Arcology Simulation Framework

Rowin Andruscavage

University of Maryland
Systems Engineering
Master of Science Thesis

June 4, 2007

Project Summary:

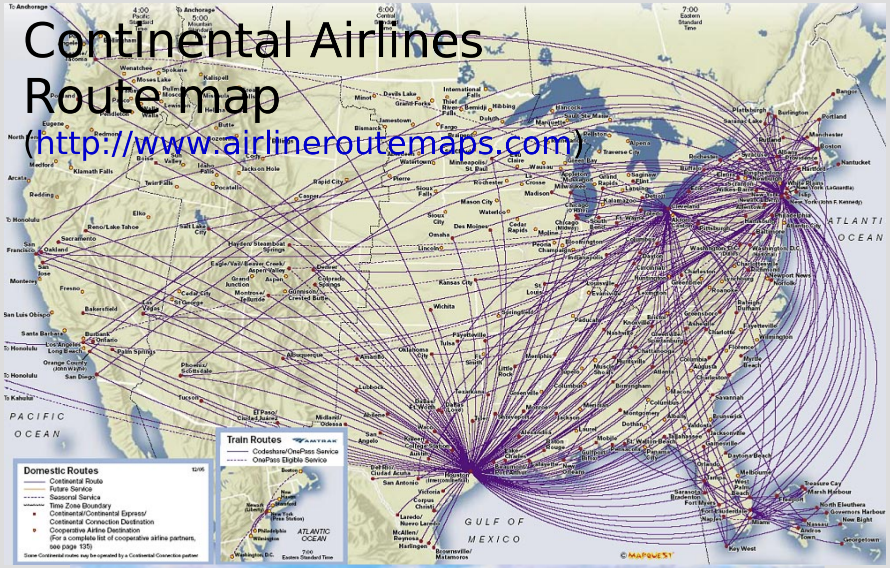
Optimization and simulation framework to analyze transit-oriented designs

Address 2 questions:

1. How can we evaluate the effectiveness of an urban complex?
   - Demand / Sustainment / Measurement framework:
     - Investigates demand distribution patterns influenced by urban planning topology
     - Quantifies effects of transportation infrastructure topology and mode of operation
     - Determines system's ability to satisfy resident / industrial needs

2. What transit paradigms succeed at making the world “smaller”?

Mass Transit Paradigms: Commercial Aviation

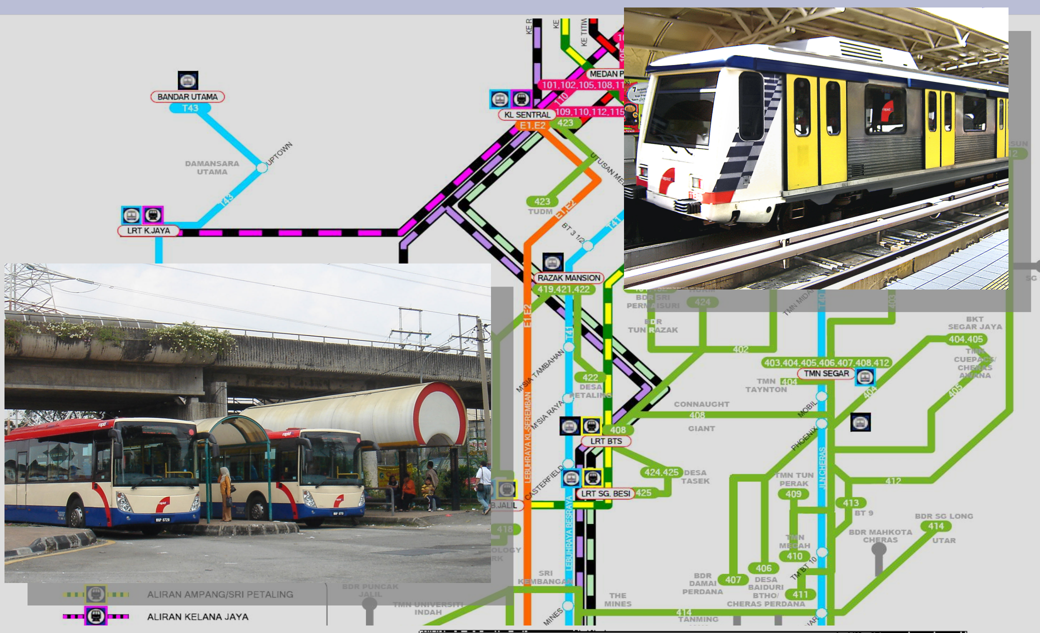


Continental Airlines Route map (http://www.airlineroutemaps.com)

- Hub-and-Spoke
  - economies of scale with mixed fleets
  - 767 & 757
- Point-to-Point
  - more direct flights with fleets of regional jets
  - SWA 737
- SATS
  - service from small local airports could take Point-to-Point concept to an extreme

Ground Transit establishes Feeder-and-Trunk model

- Bus routes often feed subway / light rail trunks
  - connecting to other modes of transportation



- HCPPT shows the capability of a more distributed demand-responsive model

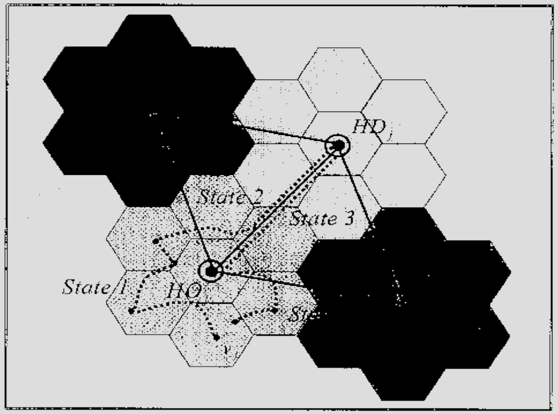
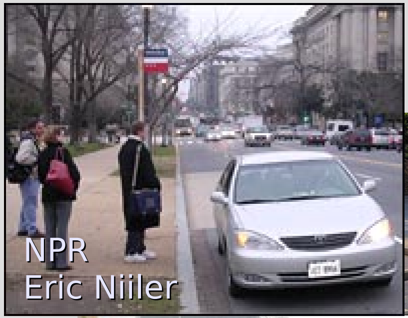


Figure 4.9 Vehicle schedule representation

(Cortes 2003 *HCPPT: A New Design Concept and Simulation-Evaluation of Operational Schemes*)

Vehicle Sharing Options and Concepts


NPR
Eric Niiler


Griffith University


Businessweek
IDEA 2006

- Carpools / HOV Slugs
- Flexcar / Zipcar rental services
- Taxi cab network
- Robotic driverless cars
- CityBike Amsterdam GPS bicycle system

Personal Rapid Transit Systems struggle along

CabinTaxi verified and tested in Germany, abruptly abandoned due to NATO commitments

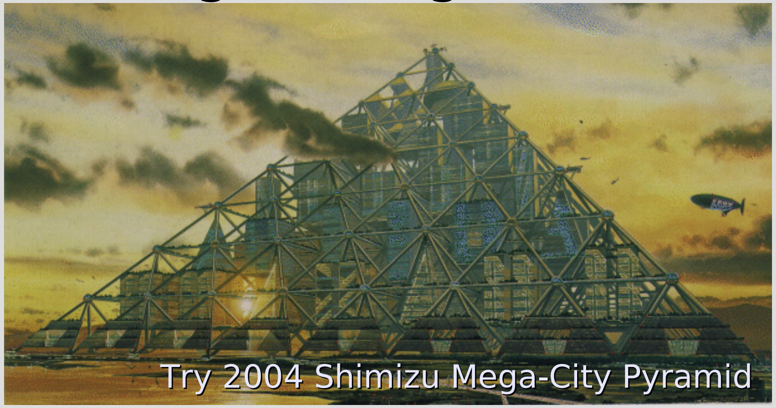
Taxi2000 branched from Raytheon

Morgantown, WVU operational group transit system; abandoned by Boeing

ULTra system slated for 2007 deployment in Heathrow airport, UK and Dubai, UAE

Transit Oriented Design should drive development of more efficient mass transit

- We often search for advanced transportation solutions to energy problems
  - We can make larger impacts by reducing travel need/distance by adjusting urban planning and logistics
- Urban Layout
  - Increase density
  - Culminating in arcology concepts
    - Increased density correlated with decreased energy use per capita



Try 2004 Shimizu Mega-City Pyramid

- Logistics
  - Stagger work schedules to reduce peak loads
  - Flexibility to optimize residence / workplace pairings
  - Mass transit effectiveness that rivals personally-owned vehicles in door-to-door performance
  - Enabled by transit-oriented design

Denser cities are more efficient per capita

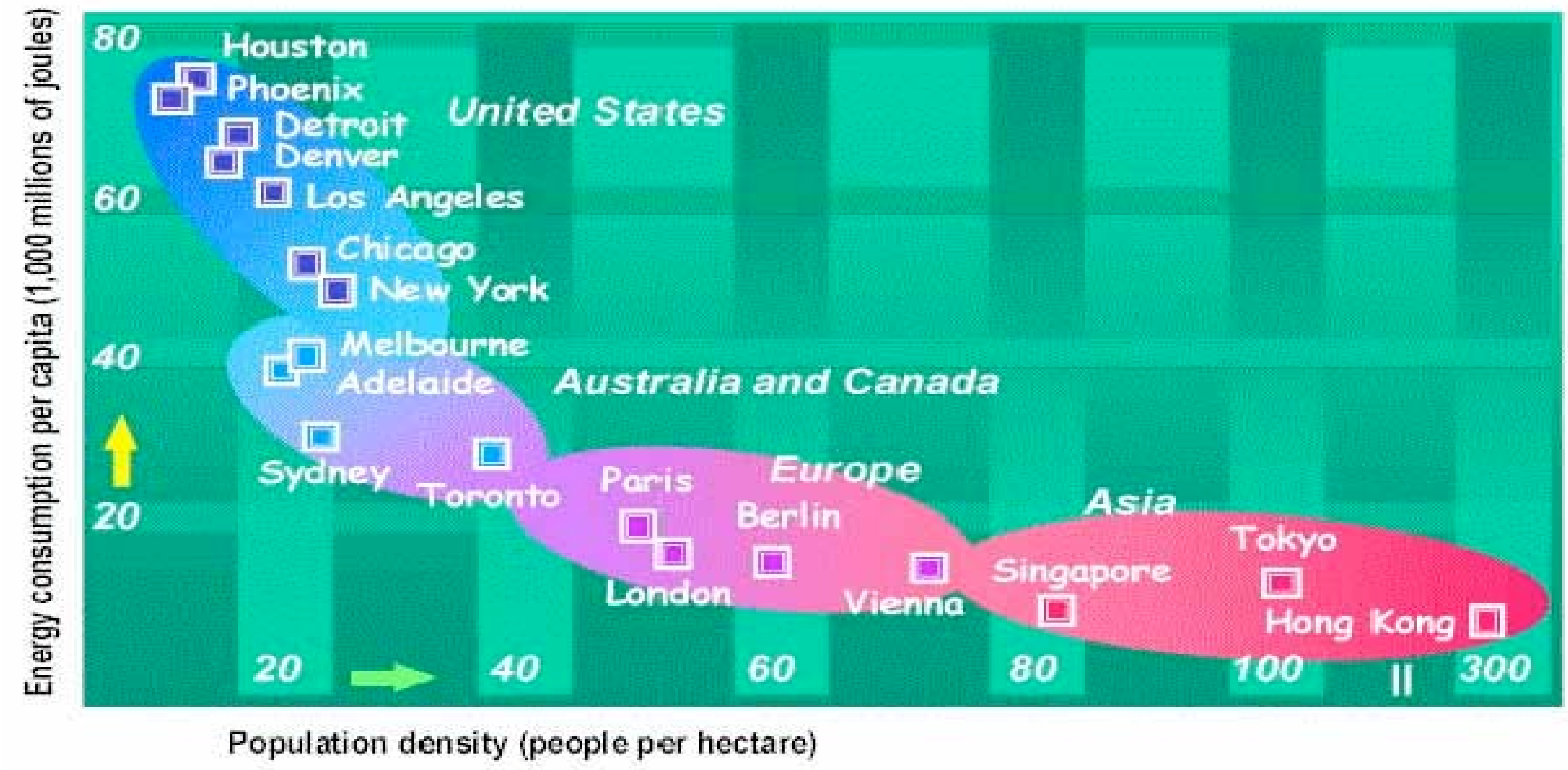
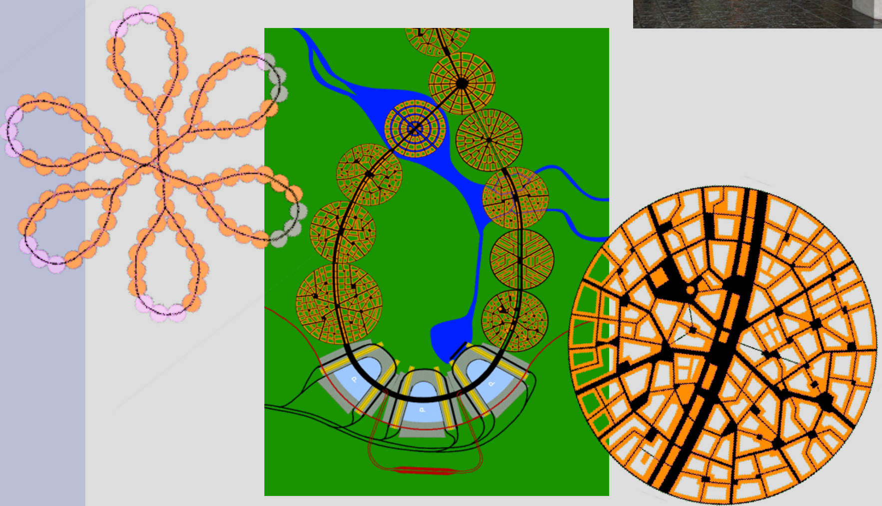


Figure 2. The relationship between population density and energy consumption in cities.

