

Arcology Simulation Framework

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University of Maryland
Systems Engineering
Master of Science Thesis

June 4, 2007

Project Summary:

Optimization and simulation framework to analyze transit-oriented designs

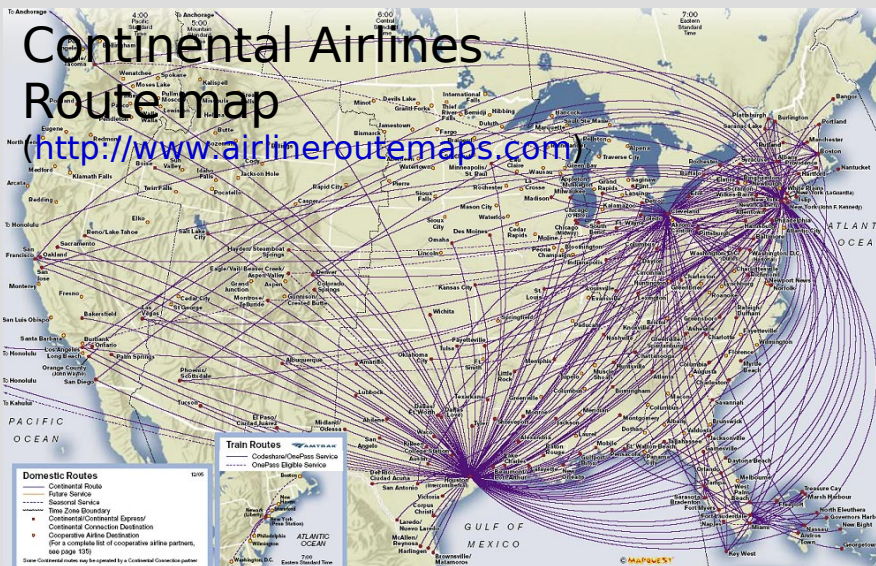
Address 2 questions:

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



NASA SATS aircraft - takeoff to landing
NASA Langley Research Center

2/3/2000

Image # EL-2000-00007

- 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

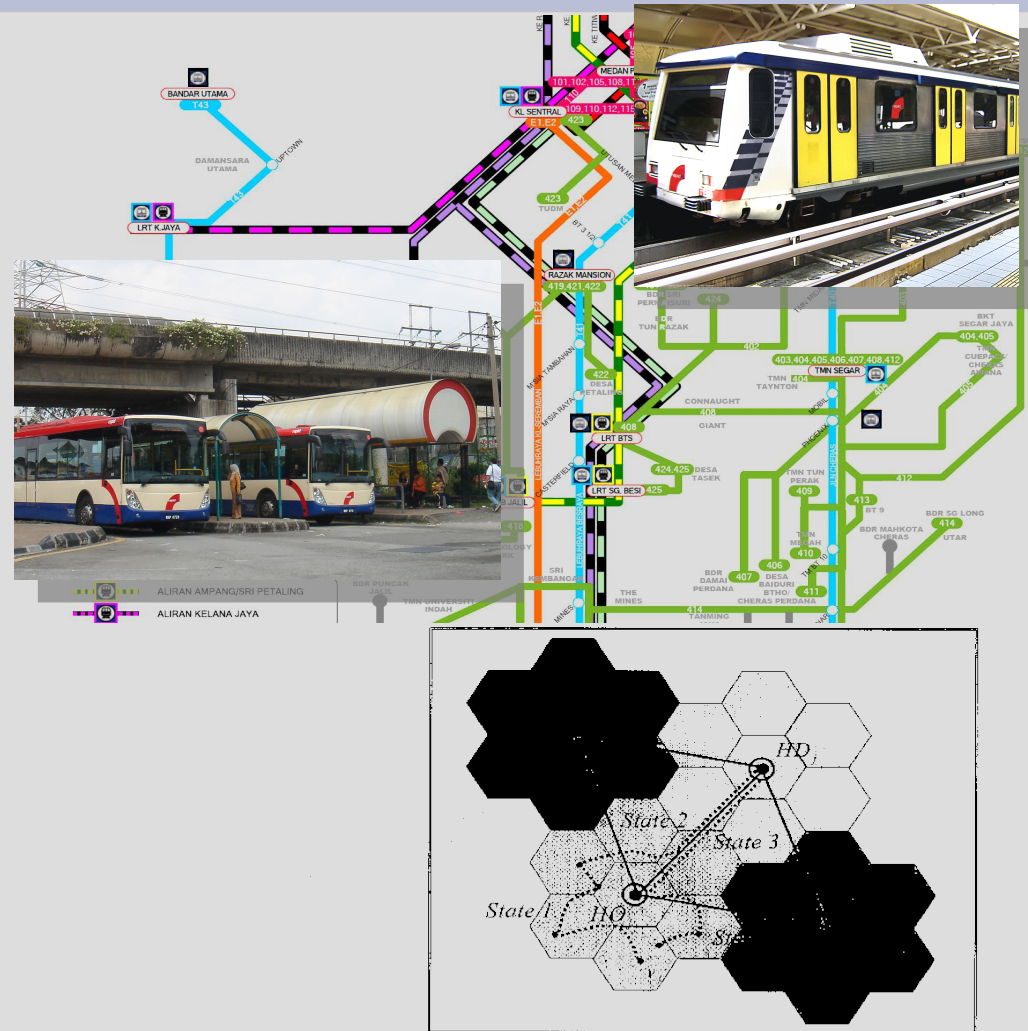
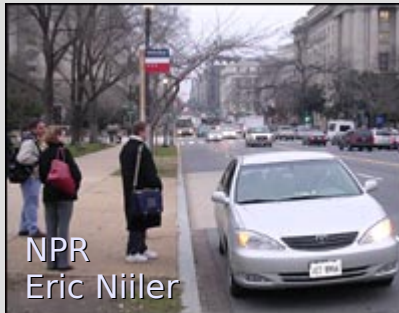


Figure 4.9 Vehicle schedule representation

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

Vehicle Sharing Options and Concepts



- 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

7 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
- 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

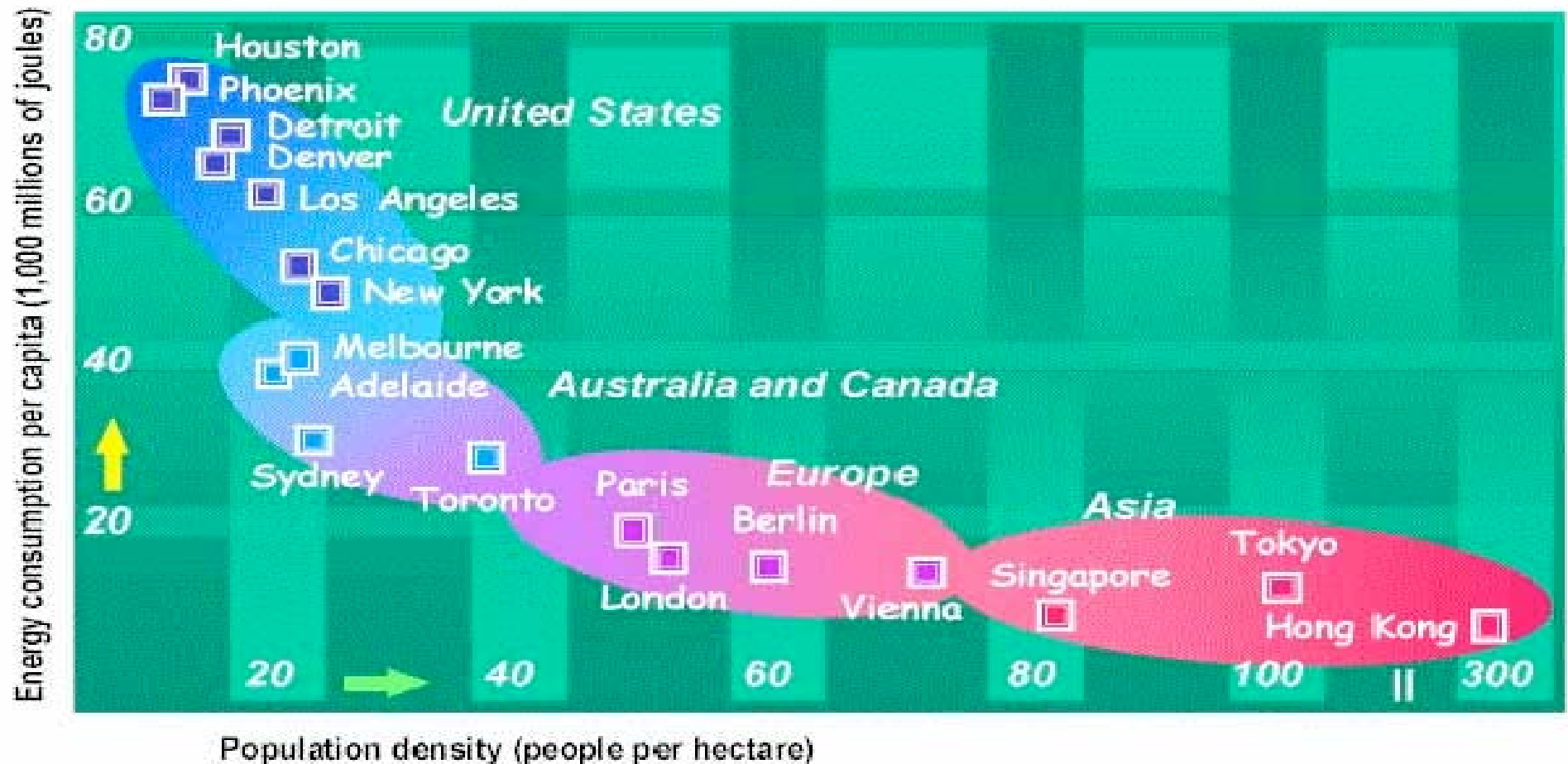


Figure 2. The relationship between population density and energy consumption in cities.

