Uber Prize Pilot Study: Sioux Faux

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1 Introduction

The inaugural Uber Prize harnesses advances in the machine learning and data science fields to facilitate data-driven transportation planning at scale, enabling city planners, academics, and others to analyze and adapt to rapidly evolving transportation realities.

Contestants will compete to develop a set of policies that bring about the greatest improvements across important indicators of transportation system performance while ensuring that the distributive impacts of the proposed policies support mobility and accessibility.

The first phase of the Uber Prize challenges contestants to optimize the transportation network of a mock city: Sioux Faux. The city's 157,000 citizens travel between activities using either their personal automobiles, public buses, on-demand ridehail services, active modes such as walking and bicyling, or a combination of multiple modes in accordance with their preferences. Utilizing the constrained transportation budget of Sioux Faux,contestants will compete to produce the best outcomes given the trade-offs among the metrics defined above.

1.1 Pilot Study Objectives

Prior to the launch of the first phase of the challenge, an internal pilot study is being conducted to pilot the Uber Prize. During the pilot study, the number of available parameters will be limited, as described in Section 2.3.

The goals of this exercise are to explore the solution space and to uncover any remaining bugs in the submission and evaluation processes. Specifically, we hope this round of testing achieves the following concrete objectives:

- How easy/difficult is it to on-board participants, and feel comfortable moving forward with a solution approach, given the starter kit and associated documentation?
  - Update documentation in response to comments.
- We are looking for optimization algorithms that explore the set of feasible solutions to the Sioux Faux scenario given the possible input variables and corresponding constraints.

  - We are not necessarily looking to generate the best solutions, but to assess the difficulty of the problem given the current dimensions of the input space
  - Ideally, we should also identify any obvious "cheats" and address them.

- Review feedback and user-generated reports to identify likely approaches/models.
- If an approach seems particularly worthwhile, then request that it be submitted as a "benchmark solution".

2 Background

2.1 Sioux Faux

Sioux Faux, like many cities around the world, is urbanizing. 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 Midwestern metropolis back on the path to sustainable growth!

2.2 Agent-Based Simulation

Agent-Based simulation, in the transportation world, is one method by which to evaluate the network-wide effects of modifications to a transportation system. Agent-based simulators synthesize the planned activities and transportation choices of socio-demographically heterogeneous populations and realize these plans on a virtual representation of physical road networks. 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.

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, agents make one or more *tours* of travel to sequential activities, starting and ending each tour at home. Each *leg* of a tour represents a trip from one activity to the next. 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 [1]. The simulator uses a realistic representation of the transportation

[1] For more information about mode choice models, see appendix...

network and a *routing algorithm* to determine the paths and travel speeds of *vehicles* as a function of the congestion in the network.

The inputs to one instance of the simulation include the configuration of the population, including agents' desired activity plans, the configuration of the transportation network, and any additional policies influencing the operation and/or cost of transportation services. Upon completion, a simulation run produces outputs of the actual paths and travel times realized by each agent and each vehicle, as well as a host of other data, further detailed in section 3. 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.

Furthermore, 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. Hyper-realistic 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 Task Description

During the pilot study, contestants are tasked with assisting the Sioux Faux Department of Transportation (SFDOT) to combat 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 city-wide policies regarding transportation: policies that control *operational* and *financial* aspects of public transit as well as *partnerships* that influence the use of ride-hail services. Representatives from SFDOT have provided *budgetary constraints* based upon their funding outlooks. Additionally, SFDOT may seek to examine the performance of the transportation policies against certain scenarios based upon their long-range plans.

For this challenge, a fully specified transportation policy consists of a set of *user-defined input variables*, including vehicle fleet compositions, possible transit trip frequency adjustments, and the details of a newly agreed upon partnership between Sioux Faux Bus Lines and on-demand ridehail providers operating within the city boundaries.

Solutions will be evaluated based on a scoring function that weighs performance measures computed from the simulation outputs, including measures of congestion, the level of service of the transportation network, and adherence to the SFDOT budget. The scoring and evaluation criteria are detailed in section

3.