(Emmi 2003 *Coupled Human–Biologic Systems in Urban Areas: Towards an Analytical Framework Using Dynamic Simulation)*

Arcologies and Compact Cities pack functionality

Arcosanti (Chris Ohlinger)

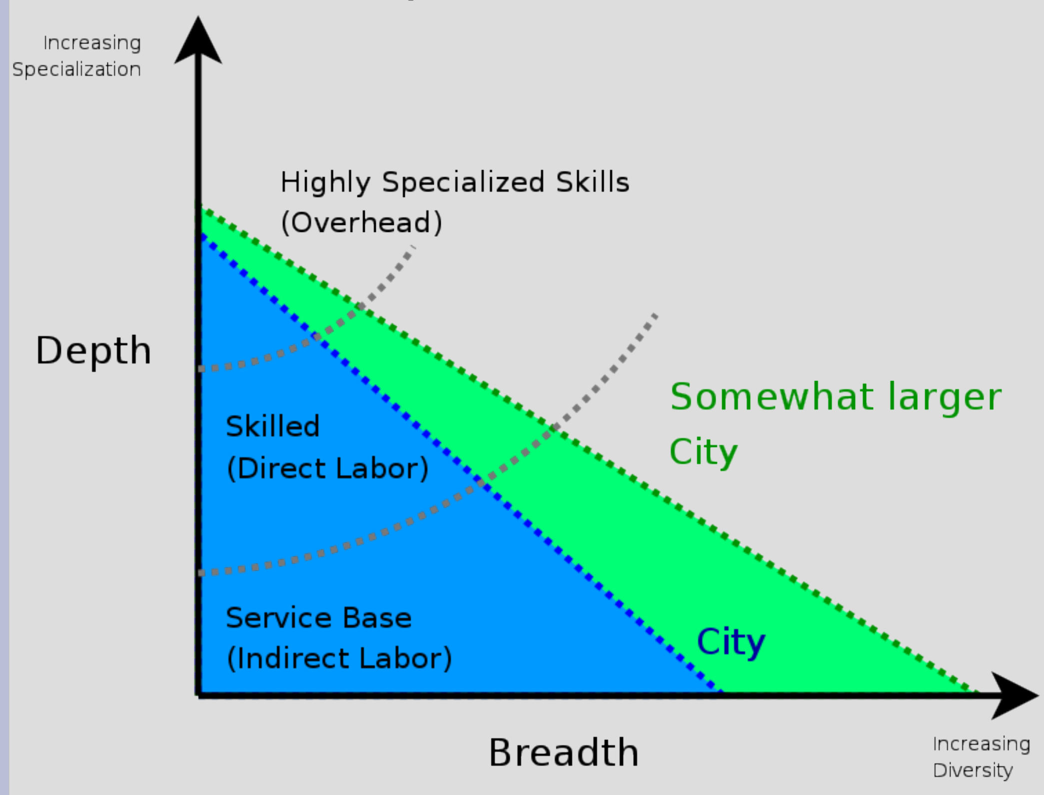


- Soleri's *Arcology*
  - Architectural implosion of cities
  - Form a human relationship to the environment
- Dantzig & Saaty's *Compact City*
  - Comprehensive proposal for many aspects of a functioning hyperstructure
- Crawford's *Carfree Cities*
  - Reference designs most applicable to transit approach and assumptions used in this thesis

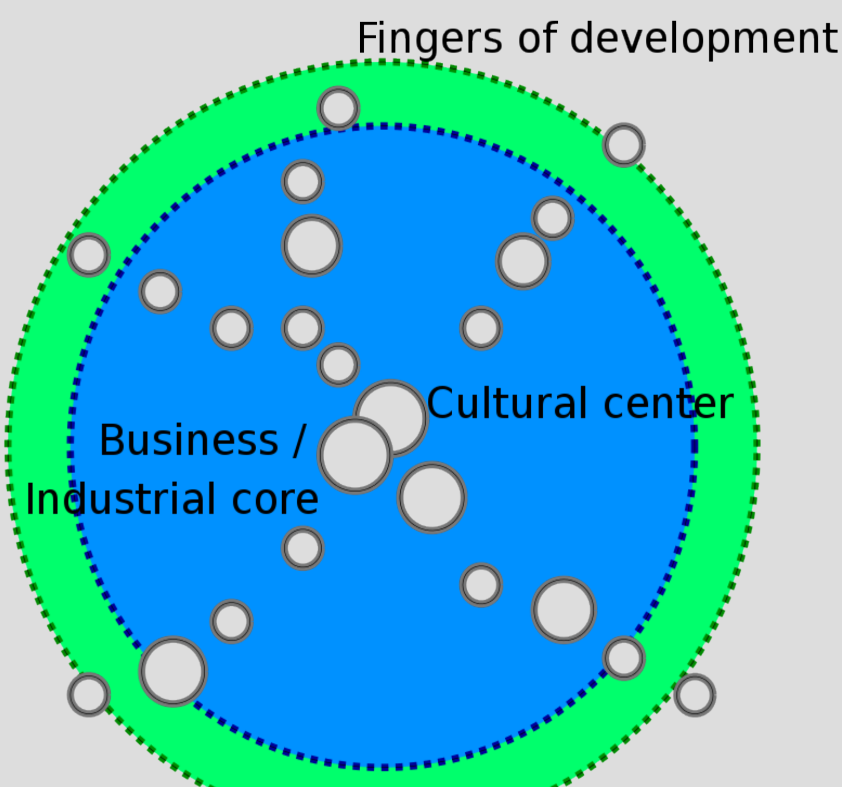
A Metropolitan complex should maximize diversity

- Offer diverse set of specialized skills and jobs
  - Well-suited for a systems approach to the design of life support infrastructure

Population Skill Distribution



Geography



Mass Transit Optimization Key Capabilities

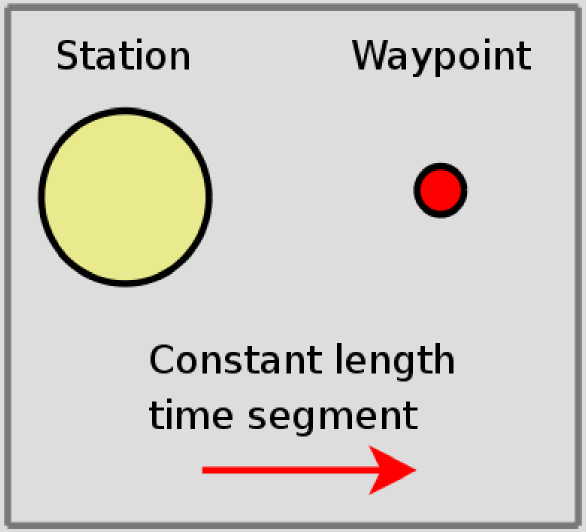
- Investigate optimal transfer strategies
  - Hub & spoke (*e.g.* bus feeders & light rail trunks)
  - Point-to-point (*e.g.* taxis, vanpools)
- Demand-responsive dynamic vehicle routing
  - Creates unique schedule based on demand inputs
  - Utilizes command, control, and monitoring networks
  - Emphasizes passenger service quality – high throughput, low latency, minimal vehicle movement
- Apply transit system constraints
  - Vehicle size (seating capacity)
  - Station size (berthing capacity)
  - Link connectivity (network topology)
- Multimodal layers of vehicles
  - various passenger capacities or network connectivity

Mass Transit Optimization Model Elements

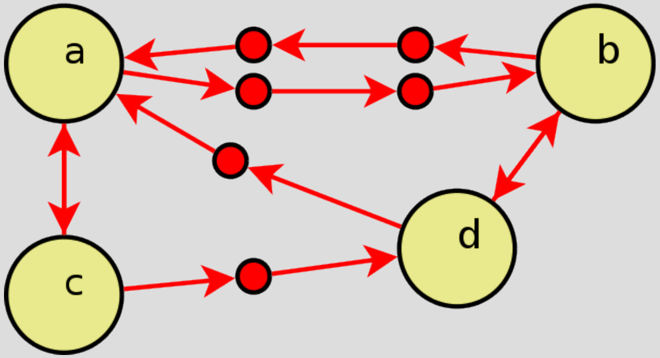
Modeled as an inventory problem

- **Station** nodes with quantities of passengers, vehicles
- **Links** between connected stations with quantities of passengers & vehicles in transit
- **Passengers**: grouped in bins by common current and final destinations
- **Vehicles**: multiple types with different capacities, station connectivity, and operating costs