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

Arcologies and Compact Cities pack functionality



Soleri's *Arcology*

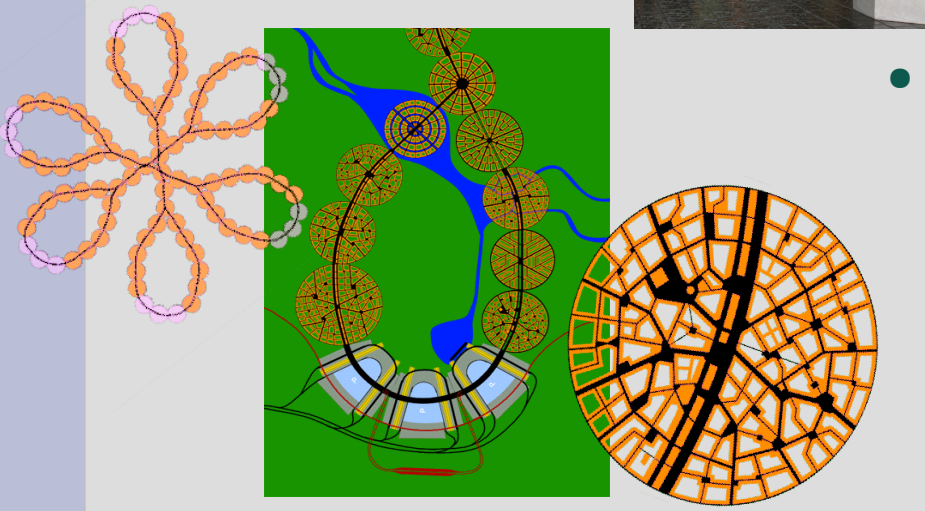
- Architectural implosion of cities
- Form a human relationship to the environment

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

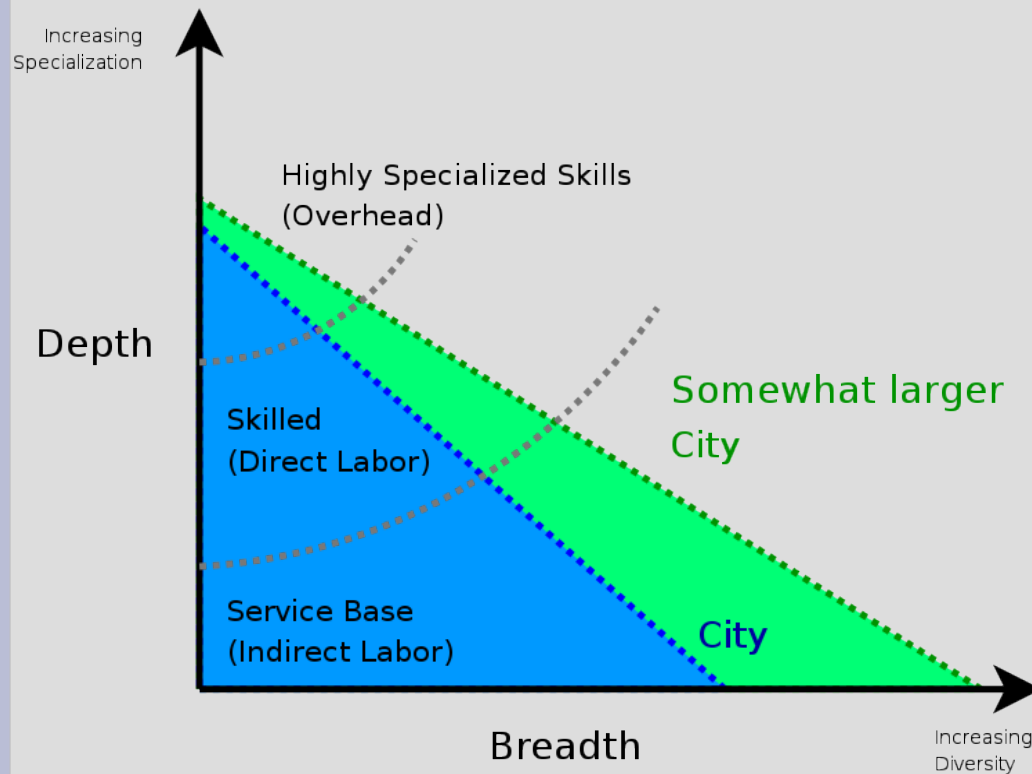


A Metropolitan complex should maximize diversity

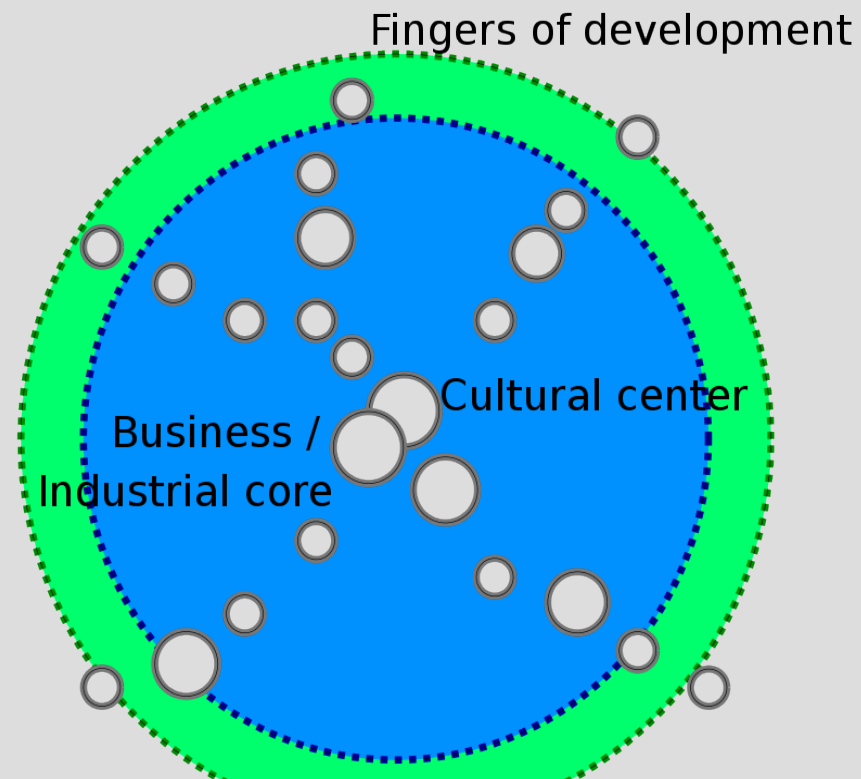
Offer diverse set of specialized skills and jobs

- Well-suited for a systems approach to the design of life support infrastructure

Population Skill Distribution



Geography



Mass Transit Optimization

Key Capabilities

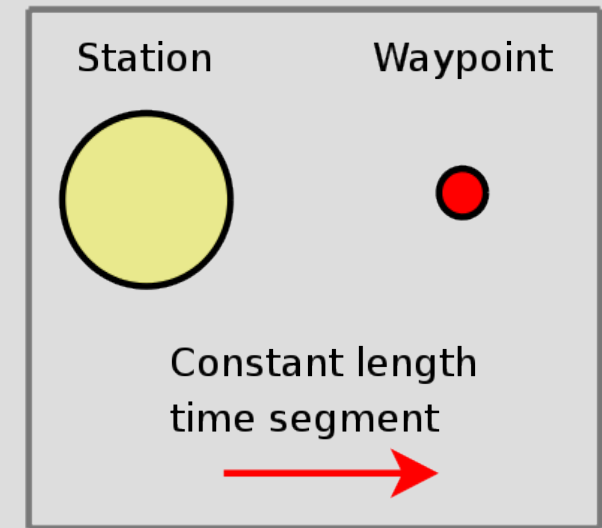
- Investigate optimal transfer strategies
 - Hub & spoke (e.g. bus feeders & light rail trunks)
 - Point-to-point (e.g. taxis, vanpools)
- Demand-responsive dynamic vehicle routing
 - Creates unique schedule based on demand inputs
 - Utilizes command, control, and monitoring networks
 - Emphasizes passenger 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