2.3.1 Public 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, buses offer an efficient means by which to service travel along corridors under high demand. Unfortunately, commuters in Sioux Faux often avoid public 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.

Contestants may alter the operational efficiency of bus service by adjusting the mix of vehicles in the bus fleet; the fares of existing bus routes will remain fixed.

Contestants will tune the parameter listed below:

1. **Fleet mix:** the number and type of vehicles assigned to service each route. A limited number of vehicles will be available to choose from, varying in seating capacity, standing capacity, fixed and variable costs (e.g., energy efficiency, operations and maintenance costs, driver training, etc.). Contestants may choose to purchase additional vehicles to include in the bus fleet for any of the existing bus routes and may choose to sell any existing vehicles in the fleet for a pre-determined resale price, based on the age of the vehicle.

2.3.2 Transit incentives and ridehail partnership policy:

In an effort to provide a viable alternative to private automobiles to as wide a population as possible SFDOT is negotiating a partnership with ridehail operators in Sioux Faux. While the exact details of the agreement are yet to be determined, SFBL staff are keenly interested in seeing the trade-offs between service provision, operational costs, and Fauxian mobility and accessibility. Additionally, SFBL is exploring options for citizens lacking access to quality transit or means to pay fares, including defraying the cost of certain qualified transit and/or ridehailing trips.

In order to specify the partnership policy, contestants can explore a few opportunities based upon a structure that provides reimbursement to qualifying individuals. In this case, the socio-demographic variables, qualifying characteristics, and value of the subsidy must be defined. Contestants may choose to defray the cost of ridehail and/or transit based on any or all of these groups, up to a total amount constrained by SFDOT's budget.

For a given transit incentive and/or ridehail partnership to be considered valid, a most-expensive case will be assumed for cost estimation: the total subsidy needed for every qualifying agent trip will be taken into account independent of the actual choice in the simulation. Inputs with total subsidies that are found to exceed the allowable budget will be rejected as invalid prior to simulation execution. The scoring criteria will utilize the output results of both the actual subsidy amounts used, and the amounts unused.

Contestants will be able to develop incentives and partnerships of the following formats:

1. **Socio-demographic:** Three socio-demographic variables are candidates for elibigibility screening: age, individual income, and employment status (employed or unemployed). These variables can be used in isolation or in combination. Reimbursement-eligible ranges for each variable can be defined, as well as the associated subsidy for each included mode: transit and/or ridehail.

3 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 user-defined input variables. The configuration variables define the geographic and physical constraints of the transportation network, the characteristics of vehicles in the public, private, and ridehail 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 user-defined input specifies the number and type of vehicles to be added to the bus fleet, the assignment of buses to specific routes in the SFBL service, the headway of each route, and the transit incentives and ridehail partnership 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 congestion in Sioux Faux, the level of service of the transportation network, and the SFDOT budget.

The following subsections detail the relevant agent- and vehicle-level outputs and the scoring criteria used for evaluation.

3.1 Agent-level output

For each tour taken by an agent in the simulation, the following data is produced as output:

1. **Transportation mode(s):** For each leg of a tour, the agent chooses one of the modes available to them. 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 the agent to use for each leg of a tour, including: walk, personal car, ridehail, bus, walk to bus, drive to bus, walk from bus, and drive from bus.
   (b) **mode choice:** the mode(s) chosen for each leg of a tour.

2. **Travel time:** the time spent by the agent in the act of traveling during each leg of a tour. Travel time has several components, including:
   (a) **In-vehicle travel time:** time spent in a vehicle by an agent while traveling to an activity.
   (b) **Wait time:** 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 a ridehail vehicle after the ride has been reserved.
   (c) **Transfer time:** time spent walking from one transportation mode to another whilst traveling. Transfer time may include walking from the bus stop of one bus route to a bus stop of another bus route.

3. **Cost:** the cost incurred by an agent during a leg of a tour. Cost may include:
   (a) Bus fares
   (b) Ridehail fares
   (c) Cost of gas consumed
   (d) Tolls paid
   (e) Amortized cost of wear and tear incurred by the use of a personal vehicle

4. **Incentives:** the amount of monetary incentive available (based on the modes available) for each leg of a tour and the amount of incentive consumed by an agent during each leg of a tour.