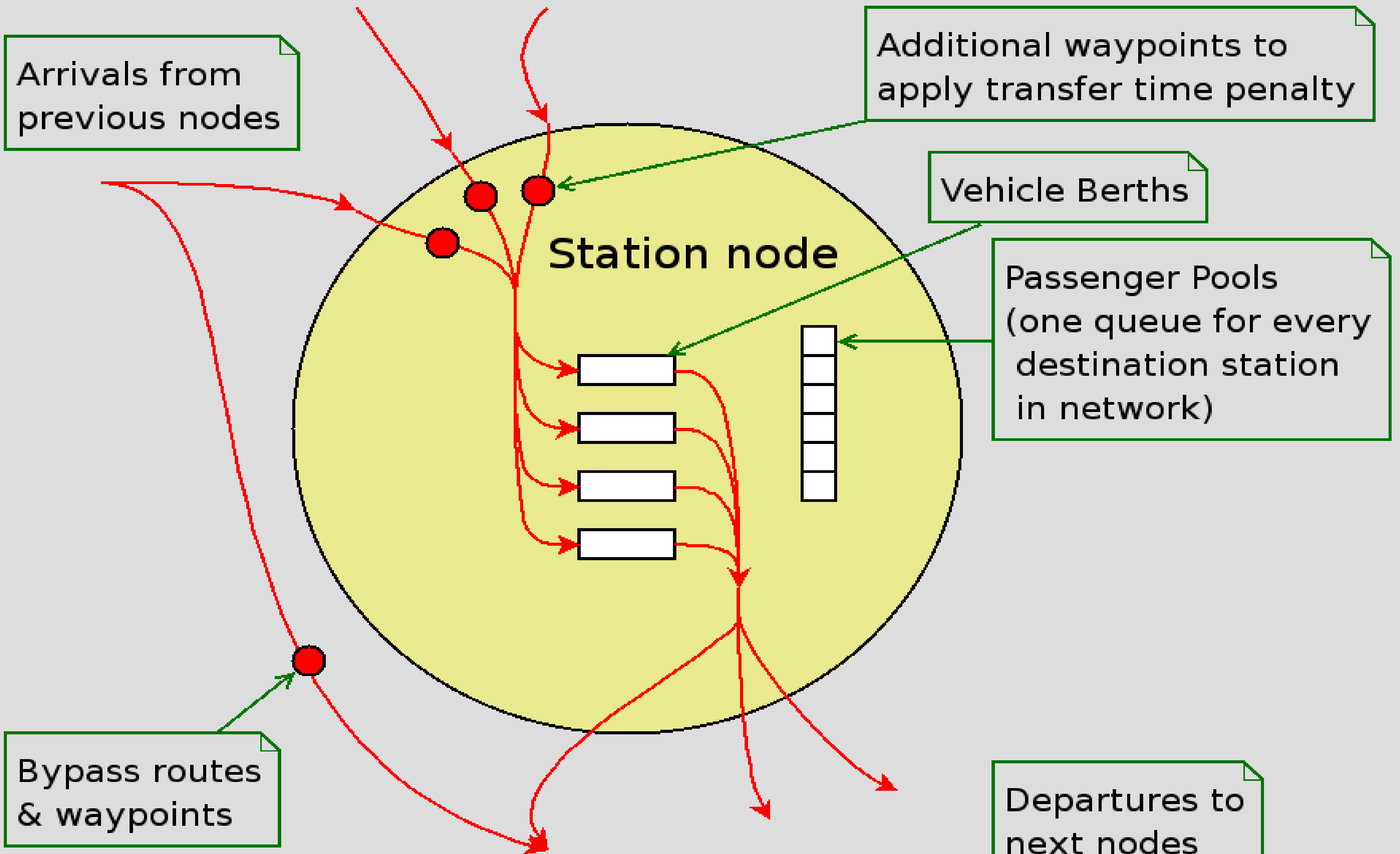
Model elements



Sample model of one transit layer

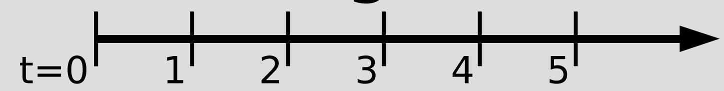


Conceptual Model of a Station



Transit Optimization Input / Output Variables

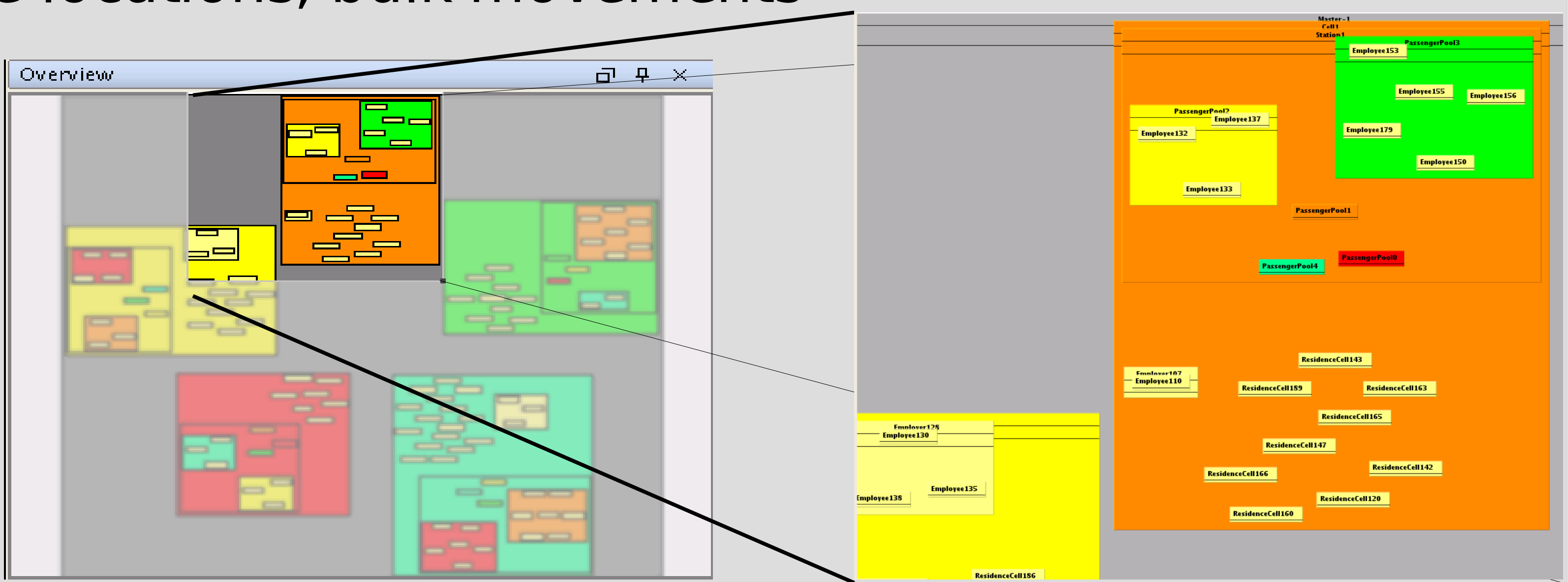
- Time represented by synchronous integer time steps



- Demand defined by initial passenger origins for each time step at each station

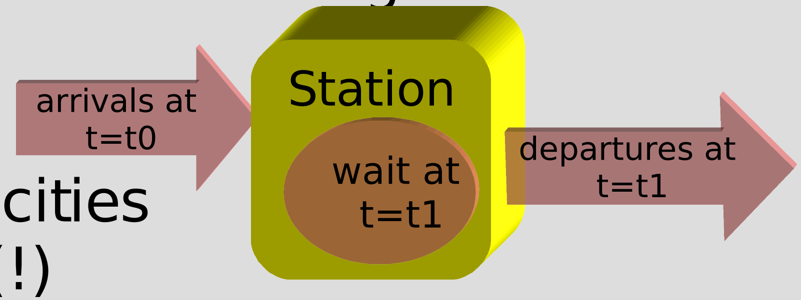
Output: schedule variables for each time step:

  - Passenger locations, bulk movements
  - Vehicle locations, bulk movements



Transit Optimization Constraints

- Inventory flow problem formulation:
  - Conservation of passengers & vehicles moving between nodes at each time step



- Passenger movement
  - constrained only by vehicle capacities
  - may transfer freely at any node (!)
- Vehicles constrained by:
  - connectivity matrix
  - station / waypoint node capacity
  - max fleet size limit

Arbitrary constraints somewhat easy to add:

- *e.g.* “max vehicles on a link segment”
- *e.g.* “max capacity on a group of waypoints”

Multiple Objectives

prioritized by weights:

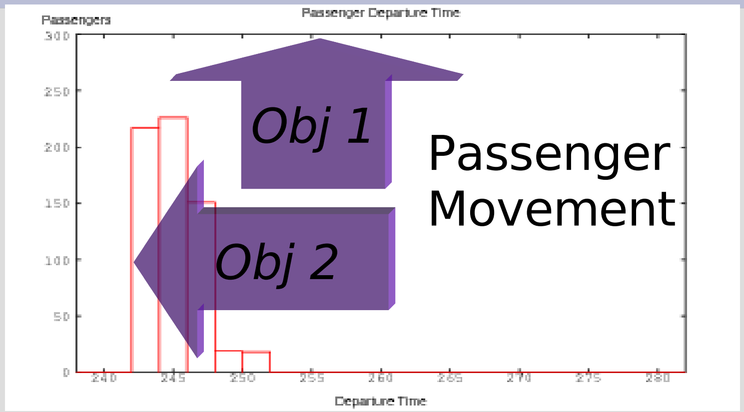
Obj 1* >> *Obj 2* >> *Obj 3* >> *Obj 4

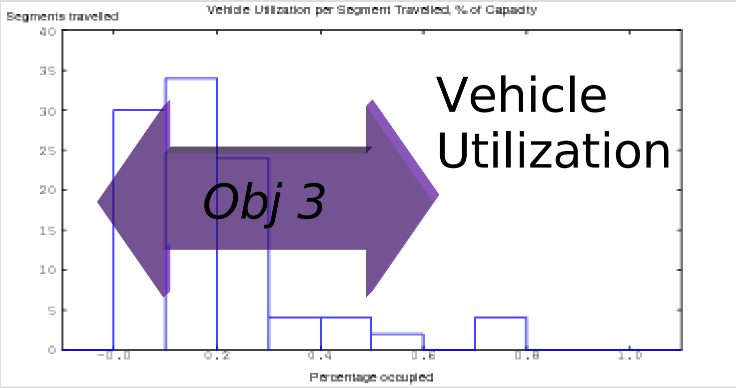
1: Throughput
- Maximize passengers sent to final destination

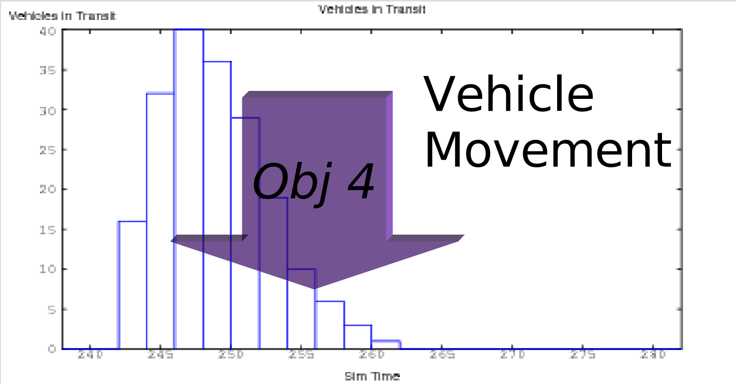
2: Latency
- Reward scheduler for delivering passengers earlier

3: Fleet Size (Optional)
- Minimize deviation from desired vehicle fleet size

4: Operating Cost
- Minimize vehicle movements

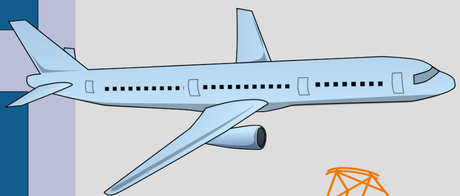
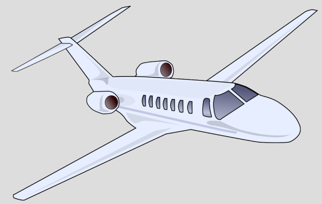


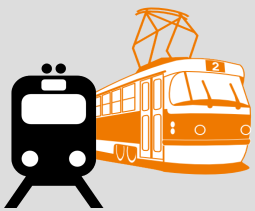


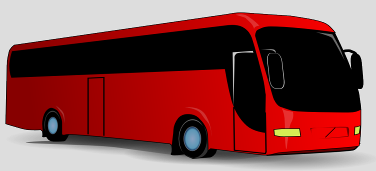
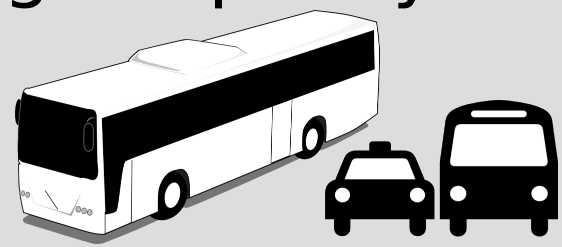


Transit Modes:

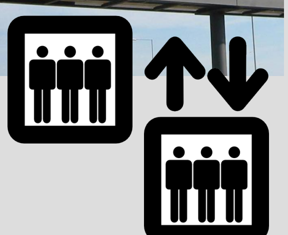
timing, capacity, and optimization parameters tuned to represent:


Aircraft

(original intent)


Subway / Rail (high capacity trunks)


Buses / Vanpools



Personal Rapid Transit networks


Elevators (!)

Automated Package Transport

Optimized Schedule Verified by Simulation

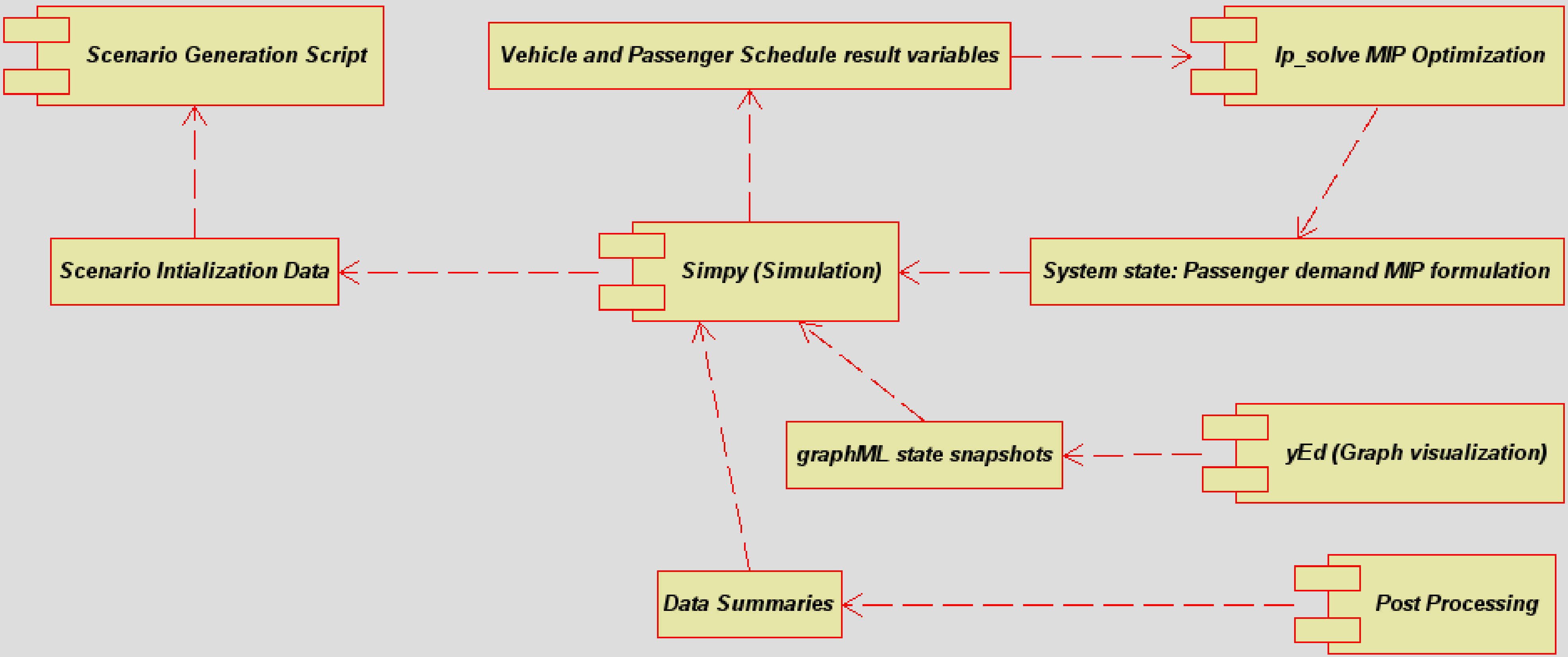
(the second half)

