (bus stops) $F \subset W$ and a set of T routes. The location of each bus stop, $f \in F$, is defined by the Boolean variable Z^f_w such that

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

The assignment of transit facilities to routes is defined by the Boolean variable $Z^f_{route,t}$ such that

$$Z^f_{route,t} = \begin{cases} 1 \text{ if bus stop } f \text{ is on bus route } t \\ 0 \text{ otherwise} \end{cases}$$

In the base case, the fare structure for SFBL is age-based and identical across all routes in the agency. The fares in the base case are defined by the set $Z_{fare} = \{Z_{fare,a}\}_{a=0,1,...,100}$ such that $Z_{fare,a}$ denotes the fare for passengers of age $a \in \{0, 1, \dots, 100\}$.

Each route $t \in \{1, 2, ..T\}$ is defined by an ordered set of p_t links, $Z^t_{path} = \{z^t_l\}_{l\in\{1,2,...,p_t\}}$. The schedules for each bus route are defined by the GTFS input, which provides the headway, $Z^t_{headway}$, and the set of all trips, $Z^t_{trips} \in \mathbb{R}^{r_t}$, to be completed for each route. For the purposes of this phase of the *Uber Prize*, each trip on a particular bus route is assigned to a unique bus id. Thus, we denote the set of all buses to be used on route t as $V_{bus,t} \in \mathbb{R}^{r_t}$, and the set of all buses in the base case as $V_{bus} = \cup^T_{t=1} V_{bus,t} \in \mathbb{R}^{Tr_t}$. Each bus, $v \in V_{bus,t}$, is given a start and end time (in seconds from the start of the simulation) for servicing the corresponding route, t, $Z^v_{start-time}$ and $Z^v_{end-time}$, respectively. Thus, the configured service period for each route, t, is the tuple $(Z^t_{start-time}, Z^t_{end-time})$ where $Z^t_{start-time}$ corresponds to the start time of the bus making the first trip on the route and $Z^t_{end-time}$ corresponds to the end time of the bus making the last trip on the route.

The set of all vehicles, V, is comprised of the union of the set of privately owned vehicles, $V_{private}$, 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 contestant-defined input. However, the number of vehicles in the bus fleet is dependent on the service periods and headways for each route, which can be altered by contestants. The type of vehicles in the transit fleet may also be altered by the contestants.

Across all vehicles, the set of possible vehicle types is the set C. Each vehicle type, $c \in C$, is defined by a seating and standing capacity (in number of person agents), $Z^c_{seating}$ and $Z^c_{standing}$, a fuel type, $Z^c_{fuel-type}$, fuel consumption rate (in units of fuel consumed per mile), $Z^c_{fuel-consumption}$, and a variable operational cost (in dollars per hour traveled), $V^c_{var-op-cost}$. The set of fuel types in this phase of the *Uber Prize* is $F = \{gasoline, diesel\}$. For each fuel type, $f \in F$, $Z^f_{fuel-cost}$ defines the cost of consumption (in dollars per unit of fuel consumed). Finally, each vehicle is defined by a Boolean variable denoting its compatibility to each of the available modes of transportation, $m \in M$.

$$Z^c_{compatibility,m} = \begin{cases} 1 \text{ if vehicle type } c \text{ is compatible with mode } m \\ 0 \text{ otherwise} \end{cases}$$

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_h, defined in the following subsection.

5.1.2 Population configuration

At the start of the simulation, a synthetic population is generated as described in 2.4.1. 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_h denotes whether vehicle $v \in V_{private}$ is owned by household h such that

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

Each person agent in the population, $n \in N$, is a member of one household, denoted by the Boolean identifier $N^n_{household,h}$, with home location denoted by $N^h_{home} \in W$ such that

$$N^n_{hhd,h} = \begin{cases} 1 \text{ if agent } n \text{ is a member of household } h \in H \\ 0 \text{ otherwise} \end{cases}$$

Additionally, each person agent is assigned fixed socio-demographic attributes, denoted by Boolean identifiers. These include variables identifying age, $N^n_{age,a}$, gender, $N^n_{gender,g}$, and income, $N^n_{income,i}$ such that

$$N^n_{age,a} = \begin{cases} 1 \text{ if agent } n \text{ is of age } a \in \{0, 1, \ldots, 100\} \\ 0 \text{ otherwise} \end{cases}$$

$$N^n_{gender,g} = \begin{cases} 1 \text{ if agent } n \text{ is of gender } g \in \{\text{female, male, other}\} \\ 0 \text{ otherwise} \end{cases}$$

$$N^n_{income,i} = \begin{cases} 1 \text{ if individual } n \text{ is in the income group } i \in I \\ 0 \text{ otherwise} \end{cases}$$

where H is the set of all households and $I = \{$no income, less than \$10,000, \$10,000 to \$24,999, \$25,000 to \$49,999, \$50,000 to \$74,999, \$75,000 to \$99,999, \$100,000 and above$\}$.