5. **Trip purpose:** the nature of the activity to which an agent is traveling during a leg of a tour. Four types of trip purposes are considered: going to work, shopping, leisure or health-related activities, and finally going back home.

3.2 Vehicle-level 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 and the resulting level of fuel remaining in the vehicle after the movement.

4. **Vehicle occupancy:** the number of passengers in a vehicle during a movement.

5. **Vehicle service status**: for buses and ridehail vehicles, the service status of a vehicle during a movement. Vehicles may move while in service or out of service. Specifically, ridehail vehicles have three service types:

   (a) *empty*: the vehicle is not carrying a passenger and is available to be reserved for service; a vehicle movement that occurs while the vehicle is empty represents repositioning of the vehicle to a location of anticipated demand,

   (b) *fetch*: the vehicle is reserved and is en-route to pickup a passenger,

   (c) *fare*: a passenger is in the vehicle traveling to its requested destination.

3.3 Scoring criteria

The scoring function will appropriately weigh several aggregate measures of the the simulation outputs that evaluate system-wide congestion, level of service, and budget.

3.3.1 Congestion

1. **Vehicle hours of delay**: total hours of delay experienced by all motorized vehicles 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.

2. **Vehicle Miles Traveled (VMT)**: total miles traveled by all motorized vehicles of the system during the simulation.

3.3.2 Level of Service (LOS)

1. **Travel cost**: total trip cost incurred by all agents during the simulation.

2. **Bus crowding**: measured as person standing hours, or the total time spent by agents standing in buses occupied above their seating capacity.

3.3.3 Budget

1. **Operational costs**: total costs incurred by SFBL operations including amortized fixed costs, the cost of fuel consumed, and variable fixed costs. The rates for each of these factors is specified in the vehicle configuration and will be known by contestants when choosing which vehicles to include in the bus fleet.

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

3. **Incentives unused**: total incentives available but unused by agents.

4. **Revenue**: total bus fares collected.

3.4 Composite Scoring Function

4 Scoring Specs

4.1 Input Variables

4.1.1 Dimensions

· **N** individual agent

· **E** education status

· **B** employment status

· **H** household

· **V** vehicles

· **C** vehicle types

· **U** fuel types

· **M** transportation modes

· **T** transit routes

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

· **L** links

· **W** nodes

· **S** types of activities

· **P** plan

· **Z** geographic zones

· $\mathbf{D}_i$ ith demographic characteristic ($i \in \{age, gender, income, education, employment, race/ethnicity\}$)

4.1.2 Network configuration

Network and fleet characteristic variables are defined during the configuration of a simulation, and remain static for each scenario. Network configuration variables are indexed by the link number $l \in L$. Vehicle type configuration variables are indexed by the vehicle type $c \in C$.

The set of all vehicles V is the union of the vehicles in the base scenario, V_{base} and the additional vehicles defined by the contestant, $V_{additional}$ such that $V = V_{base} \cup V_{additional}$. The set of vehicle in the base scenario is the union of the set of privately owned vehicles,$V_{private}$, the set of publicly owned transit vehicles, V_{public}, and the set of ridehail/for-hire vehicles, $V_{ridehail}$. All vehicles in V_base are defined during the configuration of each scenario such that $V_{base} = V_{public} \cup V_{private} \cup V_{ridehail}$. These vehicles may not be altered in any way by the contestants. $V_{additional}$ vehicles may be defined by the contestants to be included in the bus fleet. If a contestant chooses not to add any vehicles to the bus fleet, $V_{additional} = \{\}$. Thus, The set of buses in the simulation is $V_{bus} = V_{public} \cup V_{additional}$.