- Collects detailed performance metrics
  - Feasibility assurance
  - Continuous time execution of transit model based on integer time steps
  - Inspection & analysis of track logs from individual passengers and vehicles
- State persistence
  - Evolve system state with all known data
  - Reformulate and re-optimize schedule as scenario progresses and new input data is introduced
  - Eventually allow rolling horizon scheduling

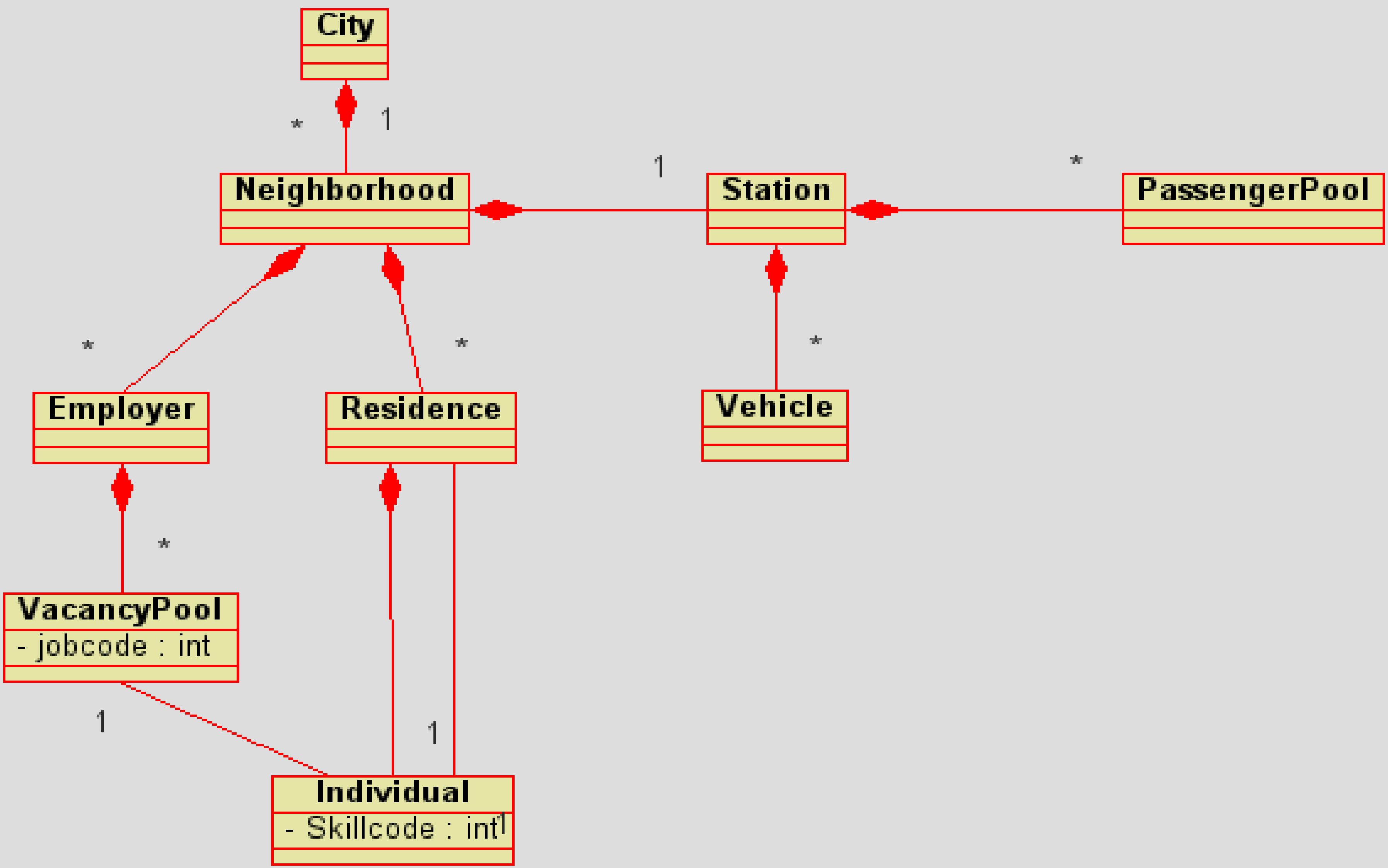
SimPy: discrete event simulation framework

LP_solve: MIP Optimization

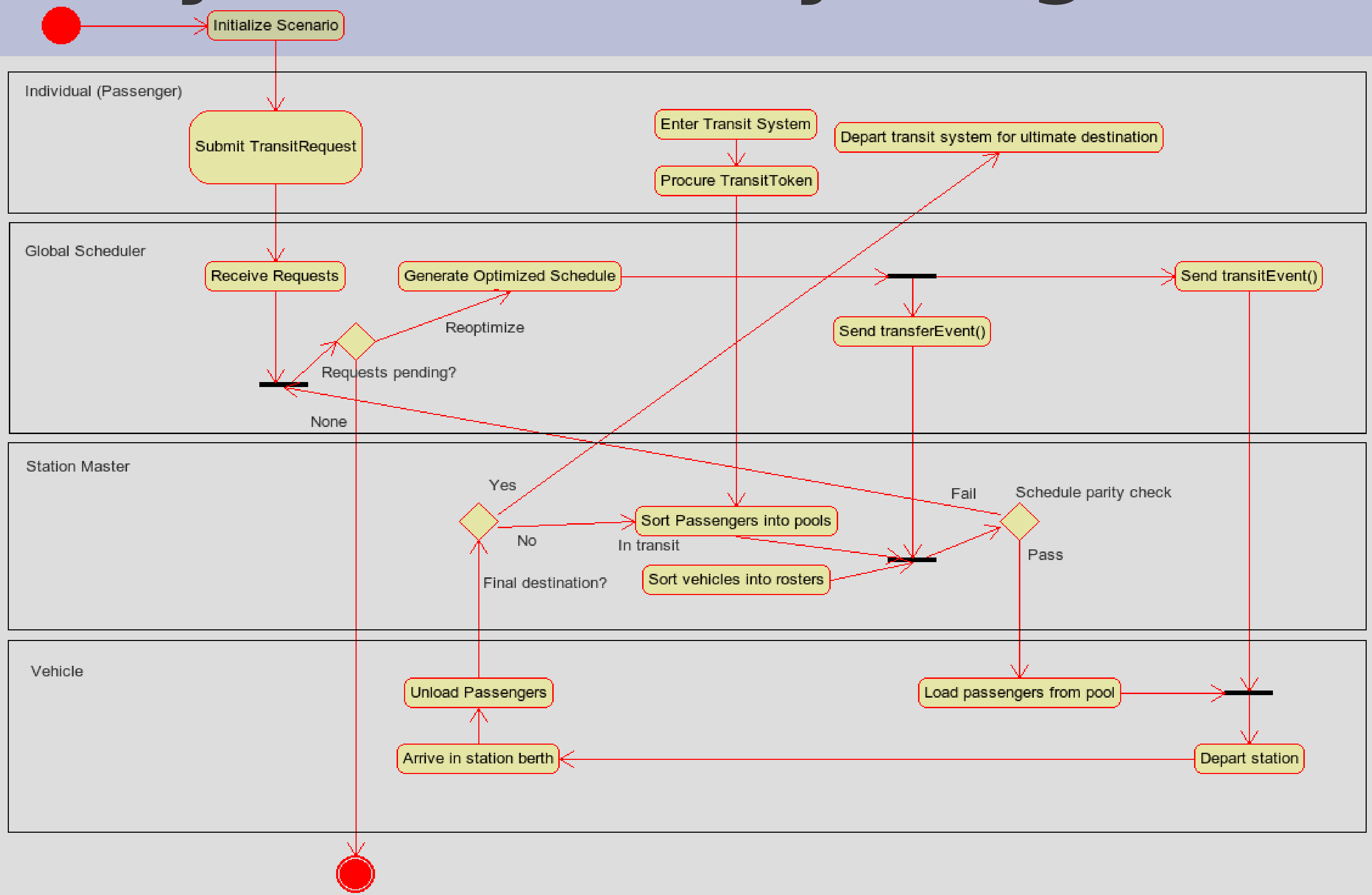
Simulation Component Diagram



Commuter Transit Model Class Structure



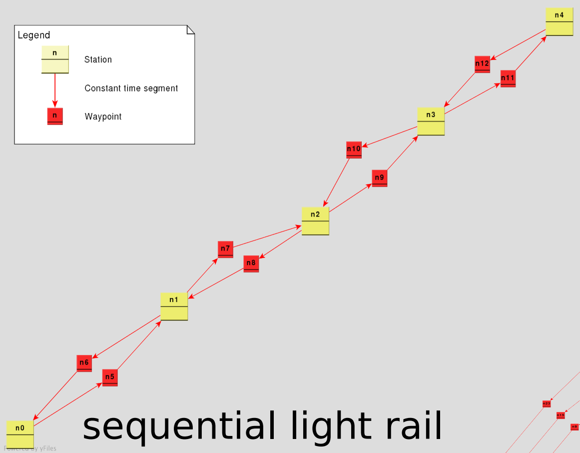
Commuter Transit Model System Activity Diagram



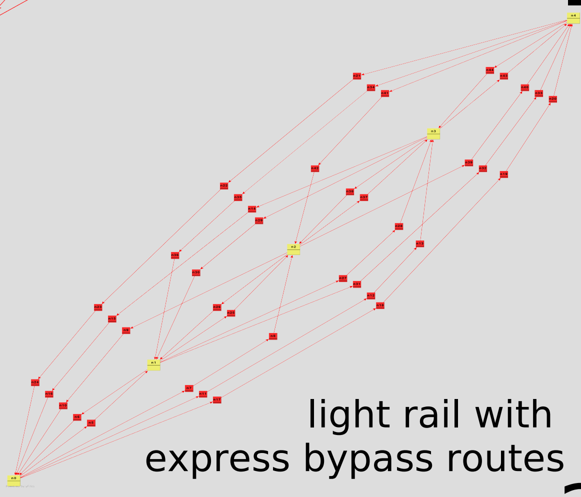
Verification and Validation

- Scenario Generation
  - Transit graph
- Demand Generation
  - Initial State
- Schedule Generation
  - MIP formulation: python code generates lp model
- Schedule Results
  - Solution variables returned
  - Spreadsheet view
- Simulation of Results
  - Final state
  - Inspect individual passenger and vehicle histories

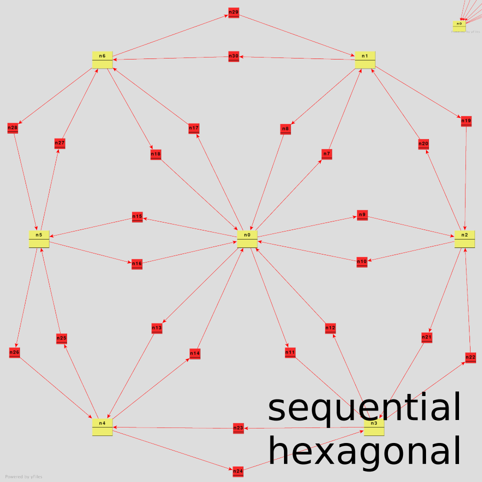
Parametric Analysis Scenarios



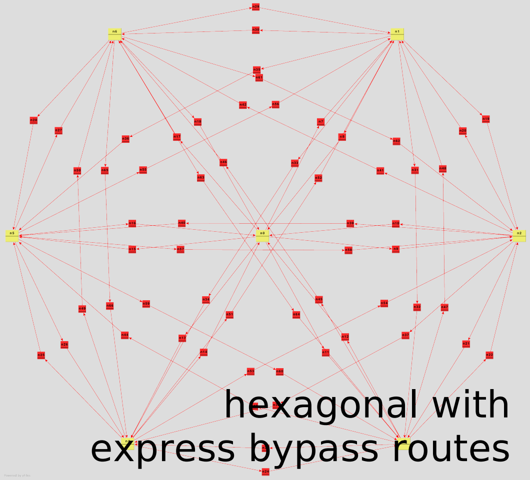
sequential light rail



light rail with express bypass routes



sequential hexagonal



hexagonal with express bypass routes

- 1D Light rail scenario
  - extreme linear topology
  - with and without express routing (station bypass)
  - 7 station nodes
- 2D Hexagonal network
  - extreme fully-connected star topology
  - with and without express routing (station bypass)
  - 7 station nodes