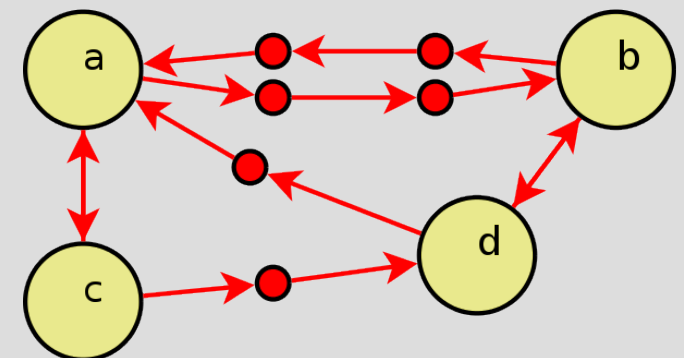
Modeled as an inventory problem

- **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

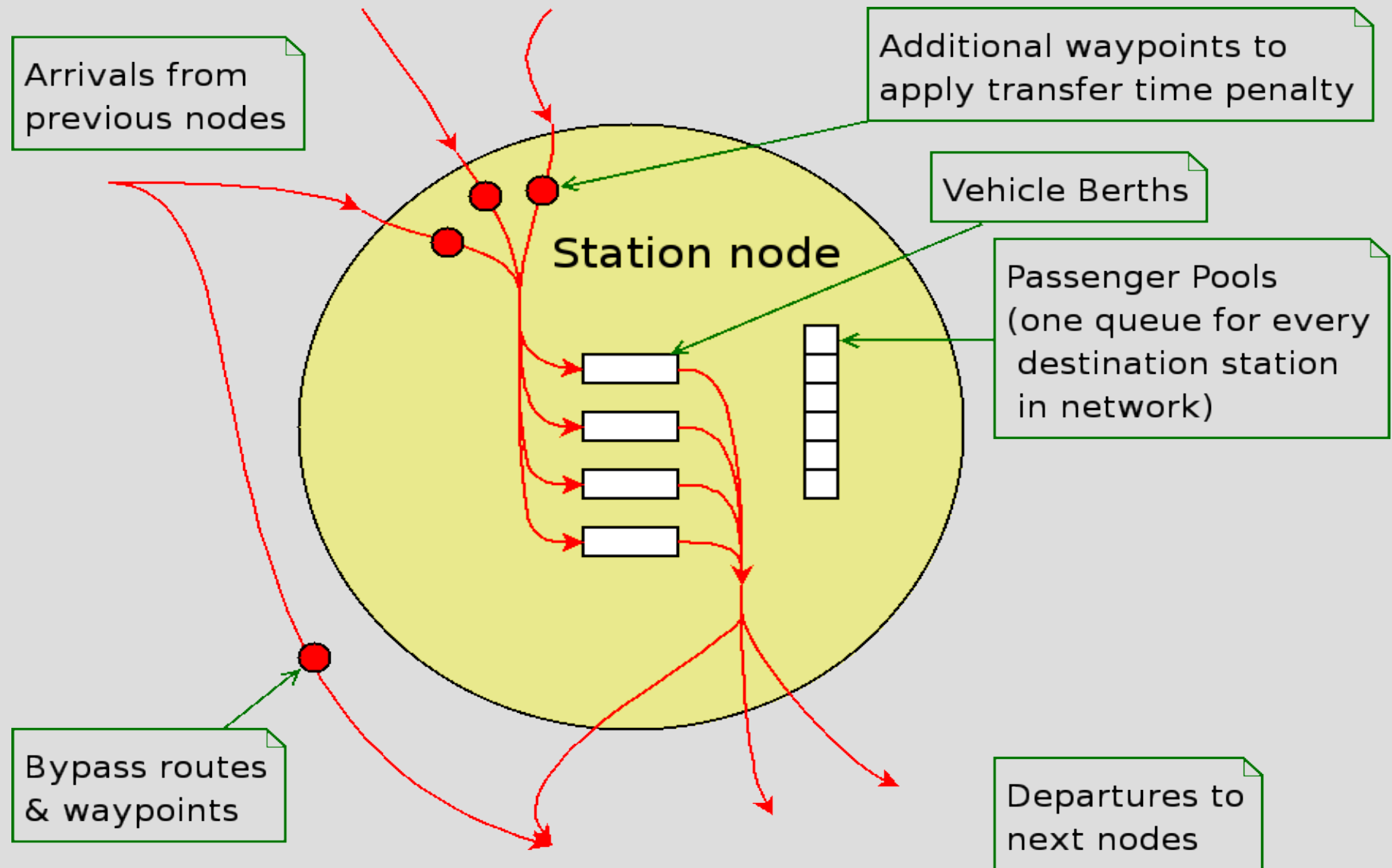
Model elements



Sample model of one transit layer



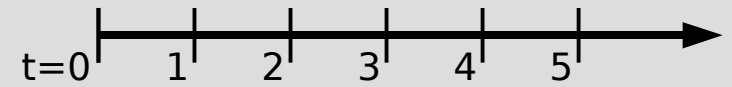
Conceptual Model of a Station



Transit Optimization

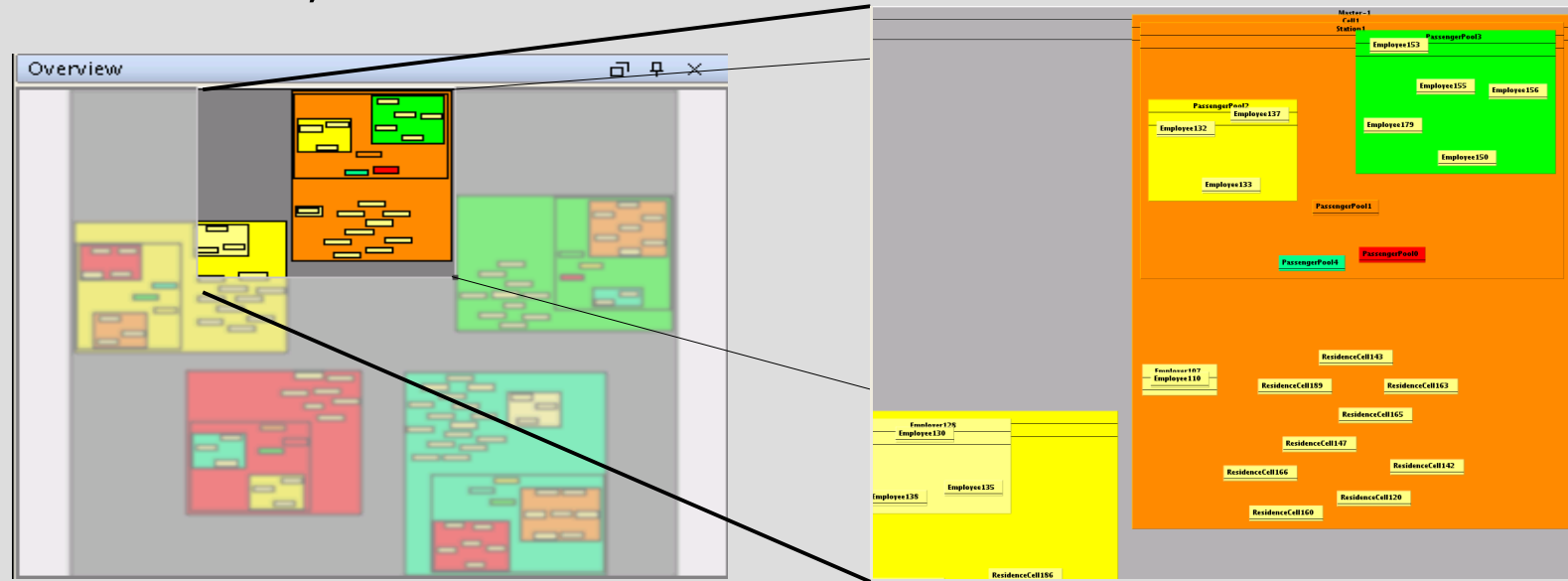
Input / Output Variables

- Time represented by synchronous integer time steps
- Demand defined by initial passenger origins for each time step at each station



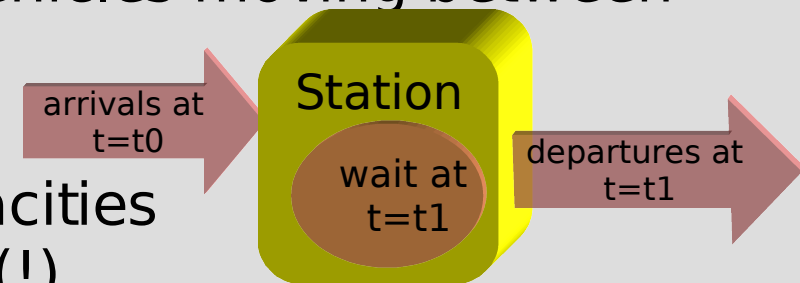
Output: schedule variables for each time step:

- 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

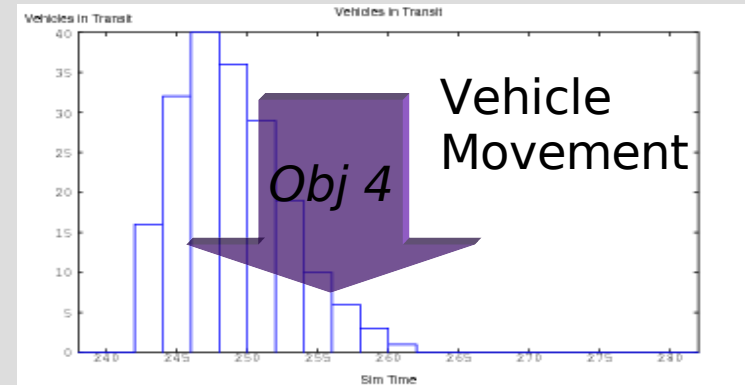
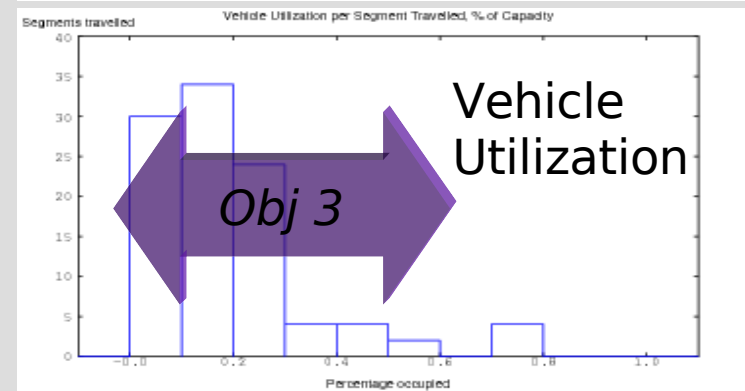
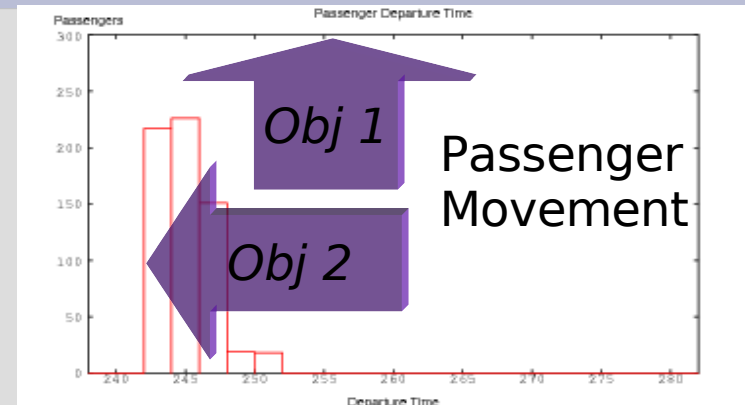
- Reward scheduler for delivering passengers earlier

3: Fleet Size (Optional)

- Minimize deviation from desired vehicle fleet size

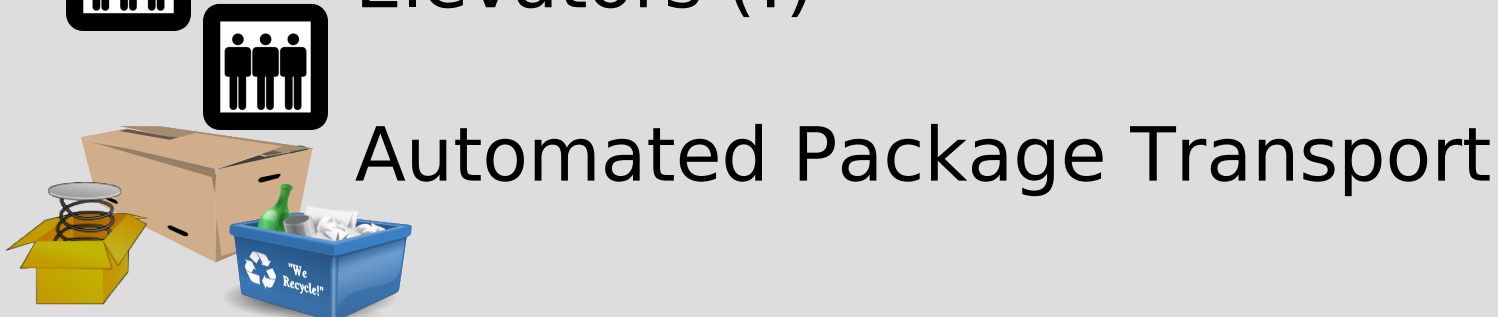
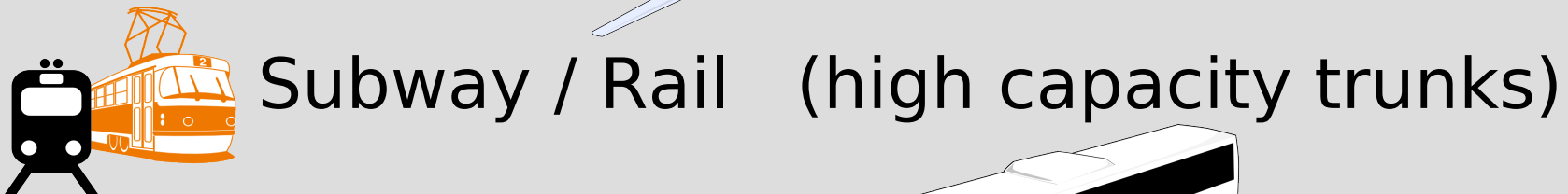
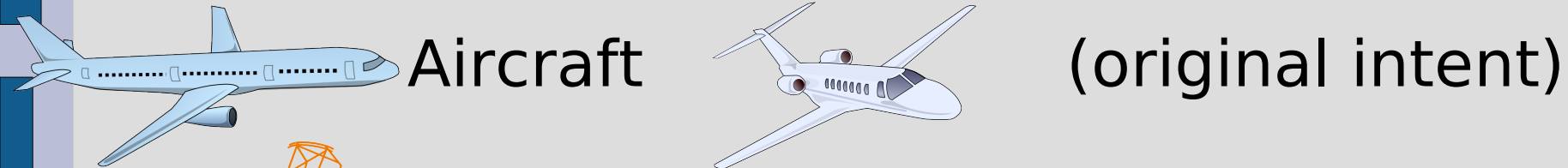
4: Operating Cost