Finally, each person is instantiated with a plan, N^n_{plan}, which is an ordered set of activities starting and ending at home. During this phase of the *Uber Prize*, plans will be simplified, with just one activity outside of the home. Thus, all agents have a plan of the form

$$N^n_{plan} = \{home, N^n_{primary-activity}, home\}$$

where $N^n_{primary-activity} \in \{\text{work, secondary}\}$. 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 Contestant-defined input

As described in section 3, contestants may redefine the transit vehicle fleet composition, bus service schedules, and fares, as well as incentive amounts for particular demographic groups to use bus and/or on-demand ride services.

In the base case, the bus fleet is homogeneous, with all vehicles in the fleet configured with the same vehicle type:

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

Contestants 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 t. Thus

$$D^t_{veh-type,c} = D^v_{veh-type,c} = D^{v'}_{veh-type,c} \ \forall v, v' \in V_{bus,t}, c \in C$$

Contestants may redefine the service period of a bus route by appending one or more tuples to the mutable, ordered array of tuples, $D^t_{service-period}$, corresponding to the bus route t. Thus, a bus route with s contestant-defined service periods is of the form:

$$D^t_{service-period} = \{(D^t_{start,1}, D^t_{end,1}), (D^t_{start,2}, D^t_{end,2}), \ldots (D^t_{start,s}, D^t_{end,s})\}$$

where

$$D^t_{start,i} > D^t_{end,i} \ \forall i = 1, 2, \ldots s$$

and

$$D^t_{end,i} \geq D^t_{start,i+1} \ \forall i = 1, 2, \ldots s - 1$$

Contestants may redefine the headway of a route using the ordered array of s variables, $D^t_{headway} = \{D^t_{headway,i}\}_{i=1,2,\ldots,s}$, corresponding to each service period. All route headways must be greater than or equal to a minimum, $Z_{headway-min}$, defined in the network configuration.

The fare for riding on route t can be redefined by the set of contestant-defined variables, $D^t_{fare} = \{D^t_{fare,a}\}_{a=0,1,\ldots,100}$. All fares must be nonnegative.

Finally, contestants may choose to allocate incentives for on-demand ride, walk to/from bus, and/or drive to/from bus trips, using the variables

$$D^{on-demand}_{incentive} = \{D^{on-demand}_{incentive,a,i}\}_{a=0,1,\ldots,100;i \in I}$$

$$D^{walk-transit}_{incentive} = \{D^{walk-transit}_{incentive,a,i}\}_{a=0,1,\ldots,100;i \in I}$$

$$D^{drive-transit}_{incentive} = \{D^{drive-transit}_{incentive,a,i}\}_{a=0,1,\ldots,100;i \in I}$$

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

5.1.4 Person agent output

The person agent output reports the choices, movements, and expenditures of each person agent in the population during a simulation run. Since all plans in Sioux Faux consist of one activity outside of the home, each person agent, $n \in N$ takes $R_n \in \mathbb{R}^2$ trips during the simulation.

The mode(s) available to person agent n for trip $r \in R_n$ are output as a set of Booleans,

$$X^{n,r}_{available} = \{X^{n,r}_{available,m}\}_{m= \{\text{walk, car, on-demand, walk-bus, car-bus }\}}$$

where

$$X^{n,r}_{available,m} = \begin{cases} 1 \text{ if mode } m \text{ is available to person } n \text{ for trip } r \in R_n \\ 0 \text{ otherwise} \end{cases}$$

The mode ultimately chosen by the agent is output as a set of Booleans,

$$X^{n,r}_{choice} = \{X^{n,r}_{choice,m}\}_{m=\text{walk, car, on-demand, walk-bus, car-bus}}$$

where

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

Trips may include multiple legs. Thus, the number of legs, $G_{n,r}$, included in trip $r \in R_n$ of agent $n \in N$, is

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

Bus trips include an access and egress leg as well as one or more bus legs, depending on the use of one or more bus routes during the trip. The leg used during each leg is denoted by the Boolean

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

The output variable $X^{n,r,g}_{route} \in \{0, 1, 2, \ldots, T\}$ records the bus route used by agent n during leg g of trip r such that $X^{n,r,g}_{route} = 0$ if the agent did not use a bus during leg g.