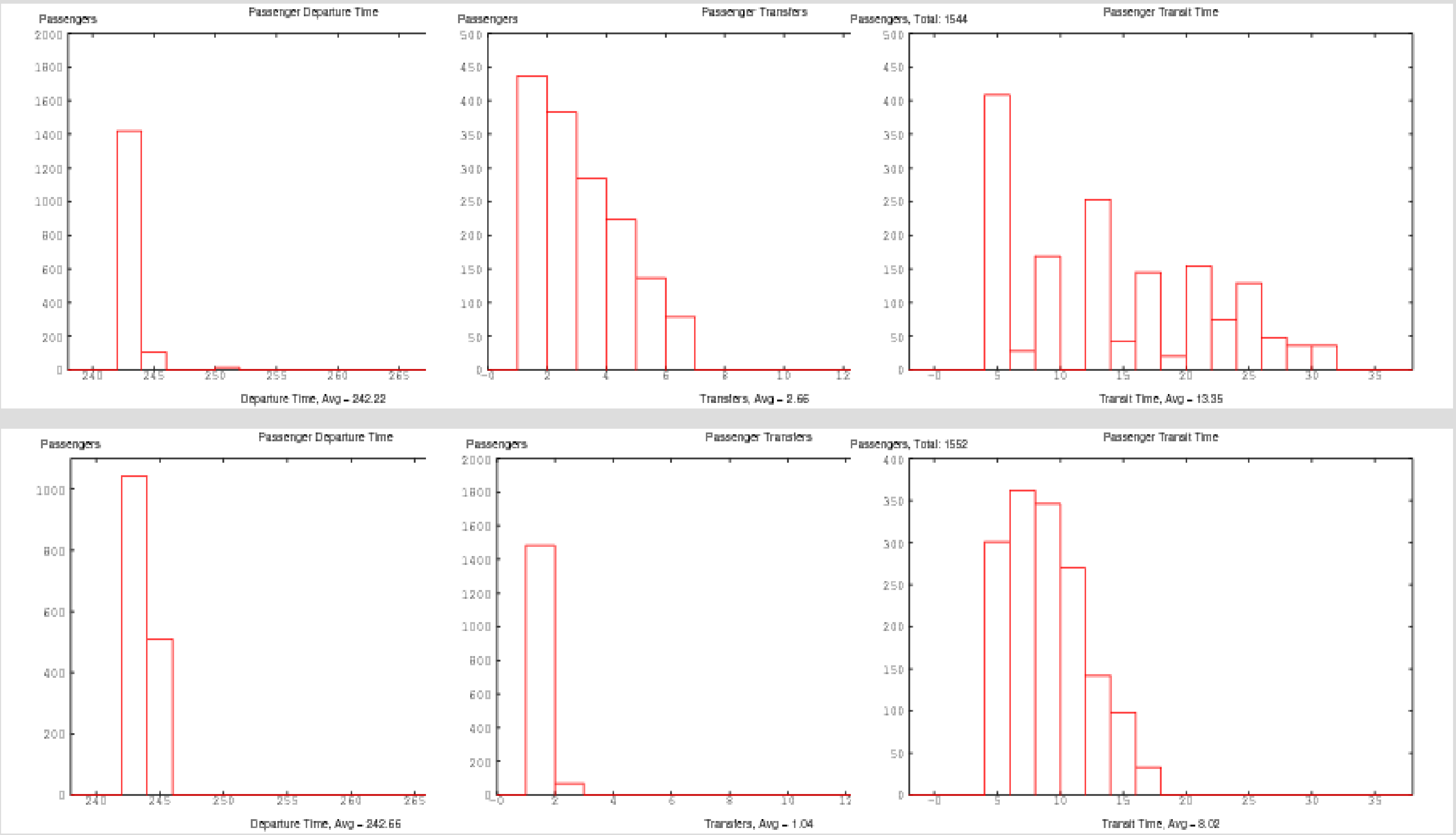
1D Rail Passenger Metrics

Response to uniform random demand pulse

waiting time (latency) | transfer stops (convenience) | travel time

Sequential routing

Express routing

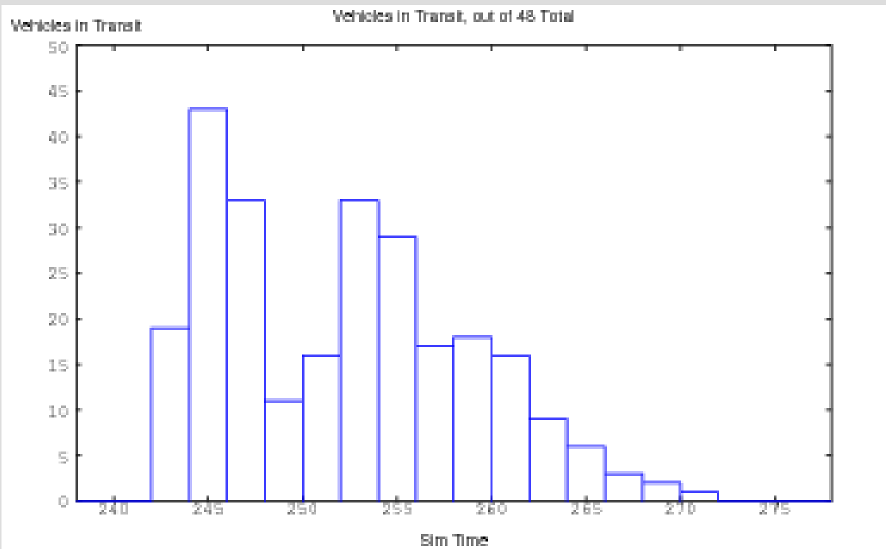


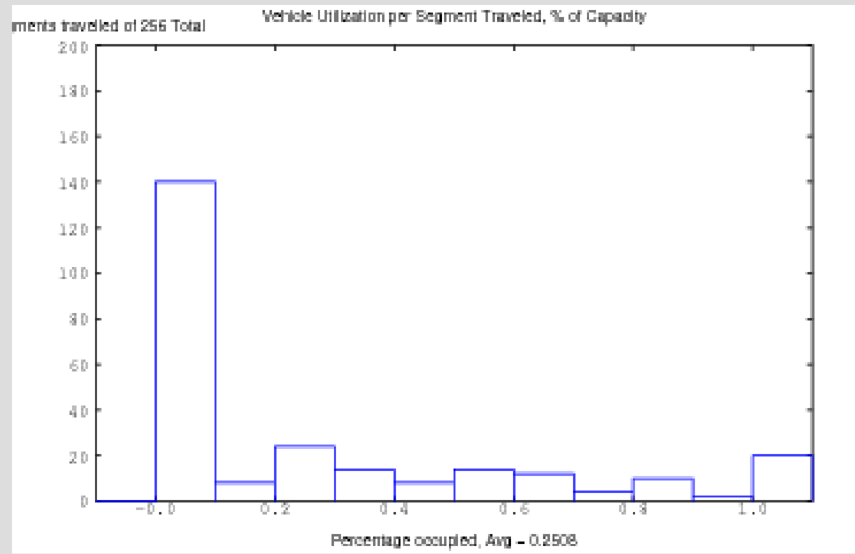
1D Rail Vehicle Metrics
Operating cost & efficiency