- Minimize vehicle movements



Transit Modes:

timing, capacity, and optimization parameters tuned to represent:



Optimized Schedule Verified by Simulation

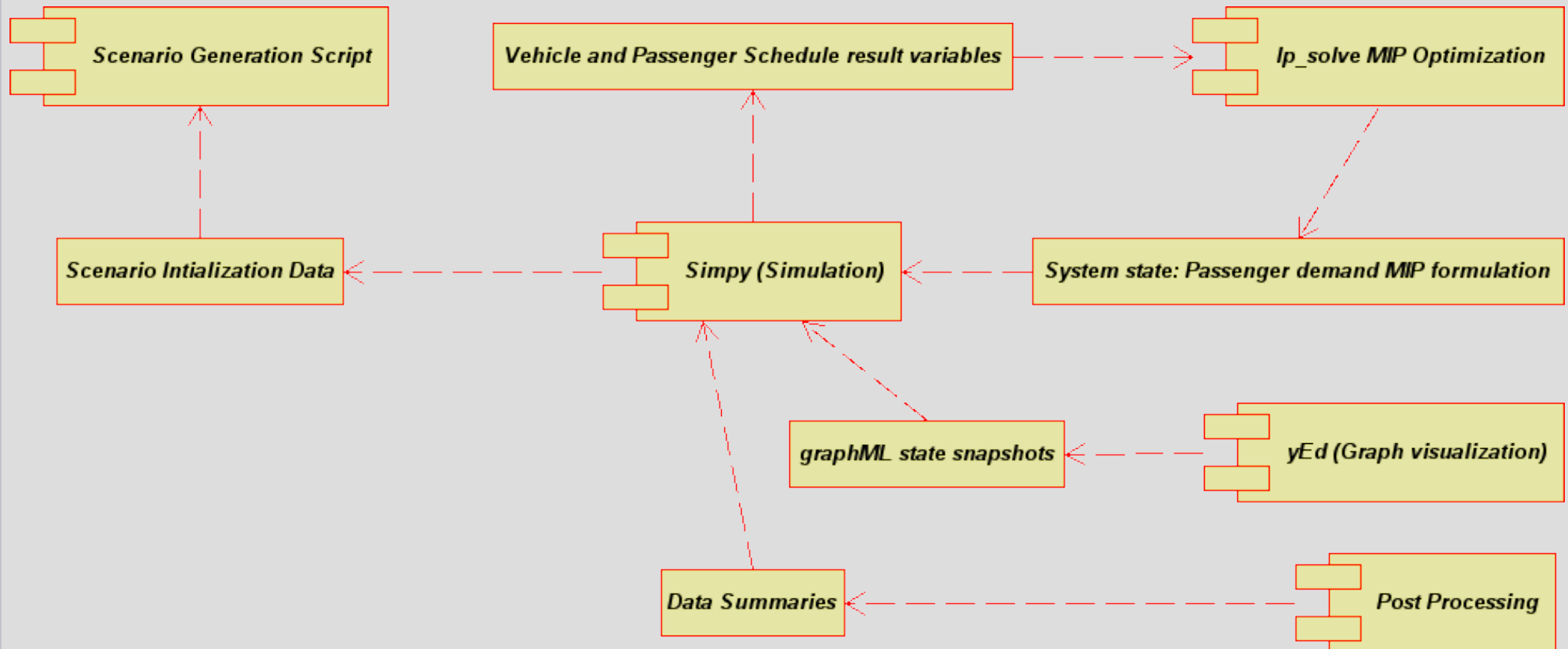
(the second half)

- 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

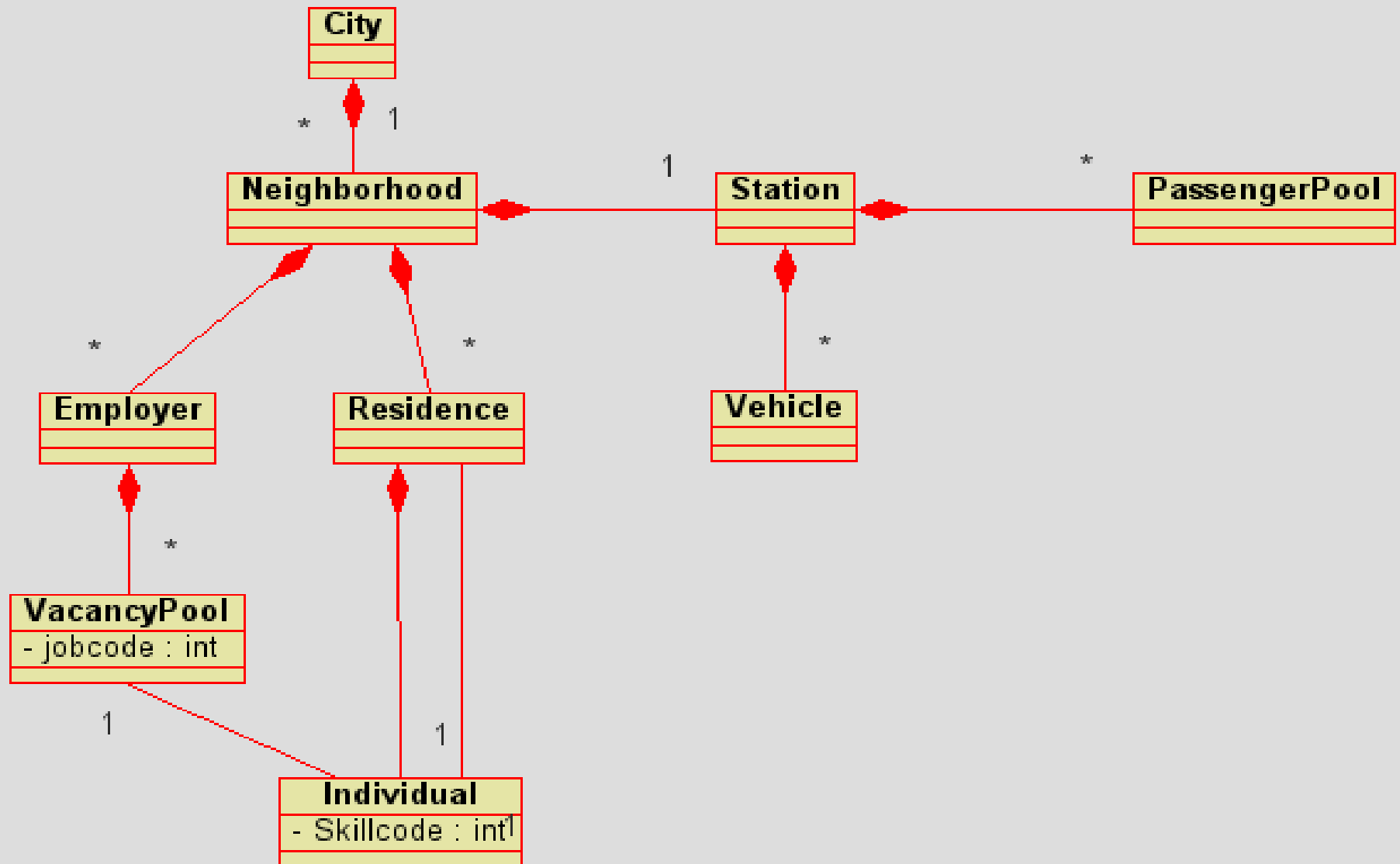
SimPy: discrete event simulation framework

LP_solve: MIP Optimization

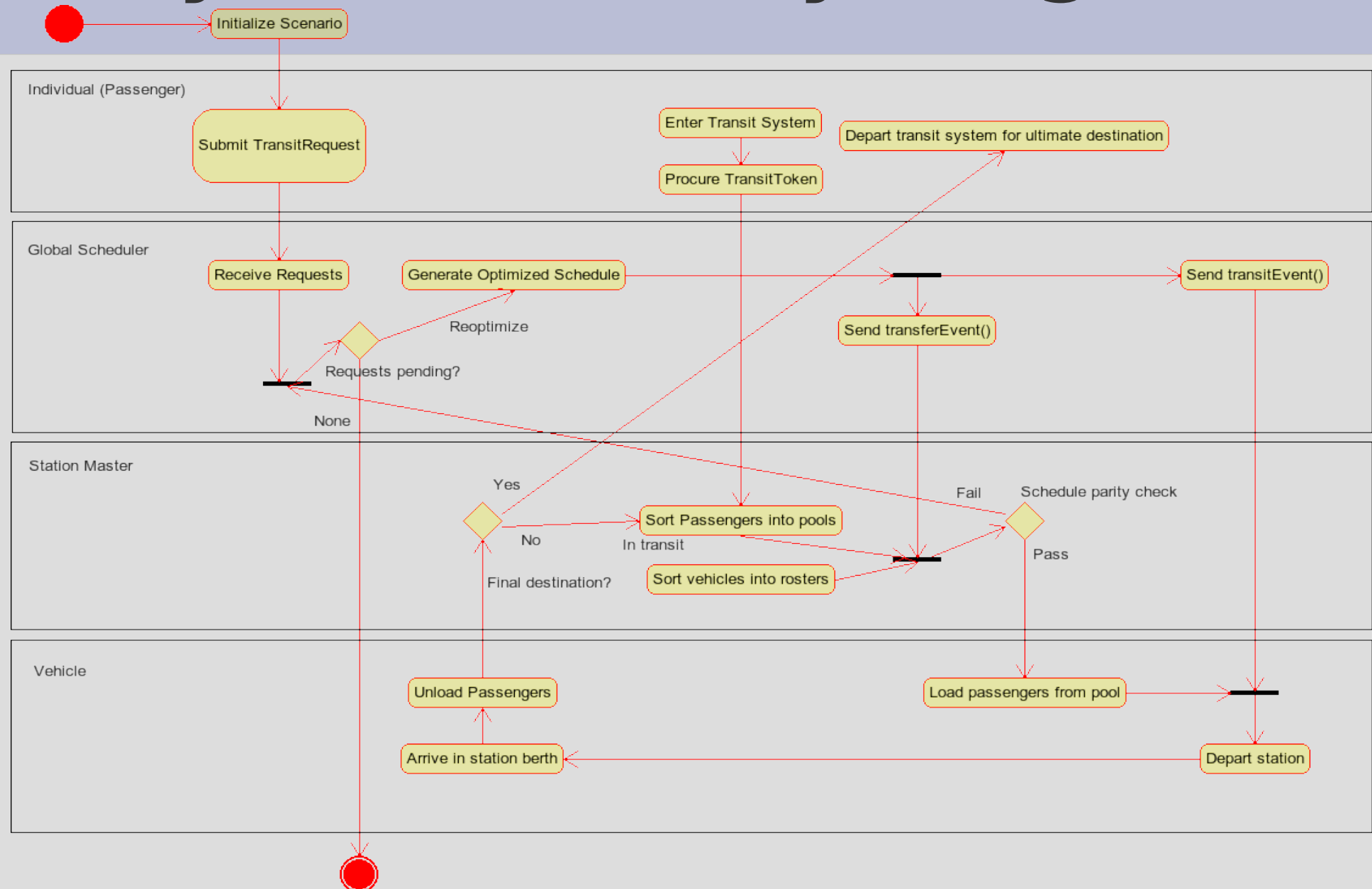
Simulation Component Diagram



Commuter Transit Model Class Structure



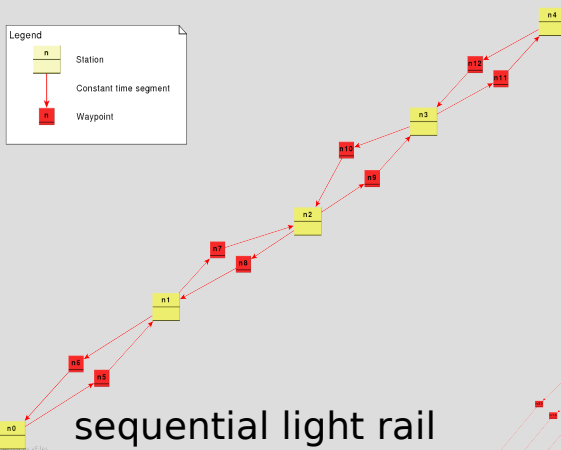
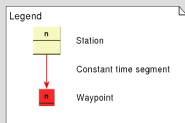
Commuter Transit Model System Activity Diagram