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

$$X^{n,r,g}_{path} = \{X^{n,r,g}_{path,l}\}_{l \in \{1,2,\ldots,p_{n,r,g}\}}$$

where $X^{n,r,g}_{path,l} \in L$ is a link in the 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 a product of the mode use identifier, and the corresponding input variables denoting the applicable fare(s) for each leg and incentive(s) for the trip. The bus fare incurred by agent n during a trip leg is

$$X^{n,r,g}_{fare,bus} = X^{n,r,g}_{mode,bus} \sum_{a=0}^{100} N^{n}_{age,a} D^{X^{n,r,g}_{route}}_{fare,a}$$

The on-demand ride fare incurred by agent n during any trip leg is

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

The cost of fuel consumed by agent n during any trip leg is

$$X^{n,r,g}_{fuel-cost} = X^{n,r,g}_{mode,car} X^{n,r,g}_{distance} \sum_{h \in H} \sum_{v \in V_p rivate} \sum c \in C N^{n}_{hhd,h} Z^{v}_{h} Z^{v}_{veh-type,c} Z^{Z^{c}_{fuel-type}}_{fuel-consumption} Z^{Z^{c}_{fuel-type}}_{fuel-cost}$$

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

$$X^{n,r}_{incentive} = \sum_{a=0}^{100} \sum_{i \in I} N^{n}_{age,a} N^{n}_{income,i} (X^{n,r}_{choice,on-demand} D^{on-demand}_{incentive,a,i} + X^{n,r}_{choice,walk-bus} D^{walk-bus}_{incentive,a,i} + X^{n,r}_{choice,drive-bus} D^{drive-bus}_{incentive,a,i})$$

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

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

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 of the trip, the agent receives an incentive amount equal to the total fare(s) incurred.

5.1.5 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 (see **??**).

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,

$$Y^{v,q}_{path} = \{Y^{v,q}_{path,l}\}_{l \in \{1,2,...,p_{v,q}\}}$$

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

Thus, the distance traveled by vehicle v during movement q is given by:

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

The duration of the movement (in seconds) is recorded by the output variable $Y^{v,q}_{duration} \geq 0$, and the fuel consumed is:

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

Thus the cost of fuel consumed by vehicle v during movement q is

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

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

5.2 Scoring Functions

All scoring functions will be assessed in comparison to the corresponding measure in the base scenario; that is, the scenario without any inputs. The following sections detail each of the scoring functions included in the composite score, which is explained in section 5.3.

5.2.1 Accessibility

Accessibility measurements utilize the network resulting for any given submission (i.e., links $l \in L$ are weighted with average travel-times during 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 given mode within a specified amount of time. Pandana is used to aggregate over the network[14].

1. **Work-based trips:**

$$F_{accessibility,work} = \frac{1}{2\sum_{w \in W}} \sum_{p \in P} \sum_{i \in W} \sum_{j \in W} I_{primary-activity=work}[d_{ij} < \tau]_p$$

where d_{ij} is the *shortest path directed network distance* on $\mathcal{G}(L, W)$ from node i to node j as follows:

$$d_{ij} = \sum_{l \in L} l_{ij} \ travel - time_{lp}$$

where l_{ij} is a Boolean indicator regarding link l being on the shortest path from i to j:

$$l_{ij} = \begin{cases} 1 \text{ if } l \text{ is in } shortest - path_{ij} \\ 0 \text{ otherwise} \end{cases}$$

and

$travel - time_{lp}$ = The average link travel-time for each hour in the specified time period of interest, p

with the time periods of interest defined as:

- **Morning Peak** 7 to 10 am
- **Evening Peak** 5 to 8 pm

2. **Secondary trips:**...

5.2.2 Measures of Level of Service

The level of service of the transportation system will be evaluated on average, across person trips. Each person, $n \in N$ completes R_n trips from one activity to another throughout a simulation run. Each trip, $r \in R_n$ includes $G_{n,r}$ legs, each using a single mode of transportation.

1. **Average Travel Expenditure**: As detailed in 4.2:3, the total travel expenditure, $X^{n,r}_{exp}$, for a person agent, $n \in N$, during any trip, $r \in R_n$, may include bus and/or on-demand ride fares, and the cost of fuel consumed less any applicable incentives.