Vehicles in operation

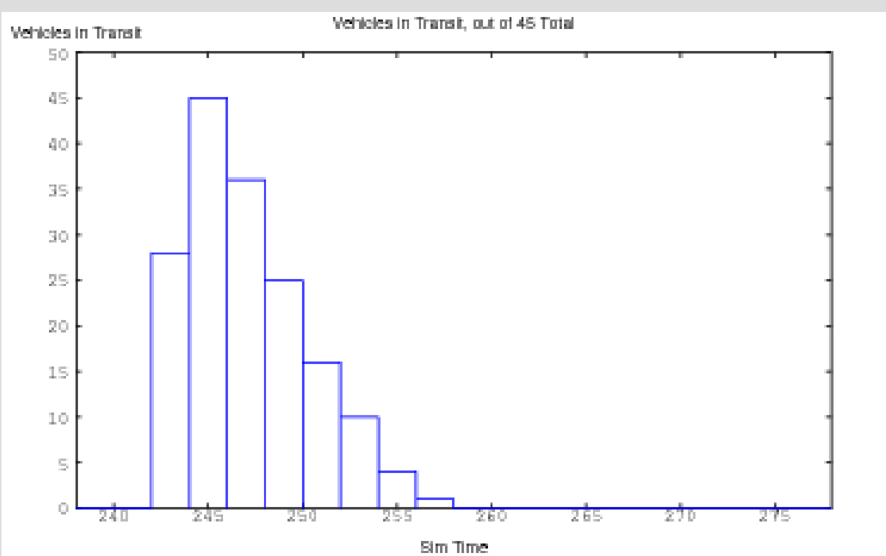
Vehicle Utilization

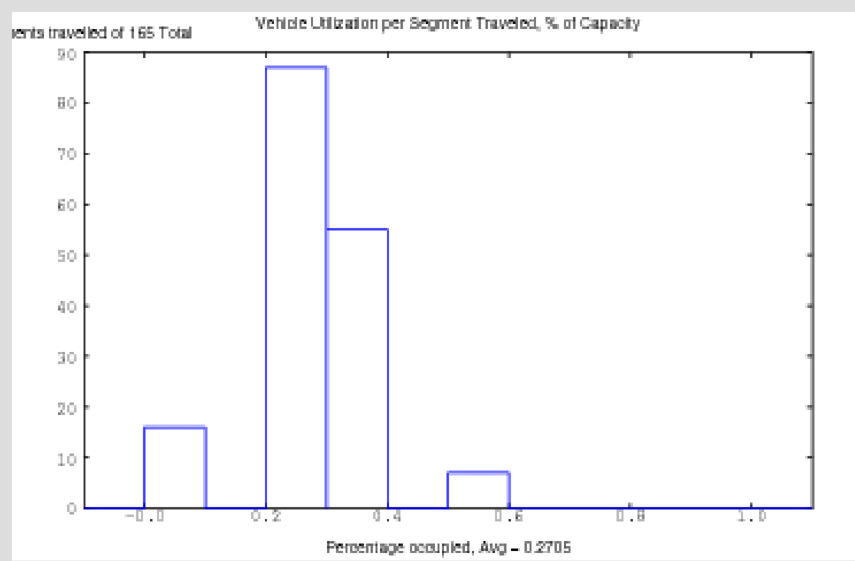
Sequential routing





Express routing



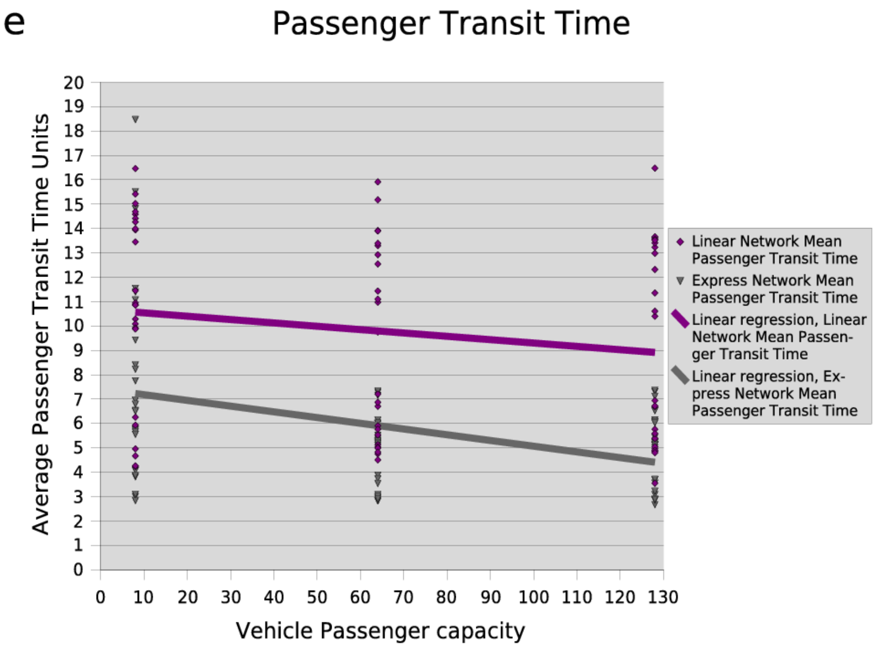


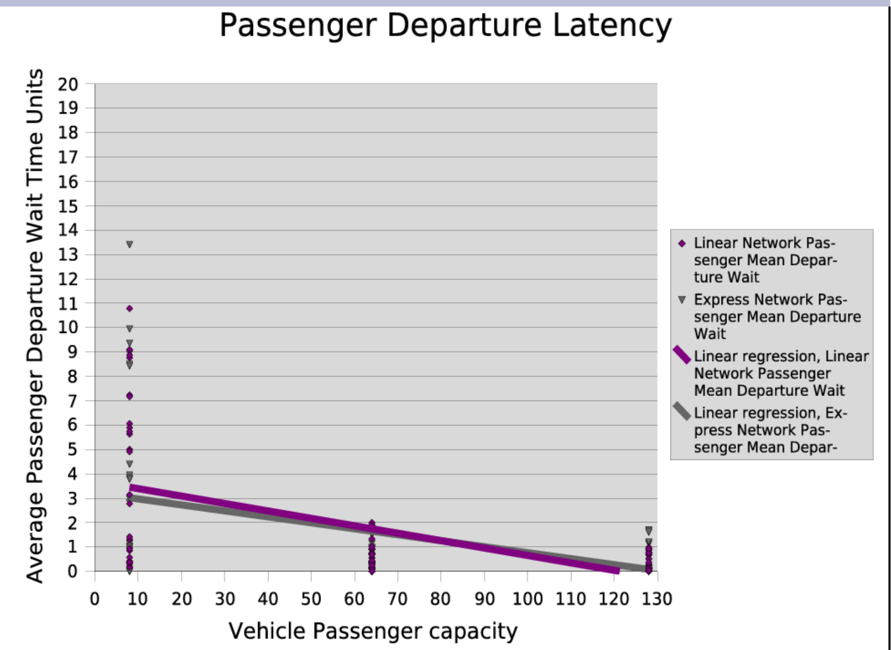
Factorial Experiments Design

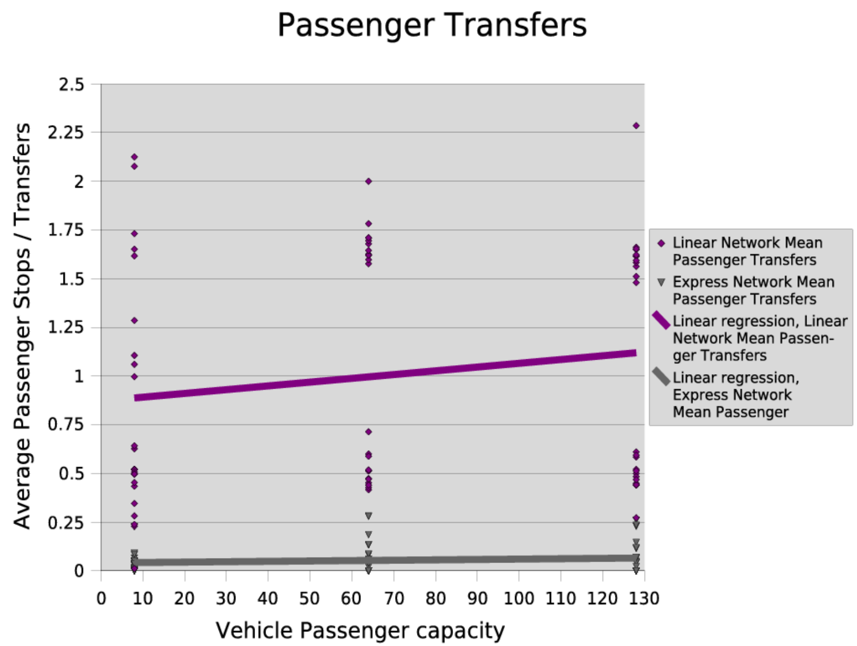
- Design Parameters
  - Topology [linear **1D** Rail, **2D** hexagonal]
  - Offline stations [**sequential** routing, **express** routing]
  - Load per station [**4**, **64**, **128**, **256**] commuters
    - uniform random distribution among origin stations
  - Vehicle size [**8**,**64**,**128**] passengers
  - Berths per station [**2**,**4**,**8**] vehicles
- Assumptions
  - Headways: 2 minute travel time across segments, 2 minute time to stop and transfer at a station
  - Impulse demand at t = 240 min
  - Vehicles must return to start configuration
  - Suboptimal & nondeterministic optimization timeout at 2 hours

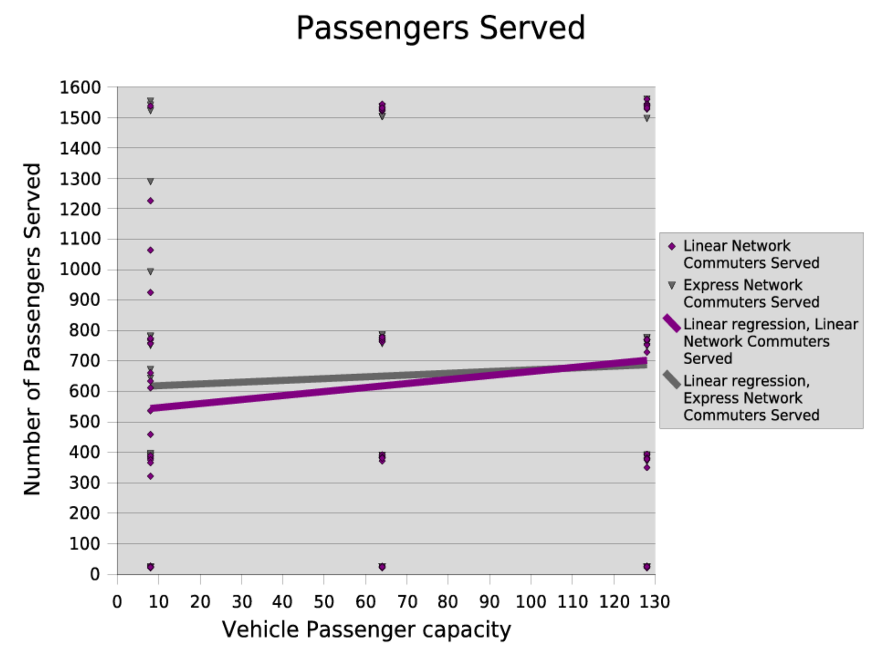
Passenger view of Sequential vs. Express routing with respect to **Vehicle Capacity**

Effect of Vehicle Capacity on Passenger Metrics



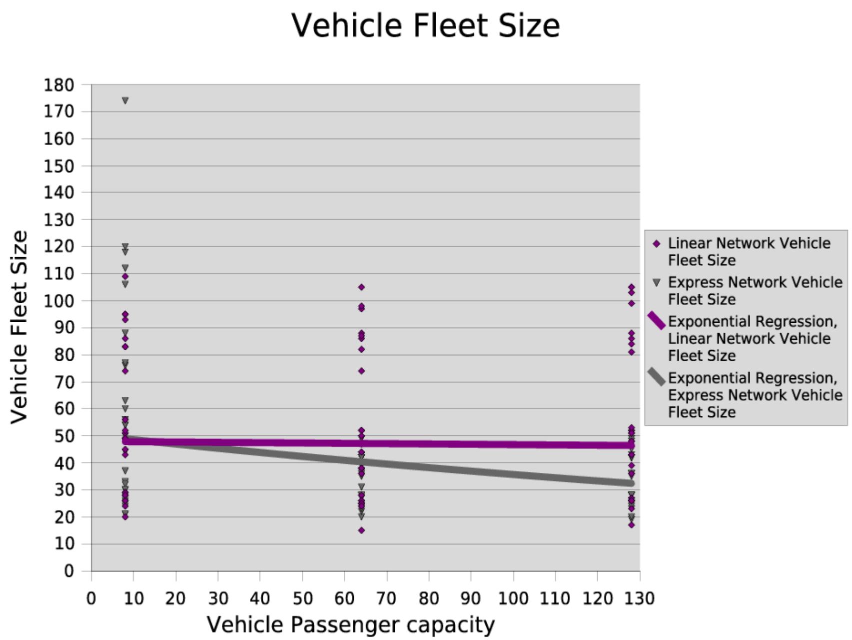


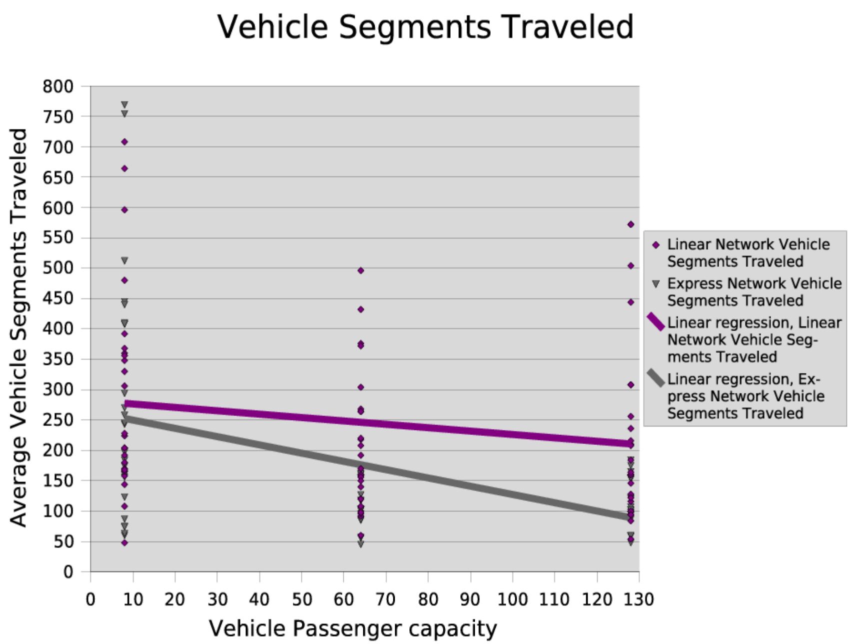


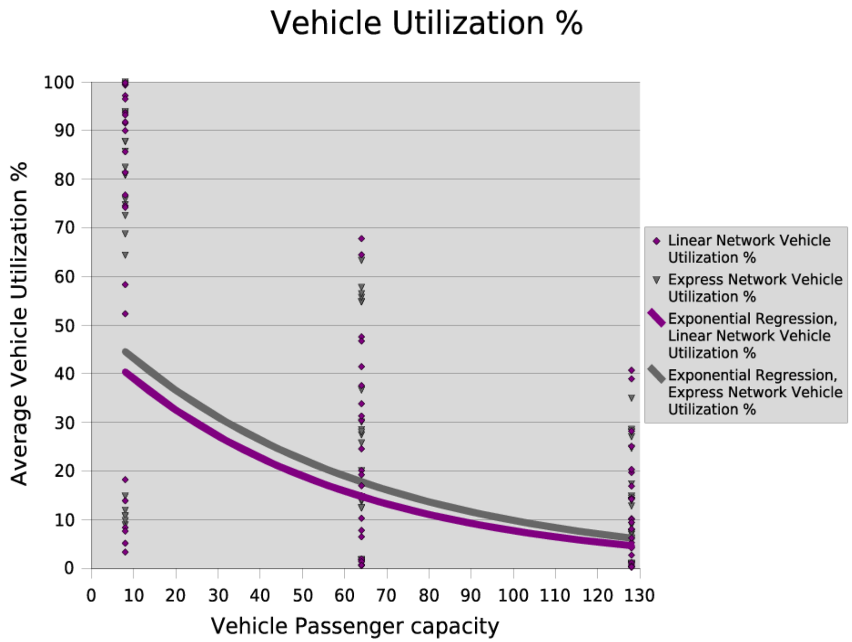


Fleet Operator view of Sequential vs. Express routing with respect to **Vehicle Capacity**