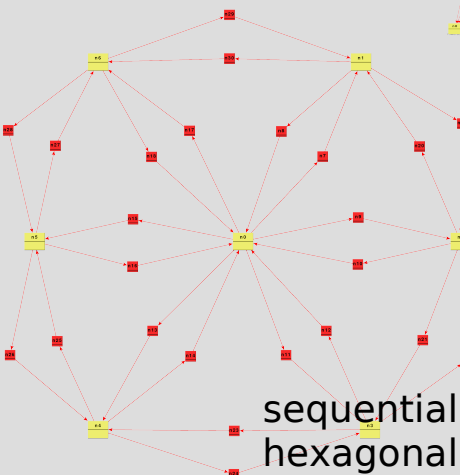
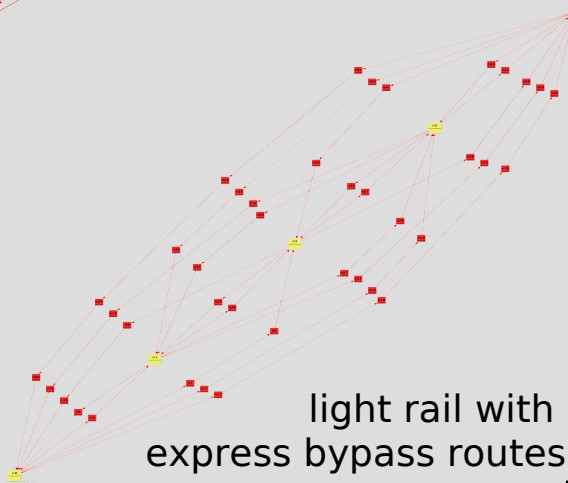
Verification and Validation

- 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

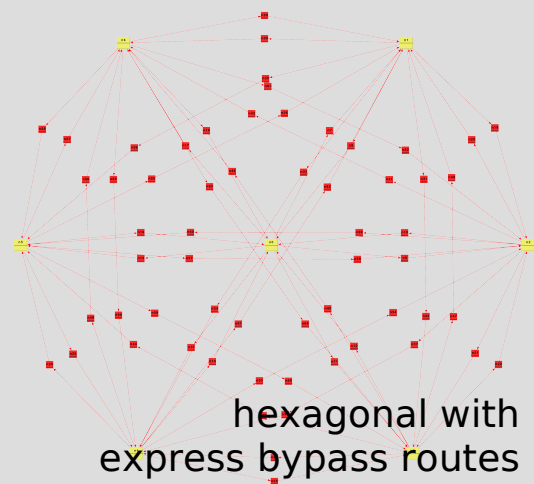
Parametric Analysis Scenarios



light rail with
express bypass routes



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

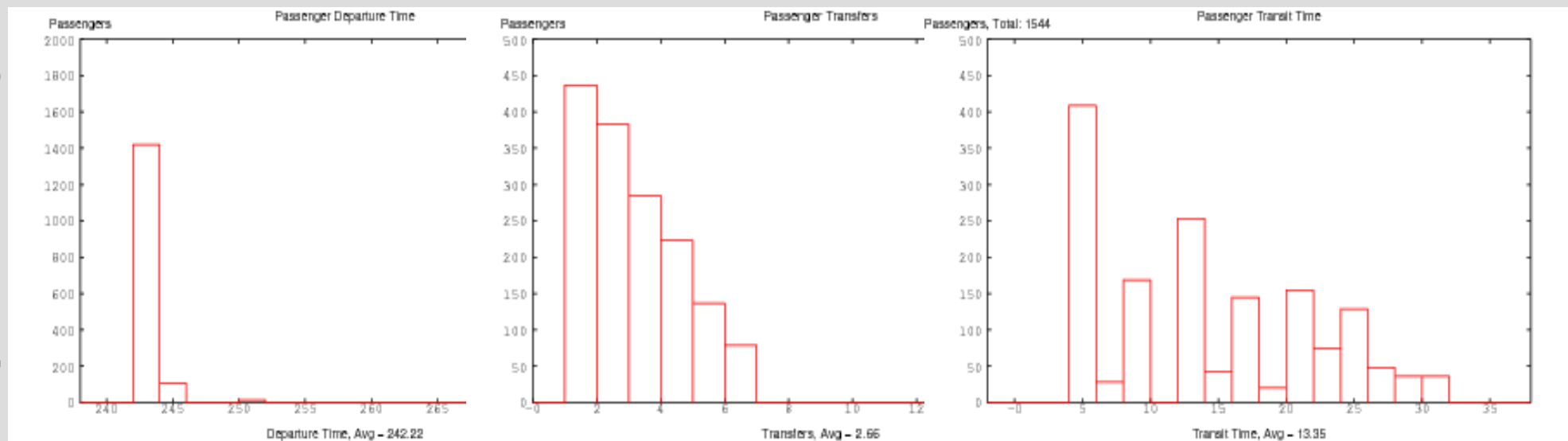
Response to uniform random demand pulse

waiting time (latency)

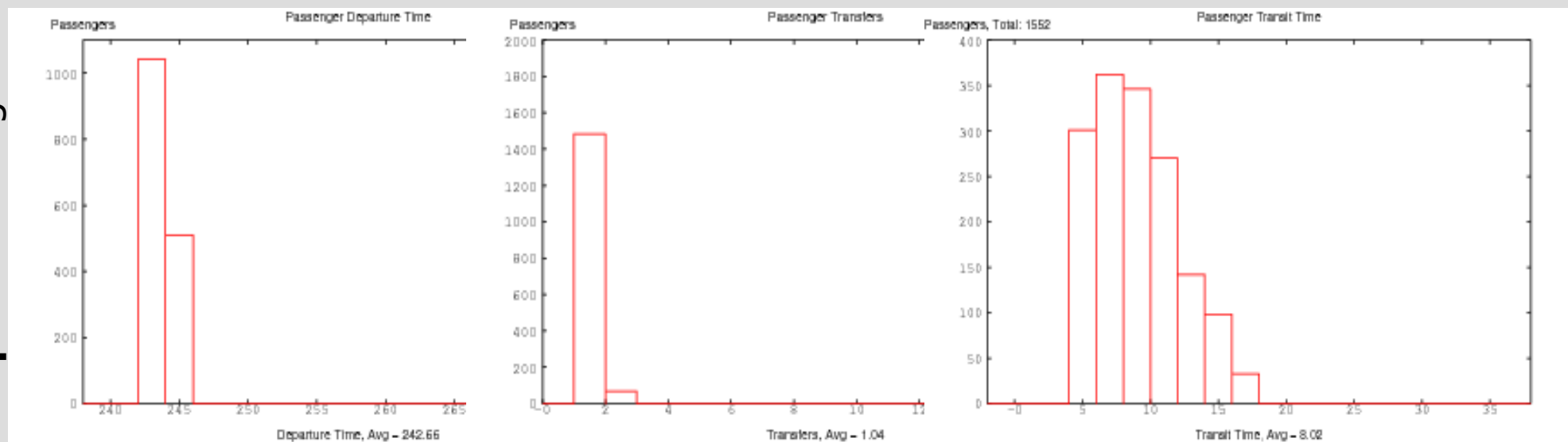
transfer stops (convenience)

travel time

Sequential routing



Express routing



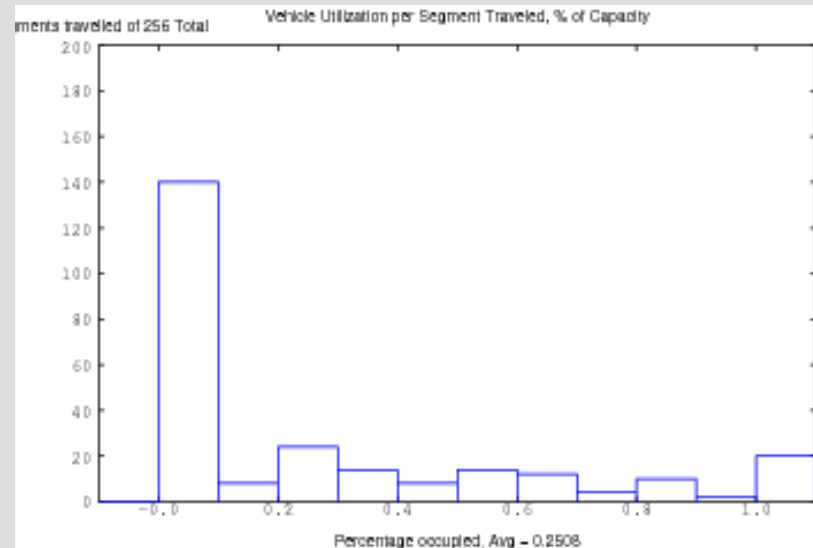
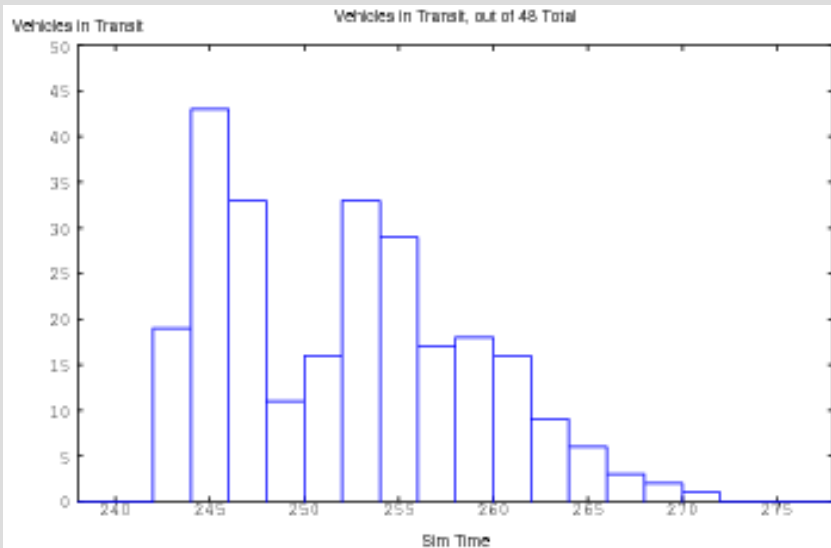
1D Rail Vehicle Metrics