· $Z^{w}_{zone,z}$: node instance

$$Z^{w}_{zone,z} = \begin{cases} 1 \text{ if node } w \text{ is in geographic zone } z \\ 0 \text{ otherwise} \end{cases}$$

· $Z^{l}_{i,j}$: link instance

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

· Z^{l}_{length} : length of link l [miles]

· $Z^{l}_{capacity}$: the capacity of link l [vehicles per hour]

· $Z^{l}_{access,m}$: mode access on link l

$$Z^{l}_{m} = \begin{cases} 1 \text{ if mode } m \text{ may access link } l \\ 0 \text{ otherwise} \end{cases}$$

· $Z^{c,l}_{free-flow}$: free-flow travel time for vehicle type c on link l

· $Z^{c}_{seating}$: seating capacity of vehicle type c [passengers per vehicle]

· $Z^{c}_{standing}$: standing capacity of vehicle type c [passengers per vehicle]

· $Z^{c}_{compatibility,m}$: mode compatibility of vehicle type c

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

· $Z^{c}_{fuel-type,u}$: fuel type used by vehicle type c

$$Z^{c}_{fuel-type,u} = \begin{cases} 1 \text{ if vehicle type } c \text{ uses fuel type } u \\ 0 \text{ otherwise} \end{cases}$$

· $Z^{u}_{fuel-cost}$: fuel cost per unit consumed for fuel type u [$ per unit fuel]

· $Z^{c}_{fuel-capacity}$: fuel capacity of vehicle type c (size of gasoline tank or of battery)

· $Z^{c}_{fuel-consumption}$: rate of fuel consumption of vehicle type c

· $Z^{c}_{var-cost}$: variable operational cost of vehicle type (not including fuel costs) c [$ per vehicle mile traveled]

· $Z^{c}_{fixed-cost}$: fixed cost for addition of one vehicle of type c to the bus fleet

· $Z^{c}_{emissions}$: emissions rate of vehicle type c [g CO_2 per vehicle mile traveled]

· $Z^{v}_{veh-type,c}$: vehicle type of vehicle $v \in V_{base}\}$

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

· $Z^{f}_{route,t}$: transit route assignment of bus stop f

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

4.1.3 Population configuration

Before starting the simulation, a synthetic population is generated. Each *agent* of the population gets assigned some fixed attributes described by the following variables:

· $N^{n}_{age,d}$: age group of agent n

$$N^{n}_{age,d} = \begin{cases} 1 \text{ if agent } n \text{ is in the age group } d \in D_{age} \\ 0 \text{ otherwise} \end{cases}$$

· $N^{n}_{gender,d}$: gender of agent n

$$N^{n}_{gender,d} = \begin{cases} 1 \text{ if agent } n \text{ is in the gender group } d \in D_{gender} \\ 0 \text{ otherwise} \end{cases}$$

· $N^{n}_{edu,d}$: educational attainment of individual n

$$N^{n}_{edu,d} = \begin{cases} 1 \text{ if agent } n \text{ has the educational attainment level } d \in D_{education} \\ 0 \text{ otherwise} \end{cases}$$

· $N^{n}_{empl,d}$: employment status of agent n

$$N^{n}_{empl,d} = \begin{cases} 1 \text{ if agent } n \text{ has the employment status } d \in D_{employment} \\ 0 \text{ otherwise} \end{cases}$$

· $N^n_{income,d}$: household income group of agent n (note, if agent n is in a household, $N^n_{income,d} = N^h_{income,d}$)

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

· N^n_h : household h where individual n lives

$$N^n_z = \begin{cases} 1 \text{ if individual } n \text{ lives in household } h \\ 0 \text{ otherwise} \end{cases}$$

· N^h_z : geographic zone z of household h

· N^h_{xcoord} : x coordinate of household h

· N^h_{ycoord} : y coordinate of household h

· $N^h_{inhabitants}$: number of inhabitants in household h

$$N^h_z = \begin{cases} 1 \text{ if household } h \text{ lives in geographic zone } z \\ 0 \text{ otherwise} \end{cases}$$

· N^h_v : number of vehicles owned by the household

· N^h_{income} : income of the household h [$]

· $N^{n,p}_{activity,s}$: activity type included in plan p of individual n

$$N^h_z = \begin{cases} 1 \text{ if activity type } s \text{ is part of the } p \text{ of individual } n \\ 0 \text{ otherwise} \end{cases}$$

· $N^{n,p,s}_{start}$: desired start time of activity s planned by individual n in his plan p

· $N^{n,p,s}_{end}$: desired end time of activity s planned by individual n in his plan p

4.1.4 Contestant-defined inputs

Contestants determine whether to include additional vehicles in the bus fleet, which vehicles are assigned to service each bus route, which stops to service by each route, and the fare of the route. The vehicle type of additional vehicles must also be specified by the contestant. Additionally, contestants may define subsidies for transit and ridehail users based on age group, income group, and/or employment status. The set of age groups is D_{age},the set of income groups is D_{income}, and the set of employment where $D_{income} \cup D_{age} \in D$.