Effect of Vehicle Capacity on Vehicle Fleet Metrics



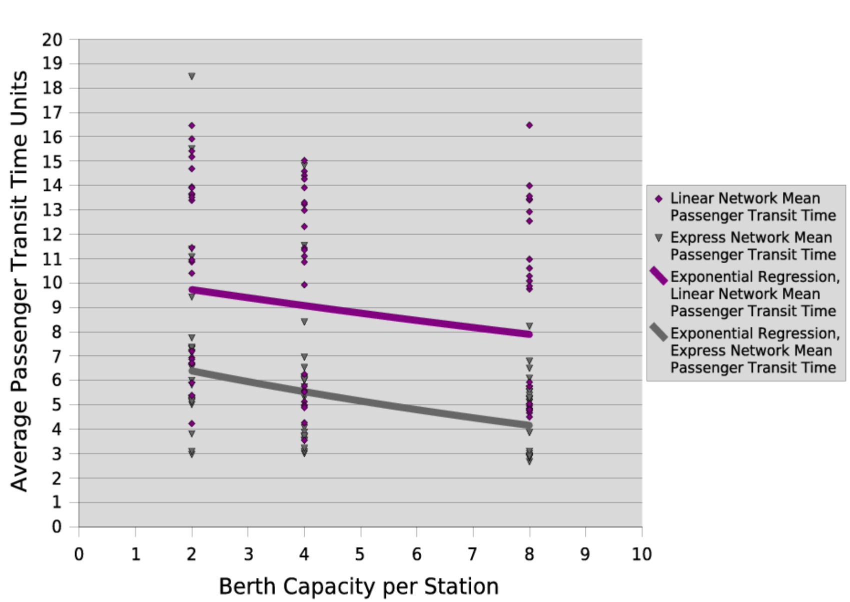




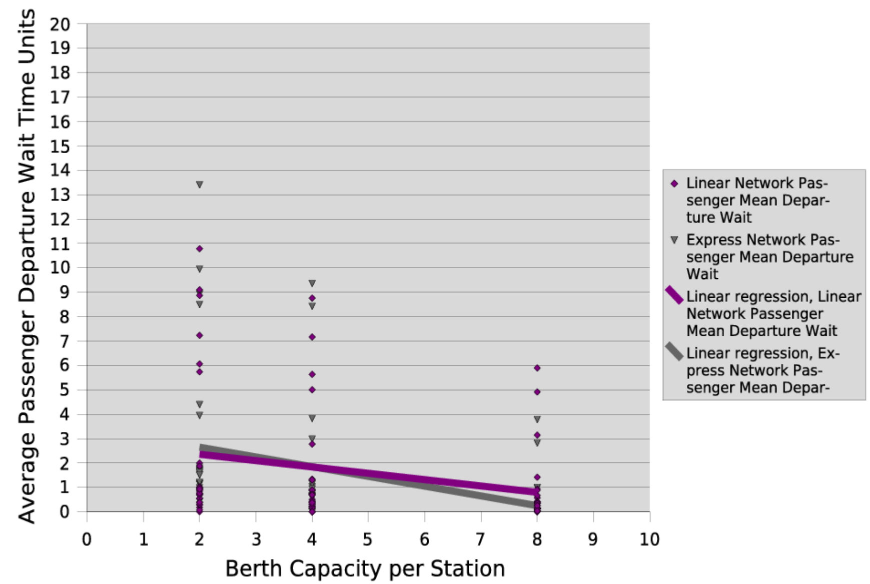
Passenger view of Sequential vs. Express routing with respect to **Station Berth Capacity**

Effect of Station Size on Passenger Metrics

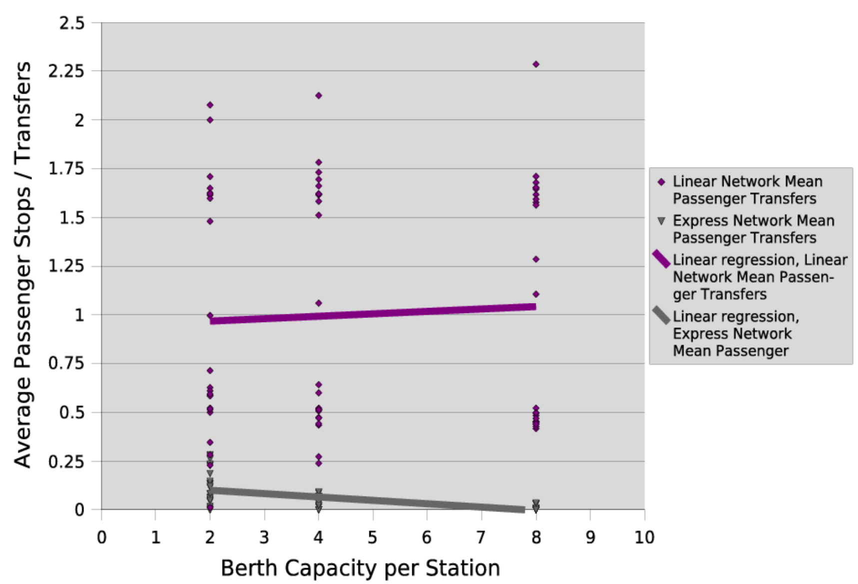
Passenger Transit Time



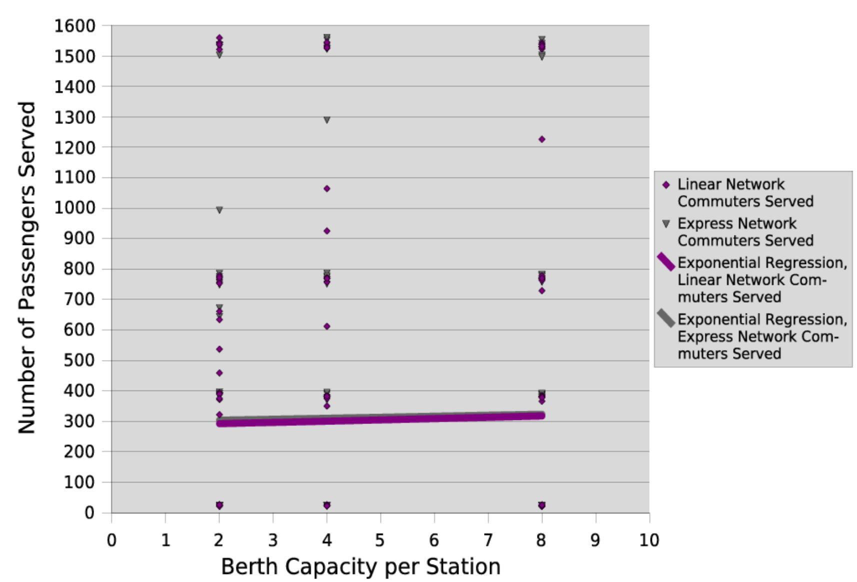
Passenger Departure Latency



Passenger Transfers

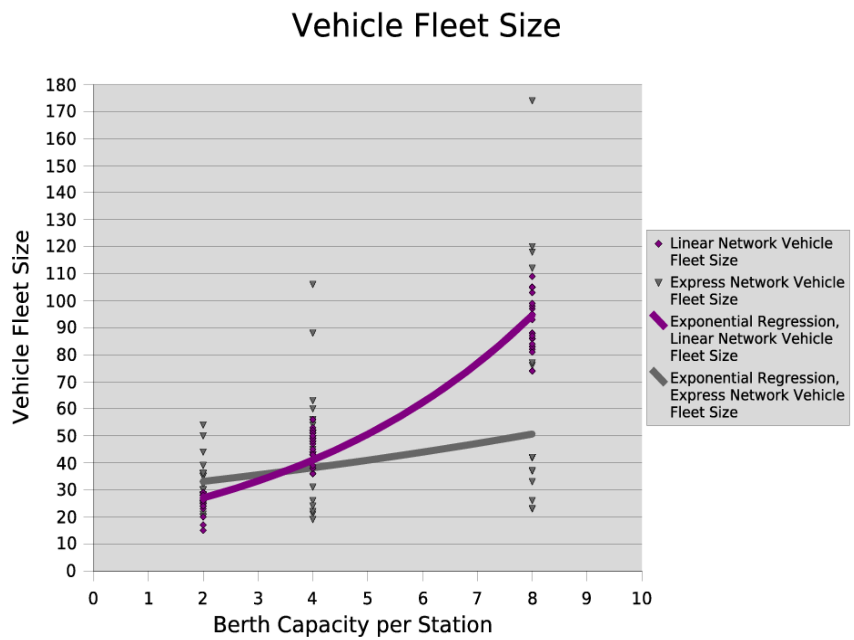


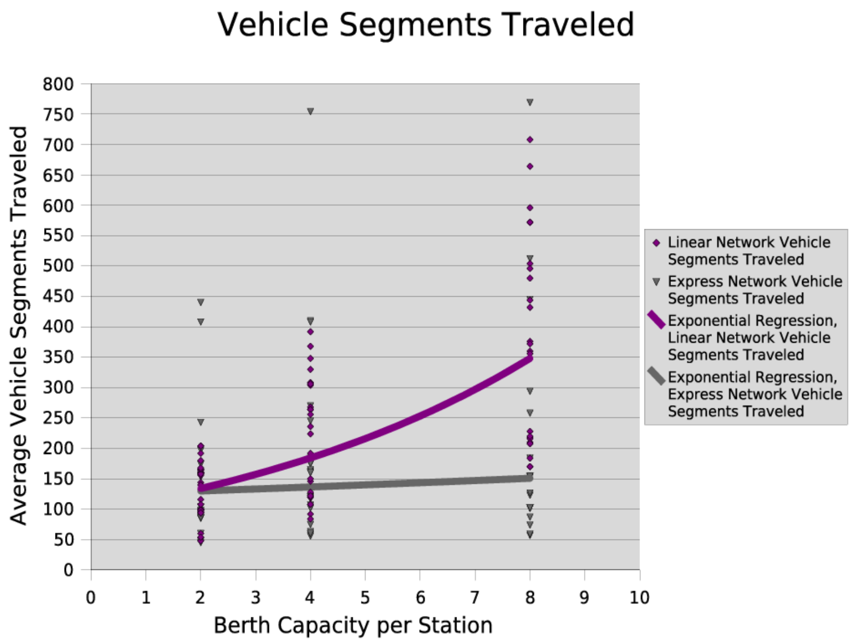
Passengers Served

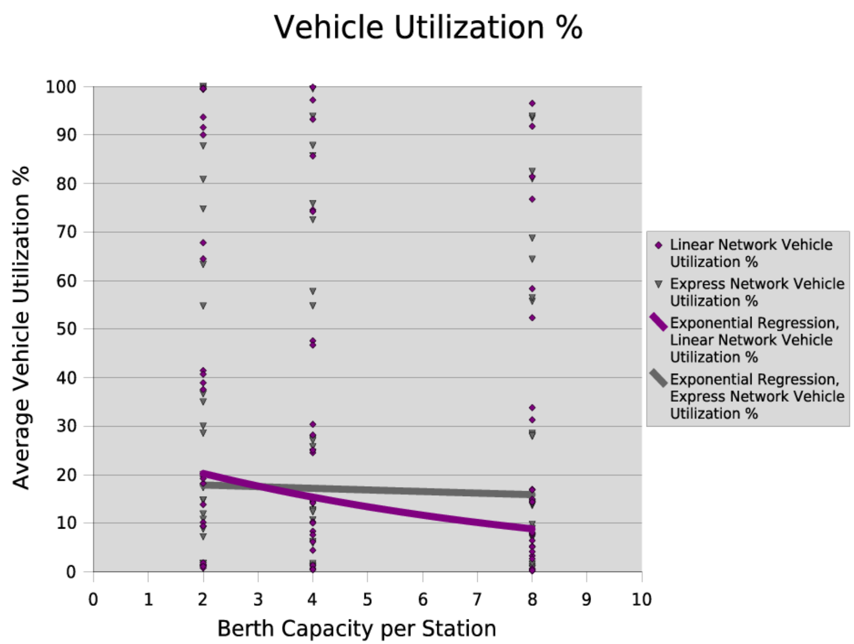


Fleet Operator view of Sequential vs. Express routing with respect to **Station Berth Capacity**