Operating cost & efficiency

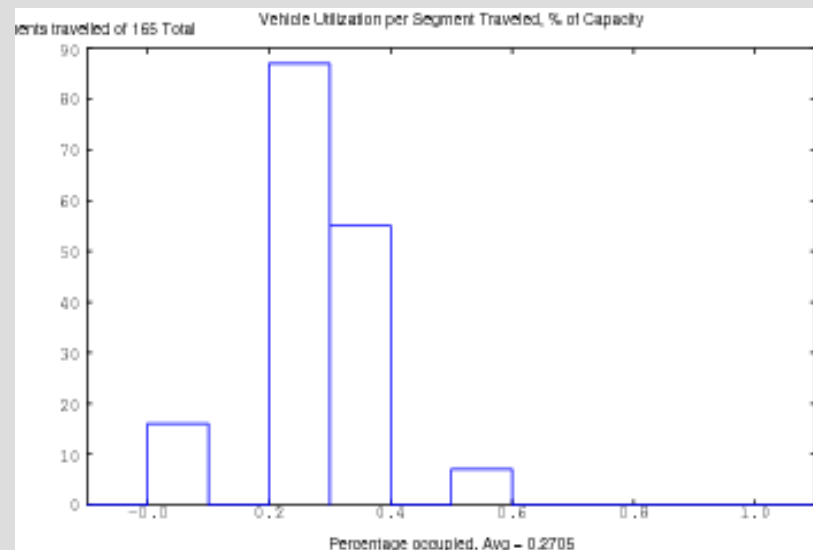
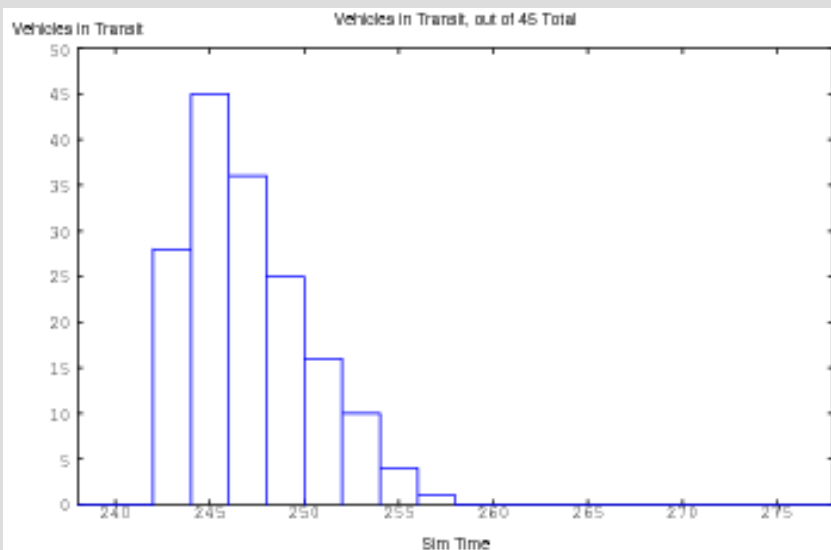
Vehicles in operation

Vehicle Utilization

Sequential routing



Express routing

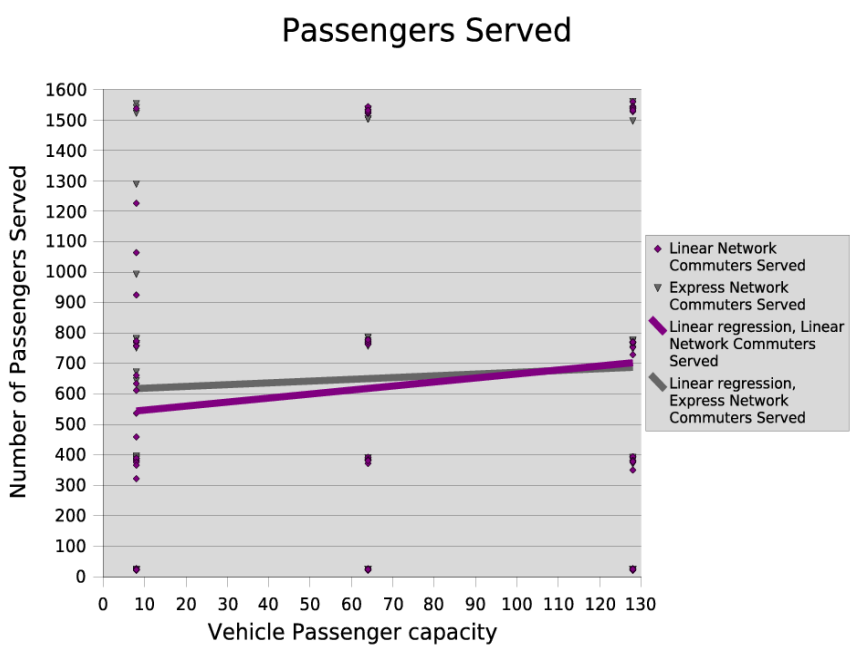
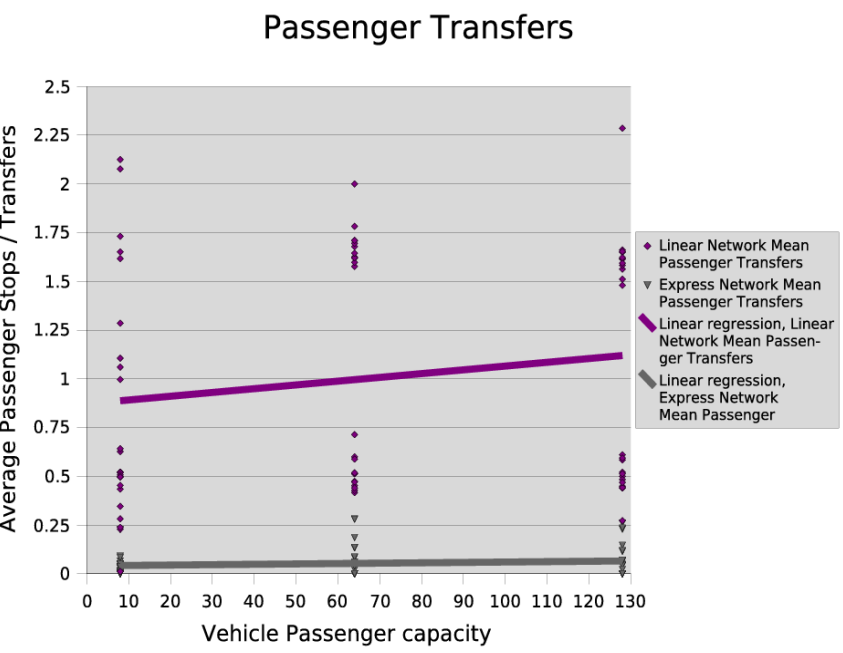
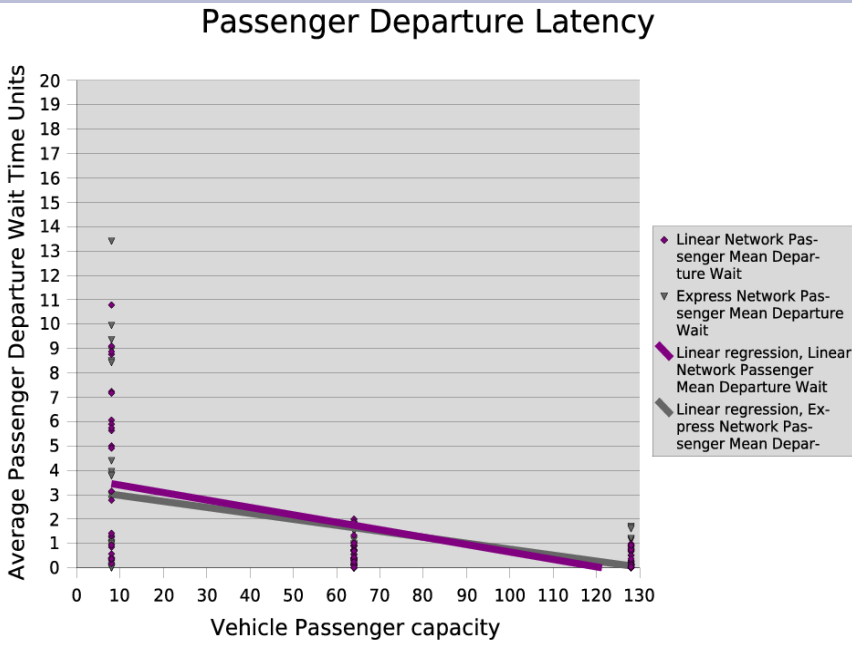
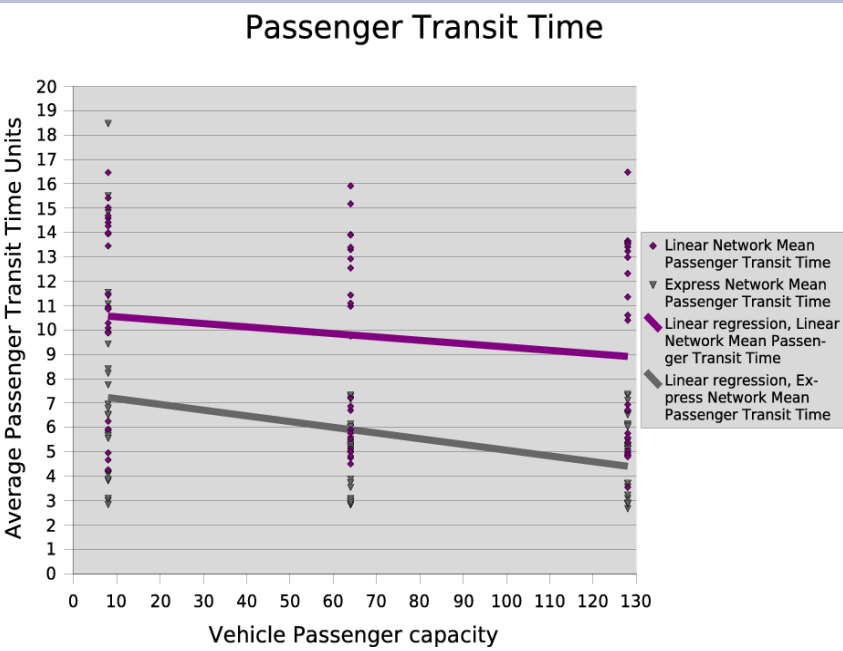