· $D^v_{veh-type,c}$: vehicle type of vehicle $v \in V_{additional}$

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

· $D^v_{route,t}$: transit route assignment of vehicle $v \in V_{public} \cup V_{additional}$

$$D^v_{route,t} = \begin{cases} 1 \text{ if vehicle } v \text{ is assigned to service bus route } t \\ 0 \text{ otherwise} \end{cases}$$

· $D^f_{route,t}$: service to bus stop f by bus route t

$$D^f_{route,t} = \begin{cases} 1 \text{ if bus stop } f \text{ is serviced by bus route } t \text{ and } Z^f_{route,t} = 1 \text{ (the stop is on the route)} \\ 0 \text{ otherwise} \end{cases}$$

· D^t_{fare} : bus fare for route t [$]

· $D^m_{subsidy,a,i}$: subsidy available for mode $m \in \{bus, ridehail, ridehail-to-transit, walk-to-transit, drive-to-transit\}$ to agents of age group $a \in D_{age}$ and income group $i \in D_{income}$ [$]

4.2 Output Variables

4.2.1 Dimensions

· **N** individual agents

· **E** education status

· **B** employment status

· **H** household

· **V** vehicles

· **C** vehicle types

· **U** fuel types

· **M** transportation modes

· **T** transit routes

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

· **L** links

· **W** nodes

· **S** types of activities

· **P** plan

· **Z** geographic zones

· **D** demographic criteria

4.2.2 Individual/Agent-level Output Variables

During the simulation, each individual $n \in N$ makes as set of trips, R_n. The following output variables are produced for each trip:

· $X^{n,r}_{activity,s}$: activity type

$$X^{n,r}_{activity,s} = \begin{cases} 1 \text{ if agent } n \text{ is traveling to activity type } s \text{ during trip } r \\ 0 \text{ otherwise} \end{cases}$$

· $X^{n,r}_{available,m}$: mode availability

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

· $X^{n,r}_{choice,m}$: mode choice

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

· $X^{n,r}_{distance}$: distanced traveled by agent n during trip r [miles]

· $X^{n,r}_{duration}$: total duration of travel by agent n during trip r [seconds]

· $X^{n,r}_{in-veh}$: time spent in a vehicle by agent n during trip r [seconds]

· $X^{n,r}_{wait}$: time spent waiting for a vehicle by agent n during trip r [seconds]

· $X^{n,r}_{transfer}$: time transferring between vehicles by agent n during trip r [seconds]

· $X^{n,r}_{cost}$: cost incurred by agent n during trip r (note, if a subsidy is applied during a trip, the cost of the trip is the remainder after subtracting the subsidy from other costs) [$]

· $X^{n,r}_{subsidy}$: subsidy used by agent n during trip r [$]

4.2.3 Vehicle-level Output Variables

During the simulation, each vehicle v makes Q_v movements. For buses, a movement consists of travel between two bus stops. For ridehail vehicles, a movement consists of the travel from origin to destination during any one of the 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 path, fuel consumption, and occupancy of each vehicle v is recorded upon every vehicle movement. The following output variables are produced for each vehicle movement:

· $Y^{v,q}_{distance}$: distance traveled by vehicle v during movement q [miles]

· $Y^{v,q}_{duration}$: duration of movement q by vehicle v [seconds]

· $Y^{v,q}_{fuel-consumed}$: fuel consumed by vehicle v during movement q [percent of vehicle fuel capacity]

· $Y^{v,q}_{fuel-level}$: amount of fuel remaining in vehicle v after movement q [percent of vehicle fuel capacity]