   We consider the average travel expenditure by trip purpose: work trips and secondary activity trips. Thus the average travel expenditure for work trips is

$$F_{expenditure,work} = \frac{1}{\sum_{n \in N} \sum_{r \in R_n} I_{(N^n_{primary-activity}=work)}} \sum_{n \in N} \sum_{r \in R_n} I_{(N^n_{primary-activity}=work)} X^{n,r}_{exp}$$

[14] For more information, see: https://udst.github.io/pandana/

where the Boolean indicator $I_{(N^n_{primary-activity}=work)}$ is defined as follows

$$I_{(N^n_{primary-activity}=work)} = \begin{cases} 1 \text{ if the primary activity of agent } n \text{ is work} \\ 0 \text{ otherwise} \end{cases}$$

Similarly, the average travel expenditure for secondary trips is

$$F_{expenditure,2ndary} = \frac{1}{\sum_{n\in N}\sum_{r\in R_n} I_{(N^n_{primary-activity}=secondary)}} \sum_{n\in N}\sum_{r\in R_n} I_{(N^n_{primary-activity}=secondary)} X^{n,r}_{exp}$$

2. **Average Bus Crowding Experienced**:

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

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

$$G_{bus} = \sum_{n\in N}\sum_{r\in R_n}\sum_{g=1}^{G_{n,r}} X^{n,r,g}_{mode,bus}$$

$I_{(Y^{v,q}_{pax} > Z^c_{seating})}$ indicates whether vehicle in the bus fleet $v \in V_{bus}$ is occupied above its seating capacity during movement q.

$$I_{(Y^{v,q}_{pax} > Z^c_{seating})} = \begin{cases} 1 \text{ if } Y^{v,q}_{pax} > Z^c_{seating} \\ 0 \text{ otherwise} \end{cases}$$

.

5.2.3 Measures of Congestion

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

1. **Total VMT**:

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

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**: ***In hours??

$$F_{pax-trip} = \frac{1}{\sum_{n\in N} R^{motorized}_n} \sum_{n\in N}\sum_{r\in R_n} \left(X^{r,n}_{duration} - \sum_{g=1}^{G_{n,r}} \sum_{l\in X^{n,r,g,}_{path}} \frac{Z^{X^{n,r,g}_{path,l}}_{length}}{Z^{X^{n,r,g}_{path,l}}_{speed-limit}} \right)$$

where $R^{motorized}_n$ indicates the number of trips taken by agent n using a motorized mode:

$$R^{motorized}_n = \sum_{r\in R_n} (X^{n,r}_{car} + X^{n,r}_{on-demand} + X^{n,r}_{walk-bus} + X^{n,r}_{car-bus})$$

5.2.4 Costs and Benefits of Mass Transit Level of Service Intervention

Any intervention on the transportation system is likely to result in costs and benefits for the operation of mass transit in Sioux Faux. The costs/benefit scoring component is computed as the difference between the total revenue collected through bus fares $F_{revenue}$ and the net cost of operation buses $F_{op-cost}$ and incentives used to encourage greater adoption of mass transit $F_{incentives-used}$:

$$F_{C/B} = F_{revenue} - (F_{op-cost} + F_{incentives-used})$$

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

$$F_{op-cost} = \sum_{c \in C} \sum_{v \in V_{transit} \cup V_{additional}} Z^{v}_{veh-type,c} \Big(\sum_{q \in Q_v} \frac{1}{3600} Y^{v,q}_{duration} Z^{c}_{var-cost} + Y^{v,q}_{fuel-consumed} Z^{c}_{fuel-cost} \Big)$$

where $Z^{v}_{veh-type,c}$ denotes the vehicle type,c, of vehicle, v, $X^{c}_{variable}$ is the variable hourly costs of operating a vehicle of type c, $Z^{c}_{fuel-cost}$ is the cost per unit of fuel consumed by vehicle type c, and $Y^{v,q}_{fuel-consumed}$ is the amount of fuel consumed by vehicle v during movement q.

2. **Incentives Used**

$$F_{incentives-used} = \sum_{n \in N} \sum_{r \in R_n} \Bigg(\sum_{g=1}^{G_{r,n}} (X^{n,r,g}_{mode,bus} X^{n}_{fare,bus} + X^{n,r,g}_{mode,drive} X^{n,r,g}_{fuel-cost} + X^{n,r,g}_{mode,on-demand} X^{n}_{fare,on-demand}) - X^{n,r}_{exp} \Bigg)$$

where $X^{n,r}_{exp}$ is the expenditure by agent n during tour leg r, $X^{n,r}_{exp} \geq 0$ as defined in section 5.1.4. Incentives may only be used by qualifying agents, as defined by contestant inputs.