Factorial Experiments Design

- 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

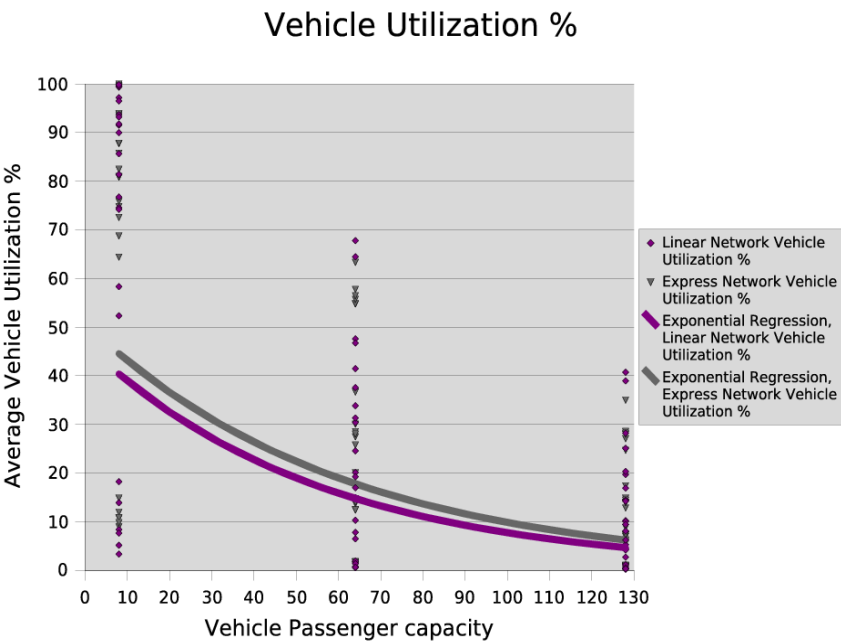
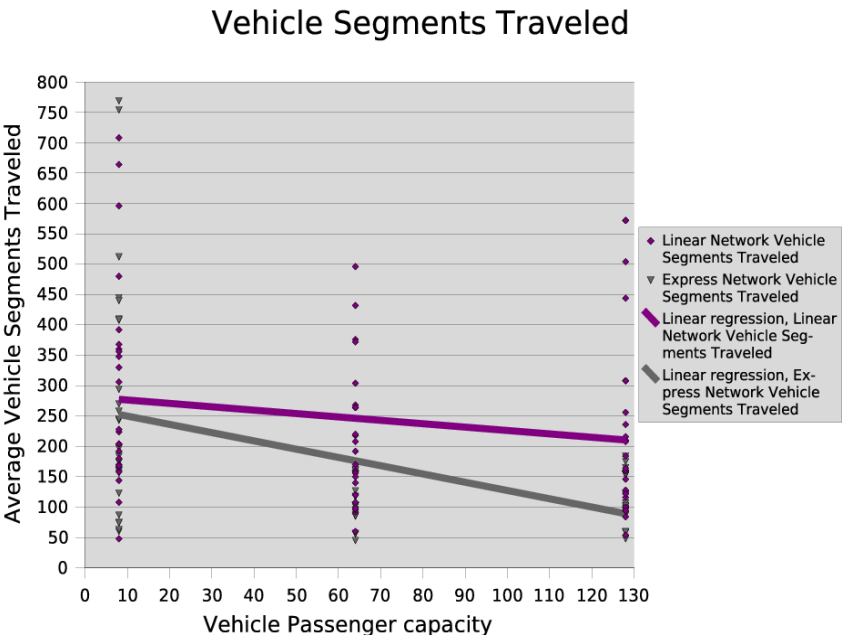
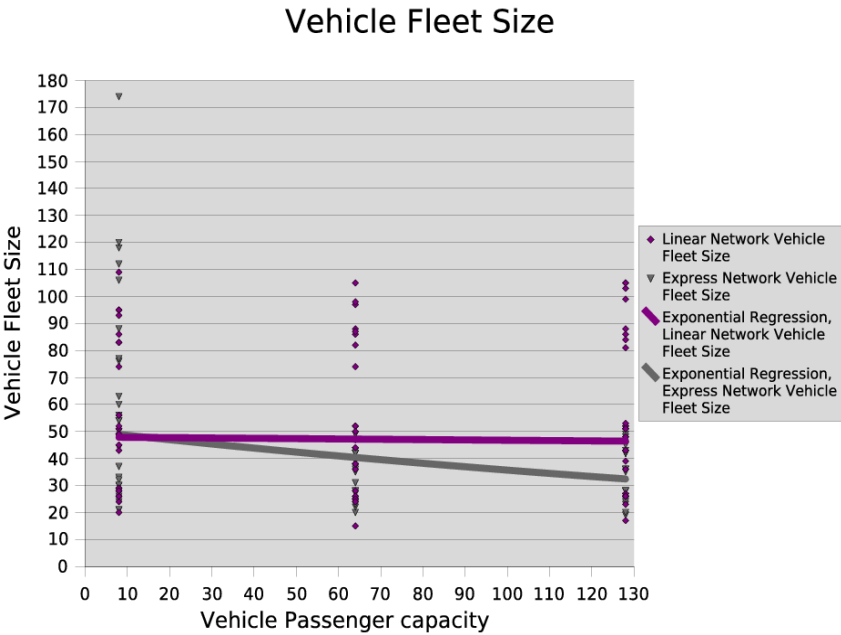
Passenger view of Sequential vs. Express routing with respect to Vehicle Capacity

Effect of Vehicle Capacity on Passenger Metrics



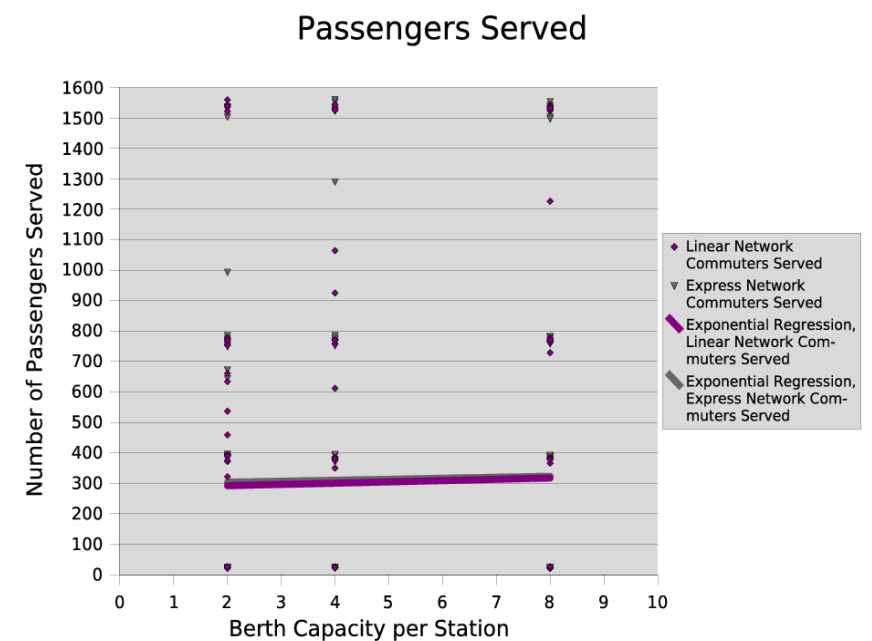
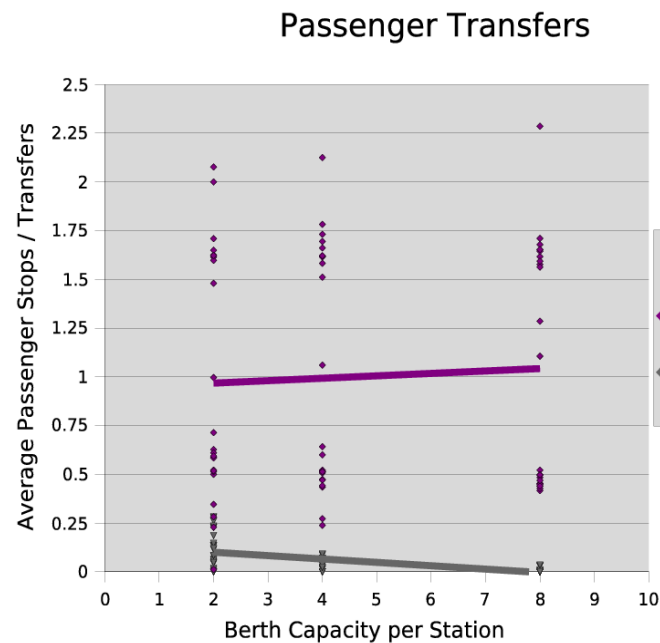
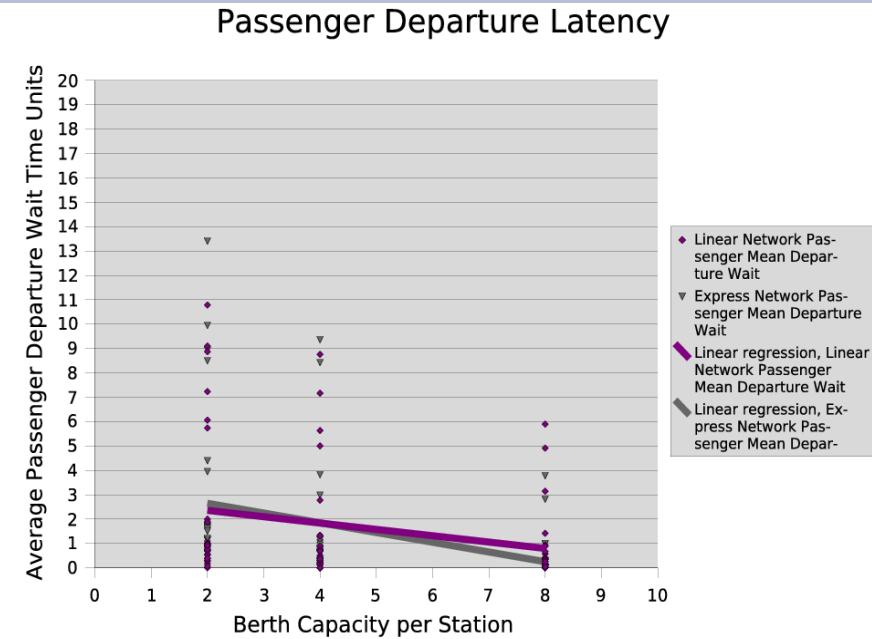
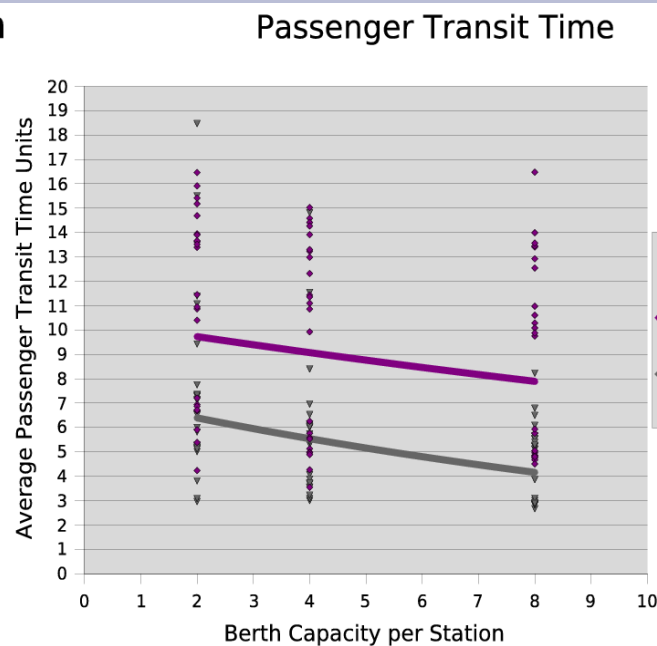
Fleet Operator view of Sequential vs. Express routing with respect to Vehicle Capacity