· $Y^{v,q}_{pax}$: number of passengers in vehicle v during movement q

· $Y^{v,q}_{status}$: service status of vehicle v during movement q

$$Y^{v,q}_{status} = \begin{cases} 1 \text{ if vehicle } v \text{ is either en-route to or carrying a passenger during movement } q \\ 0 \text{ otherwise} \end{cases}$$

· $Y^{v,q}_{l}$: path traversal during movement q

$$Y^{v,q}_{l} = \begin{cases} 1 \text{ if vehicle } v \text{ traverses link } l \text{ during movement } q \\ 0 \text{ otherwise} \end{cases}$$

4.3 Scoring Functions

All scoring functions will be assessed as a deviation from the corresponding measure in the base scenario.

4.3.1 Measures of Congestion

1. **Vehicle Hours of Delay**: difference of total vehicle movement-hours and free-flow vehicle movement hours

$$F_{veh-delay} = \sum_{v \in V} \sum_{q \in Q_v} \left(Y^{v,q}_{duration} - \sum_{l \in L} \sum_{c \in C} D^v_c Y^{v,q}_l Z^{c,l}_{free-flow} \right)$$

2. **Vehicle Miles Traveled**: total miles traveled by motorized vehicles

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

4.3.2 Measures of Level of Service

1. **Travel Cost**: total cost incurred by agents

$$F_{travel-cost} = \sum_{n=1}^{N} \sum_{r=1}^{R_n} X^{n,r}_{cost}$$

2. **Bus Crowding**: total agent-hours spent in buses that are over their seating capacity.

$$F_{crowding} = \sum_{v \in V_{bus}} \sum_{q \in Q_v} \left(Y^{v,q}_{duration} \sum_{c=1}^{C} D^v_c (Y^{v,q}_{pax} - Z^c_{seating})_+ \right)$$

where $(Y^{v,q}_{pax} - Z^c_{seating})_+ = \max\{0, Y^{v,q}_{pax} - Z^c_{seating}\}$.

3. **Agent Hours of Delay**: have to figure out how to/if we want to record 'quoted' travel time

4.3.3 Budget

1. **Operational costs**: fixed costs, variable per-mile costs (if applicable), and fuel costs

$$\begin{aligned} F_{op-cost} = & \sum_{v \in V_{public}} \Bigg(\sum_{c \in C} Z^v_{veh-type,c} Z^c_{fixed-cost} \\ & + \sum_{q \in Q_v} \Big(Y^{v,q}_{distance} (\sum_{c \in C} Z^v_{veh-type,c} Z^c_{var-cost}) + Y^{v,q}_{fuel-consumed} \big(\sum_{u \in U} Z^c_{fuel-type,u} Z^u_{fuel-cost} \big) \Big) \Bigg) \\ & + \sum_{v \in V_{additional}} \Bigg(\sum_{c \in C} Z^v_{veh-type,c} Z^c_{fixed-cost} \\ & + \sum_{q \in Q_v} \Big(Y^{v,q}_{distance} (\sum_{c \in C} D^v_{veh-type,c} Z^c_{var-cost}) + Y^{v,q}_{fuel-consumed} \big(\sum_{u \in U} Z^c_{fuel-type,u} Z^u_{fuel-cost} \big) \Big) \Bigg) \end{aligned} \quad (1)$$

2. **Subsidies payed**

$$F_{subsidies-paid} = \sum_{n=1}^{N} \sum_{r=1}^{R_n} X_{subsidy}^{n,r}$$

3. **Subsidies unpaid**

$F_{subsidies-unpaid} =$

$$\sum_{n \in N} \sum_{r \in R_n} \sum_{m \in M} X_{available,m}^{n,r} \sum_{a \in D_{age}} \sum_{i \in D_{income}} D_{subsidy,a,i}^{m} N_{income,i}^{n} N_{age,a}^{n} - F_{subsidies-paid}$$

4. **Revenue**:

$$F_{revenue} = \sum_{n=1}^{N} \sum_{r=1}^{R_n} X_{choice,bus}^{n,r} X_{cost}^{n,r}$$