3. **Revenue**:

$$F_{revenue} = \sum_{n \in N} \sum_{r \in R_n} \sum_{g \in G_{n,r}} X^{n,r,g}_{choice,bus} X^{n,r,g}_{fare}$$

where $X^{n,r,g}_{choice,bus}$ indicates that agent n chose to use the bus for leg g of trip r. $X^{n,r,g}_{fare}$ is the fare paid, and $X^{n,r,g}_{incentive}$ is the incentive amount received by agent n for leg g of trip r.

5.2.5 Measures of Sustainability

Sustainability will be assessed as the total particulate matter $PM_{2.5}$ running exhaust (RUNEX) emissions from all vehicle movements in a simulation run. $PM_{2.5}$ emissions vary by mode and by fuel type; in Phase 1 there are only two possible vehicle-fuel type combinations: gasoline auto and diesel bus, simplifying the summation to:

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

$$F_{sust} = \sum_{c \in C} \sum_{v \in V} \sum_{f \in F} \sum_{q=1}^{Q_v} Y^{v,q}_{distance} PM^{c,f}_{2.5}$$

where $Y^{v,q}_{distance}$ is the total distance (in miles) traveled by vehicle v during movement q and PM_c is defined as follows:

$$PM^{c,diesel}_{2.5} = \begin{cases} 0.259366648 \; grams/mile \text{ if } Z^{c}_{compatibility,bus} = 1 \\ 0.018403666 \; grams/mile \text{ if } Z^{c}_{compatibility,car} = 1 \text{ or } Z^{c}_{compatibility,on-demand} = 1 \\ 0 \text{ otherwise} \end{cases}$$

$$PM_{2.5}^{c,gas} = \begin{cases} 0.002517723 \; grams/mile \text{ if } Z^c_{compatibility,bus} = 1 \\ 0.001716086 \; grams/mile \text{ if } Z^c_{compatibility,car} = 1 \text{ or } Z^c_{compatibility,on-demand} = 1 \\ 0 \text{ otherwise} \end{cases}$$

5.3 Composite Score

The composite score is a function of the relative improvement in each of the scoring metrics achieved by contestant submissions.

$$\Phi\left(C_s, \mathbb{P} = \left(\vec{F}, \vec{\omega_F}, \vec{\tau_F}\right)\right) = \prod_{\{F,\omega,\tau\}\in\mathbb{P}} \left(\left(\frac{F(C_s)}{F(C_{BAU})}\right)^{\omega_F} \mathcal{H}\left(\operatorname{sgn}(\omega_F)\left(\frac{F(C_s)}{F(C_{BAU})} - \tau_F\right)\right)\right) - 1.$$

Where $\vec{F}$ is the vector of all scoring functions defined previously, including:

- accessibility to work-based trips,
- accessibility to all other trips,
- average travel expenditure per person agent trip,
- average bus crowding experienced per agent trip,
- total VMT,
- total vehicle hours of delay,
- average vehicle delay per agent trip,
- costs and benefits of mass transit LoS intervention,
- particulate matter emissions.

C_s and C_{BAU} are the sets of all scoring function parameters of a contestant submission and the business as usual scenario, respectively. Thus $F(C_s)$ and $F(C_{BAU})$ are the values of the metric vector for outputs of the submission and business as usual simulations, respectively. The parameters ω_F and τ_F represent the weights threshold of the metrics, respectively.

6 Appendix A: Variable Specification

6.1 Notation

· **H** households

· **N** individual agents

· **P** agent plans (tours)

· **S** types of activities

· **V** vehicles

· **C** vehicle types

· **M** transportation modes

· **T** transit routes

· **F** transit facilities (bus stops)

· **L** links

· **W** nodes

· **Z** geographic zones

7 Appendix B: Input Variable Values (WORK IN PROGRESS)

Route, t	**Service period**	**Headway**	**Fare(s)**
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			

Table 2: Bus Route Configuration

Fuel type, $\boldsymbol{f} \in \boldsymbol{F}$	**Fuel cost ($\boldsymbol{\$/MJoule}$)**
Gasoline	0.03
Diesel	0.02
Electricity	0.01
Biodiesel	0.01

Table 3: Fuel Types

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 4: Vehicle Types