Effect of Station Size on Vehicle Fleet Metrics







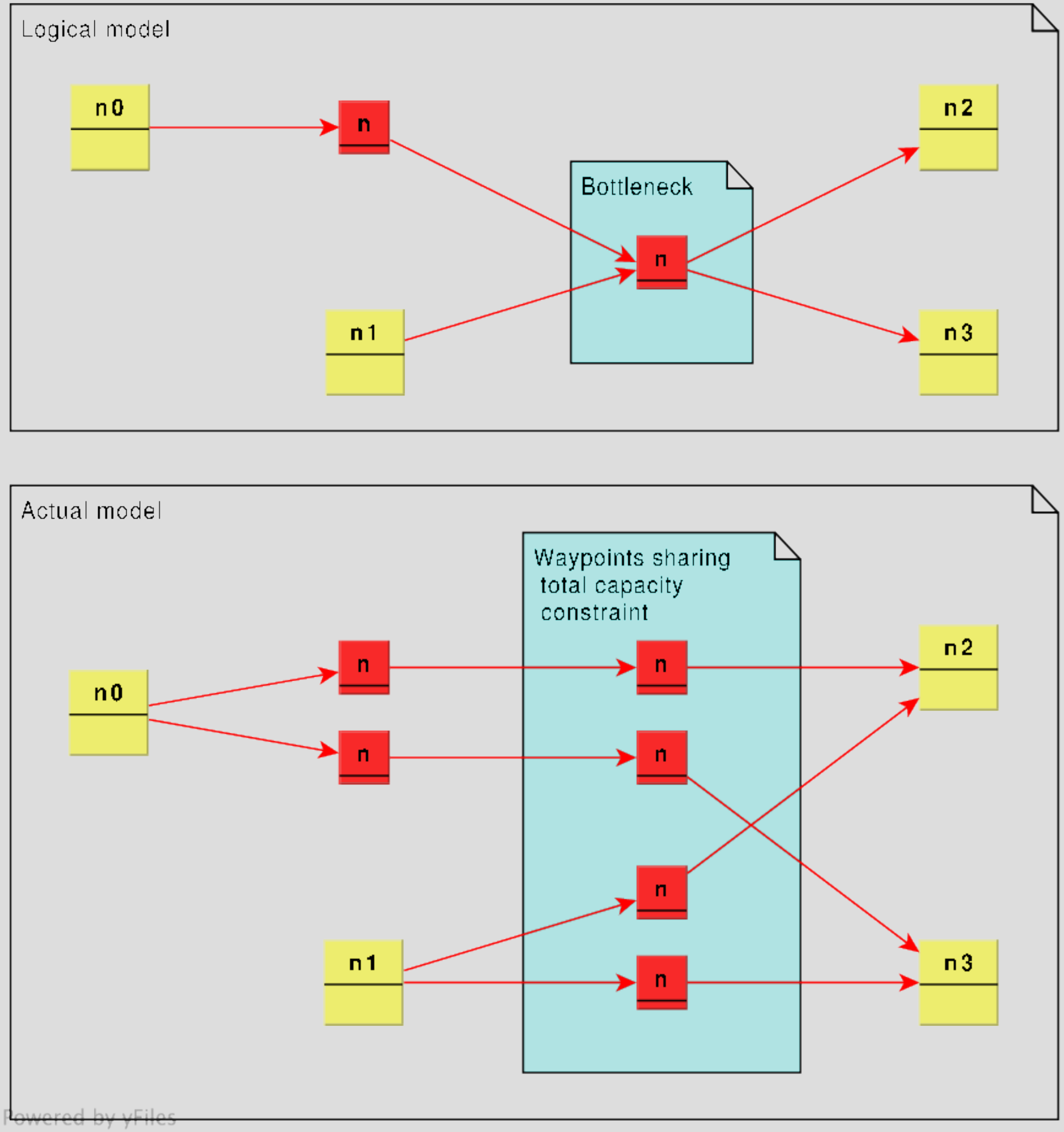
Conclusion:

This tool can do interesting things

- Dramatic improvement in mass transit performance possible by:
  - Using demand-responsive routing optimization
  - Constructing transfer stations off-line
- We can make mass transit perform as well as personally-owned vehicles
  - But this comes at a cost
  - Design transit-oriented development to keep network utilization at sustainable levels
- Analysts might use this tool to generate interesting data for trade studies

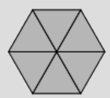
Future Work: Model feature completion

- State initialization to allow rolling time horizon
- Vehicle blocking on grouped constraints
- Priority passenger service via station queue manipulation

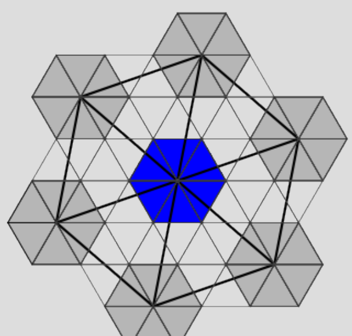


Future Work: Scalability

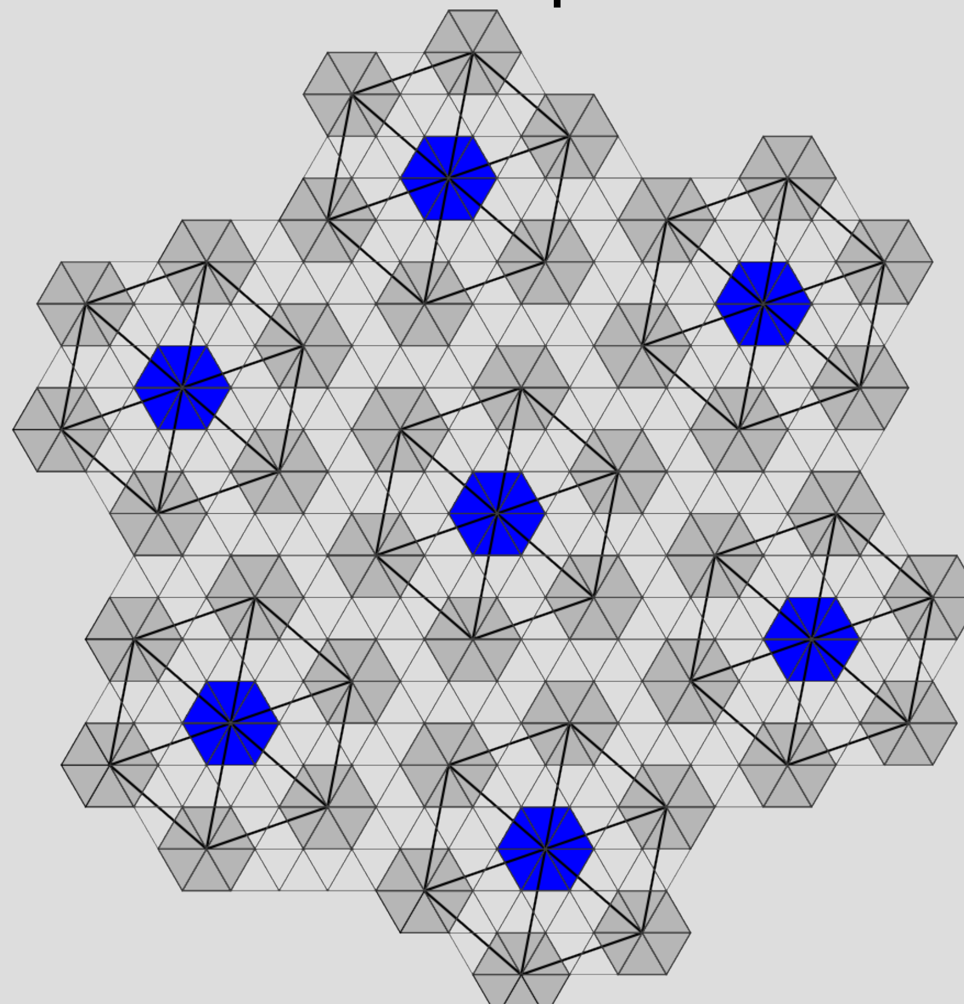
- Recursive Self-similar Hierarchical Space-Filling Structures



Basic 7-node unit

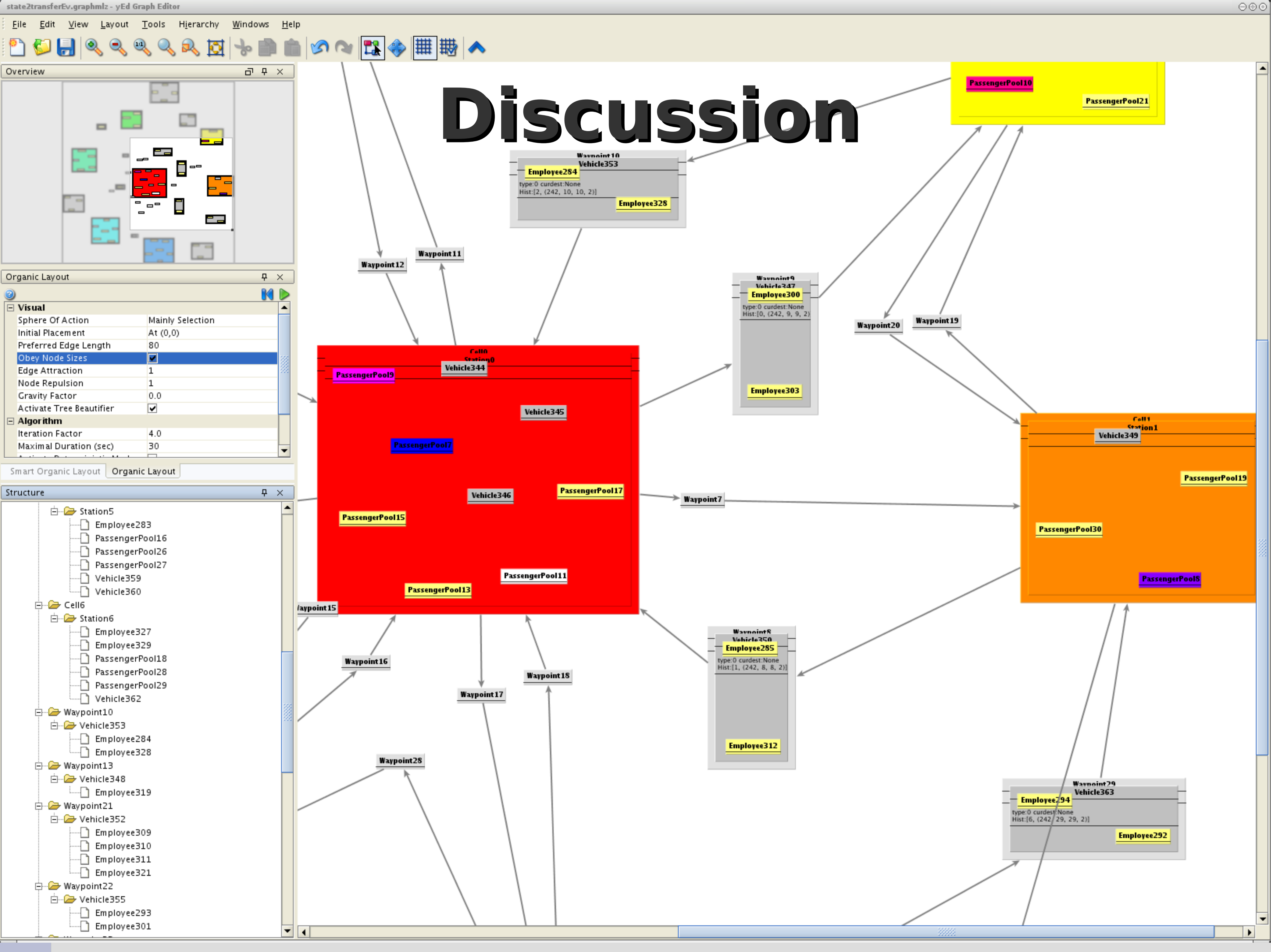


2nd level cluster of 49 nodes



3rd level cluster of 343 nodes

Discussion


state2transferEv.graphmlz - yEd Graph Editor
File
Edit
View
Layout
Tools
Hierarchy
Windows
Help
Overview
Organic Layout
Visual
Sphere Of Action
Mainly Selection
Initial Placement
At (0,0)
Preferred Edge Length
80
Obey Node Sizes
Edge Attraction
1
Node Repulsion
1
Gravity Factor
0.0
Activate Tree Beautifier
Algorithm
Iteration Factor
4.0
Maximal Duration (sec)
30
Smart Organic Layout
Organic Layout
Structure
Station5
Employee283
PassengerPool16
PassengerPool26
PassengerPool27
Vehicle359
Vehicle360
Cell6
Station6
Employee327
Employee329
PassengerPool18
PassengerPool28
PassengerPool29
Vehicle362
Waypoint10
Vehicle353
Employee284
Employee328
Waypoint13
Vehicle348
Employee319
Waypoint21
Vehicle352
Employee309
Employee310
Employee311
Employee321
Waypoint22
Vehicle355
Employee293
Employee301
PassengerPool10
PassengerPool21
Waypoint10
Vehicle353
Employee284
type:0 curdest:None
Hist:[2, (242, 10, 10, 2)]
Employee328
Waypoint12
Waypoint11
Waypoint9
Vehicle347
Employee300
type:0 curdest:None
Hist:[0, (242, 9, 9, 2)]
Employee303
Waypoint20
Waypoint19
Cell0
Station0
Vehicle344
PassengerPool9
Vehicle345
PassengerPool7
Vehicle346
PassengerPool17
PassengerPool15
PassengerPool11
PassengerPool13
Waypoint7
Cell1
Station1
Vehicle349
PassengerPool19
PassengerPool30
PassengerPool8
aypoint15
Waypoint16
Waypoint17
Waypoint18
Waypoint8
Vehicle350
Employee285
type:0 curdest:None
Hist:[1, (242, 8, 8, 2)]
Employee312
Waypoint28
Waypoint29
Vehicle363
Employee294
type:0 curdest:None
Hist:[6, (242, 29, 29, 2)]
Employee292