Effect of Vehicle Capacity on Vehicle Fleet Metrics



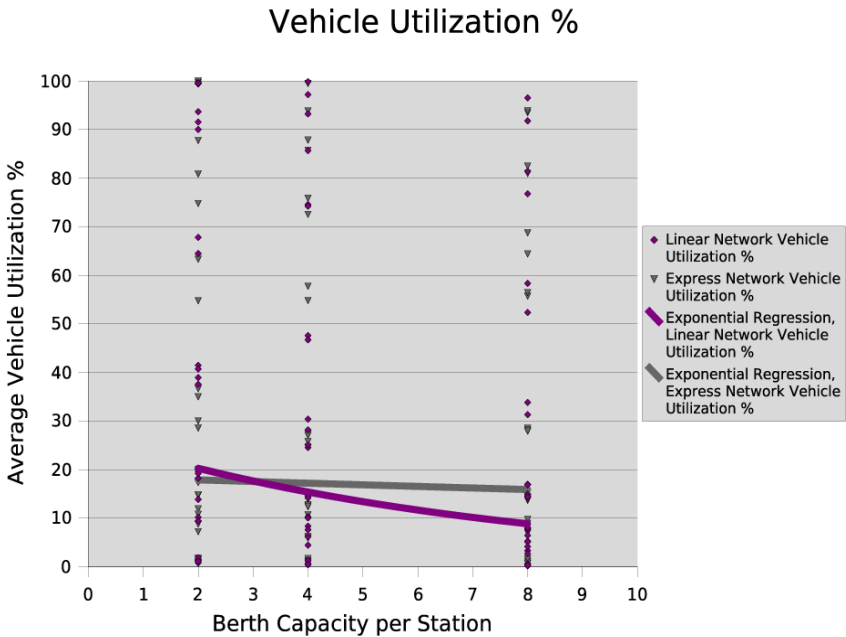
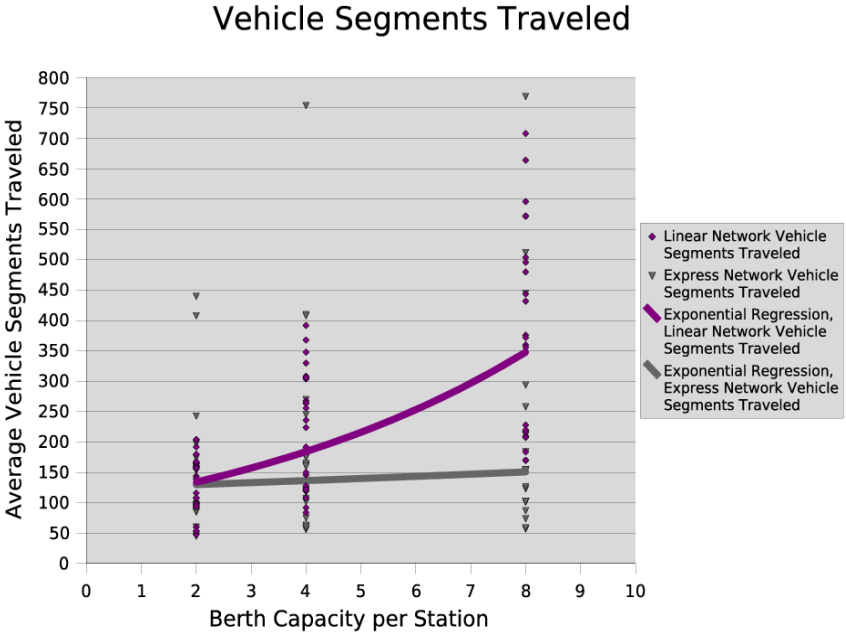
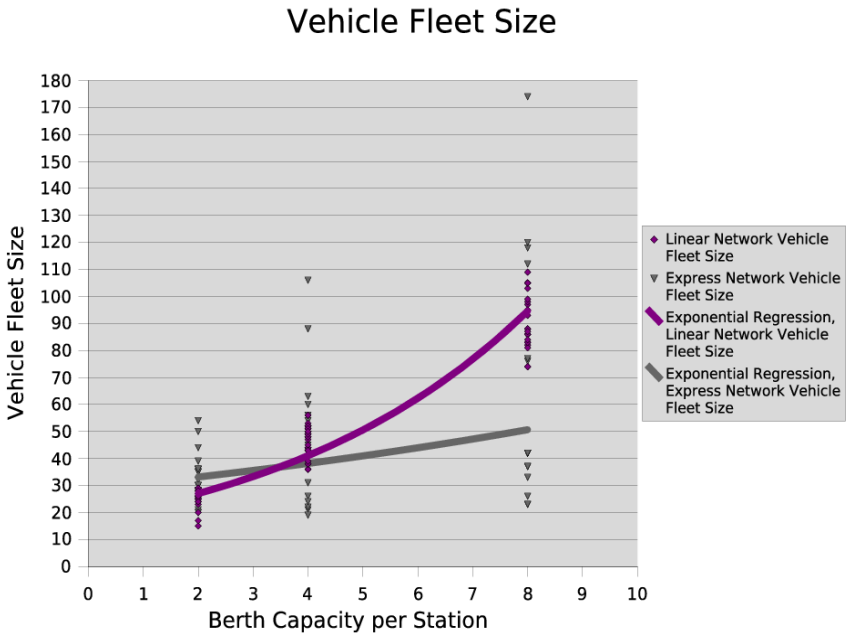
Passenger view of Sequential vs. Express routing with respect to Station Berth Capacity

Effect of Station Size on Passenger Metrics



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

Effect of Station Size on Vehicle Fleet Metrics



Conclusion:

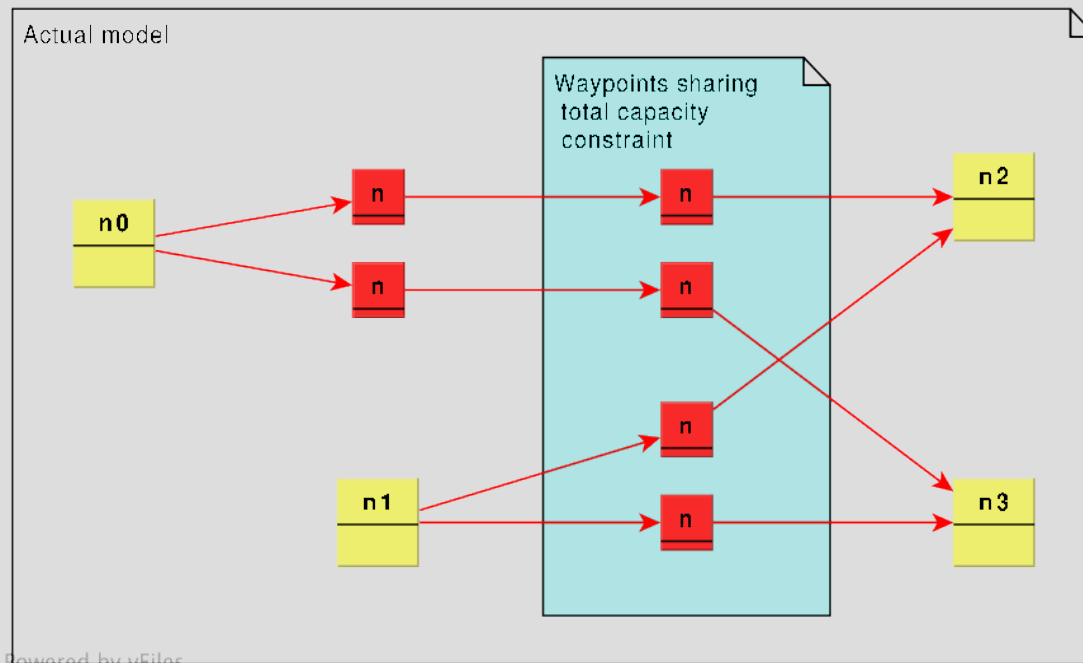
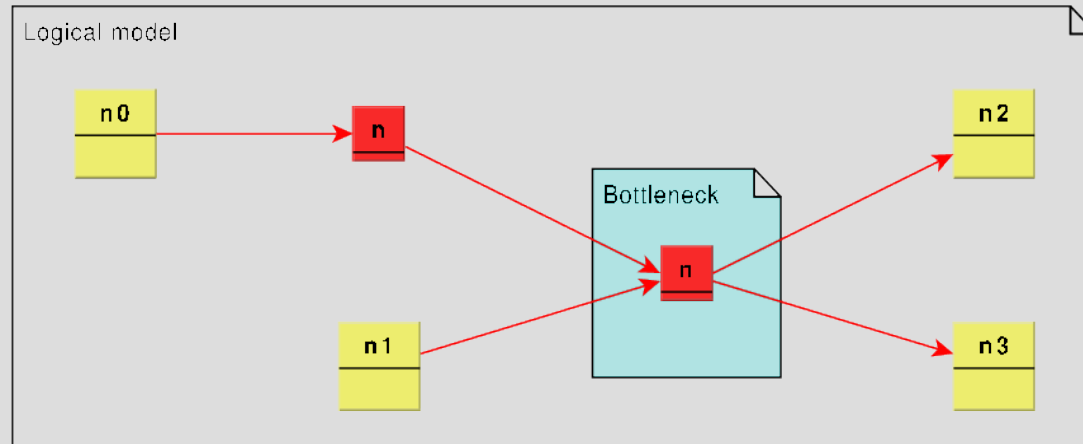
This tool can do interesting things

- 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

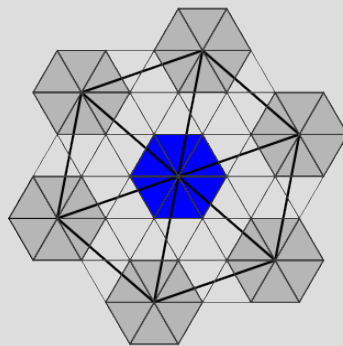


Future Work: Scalability

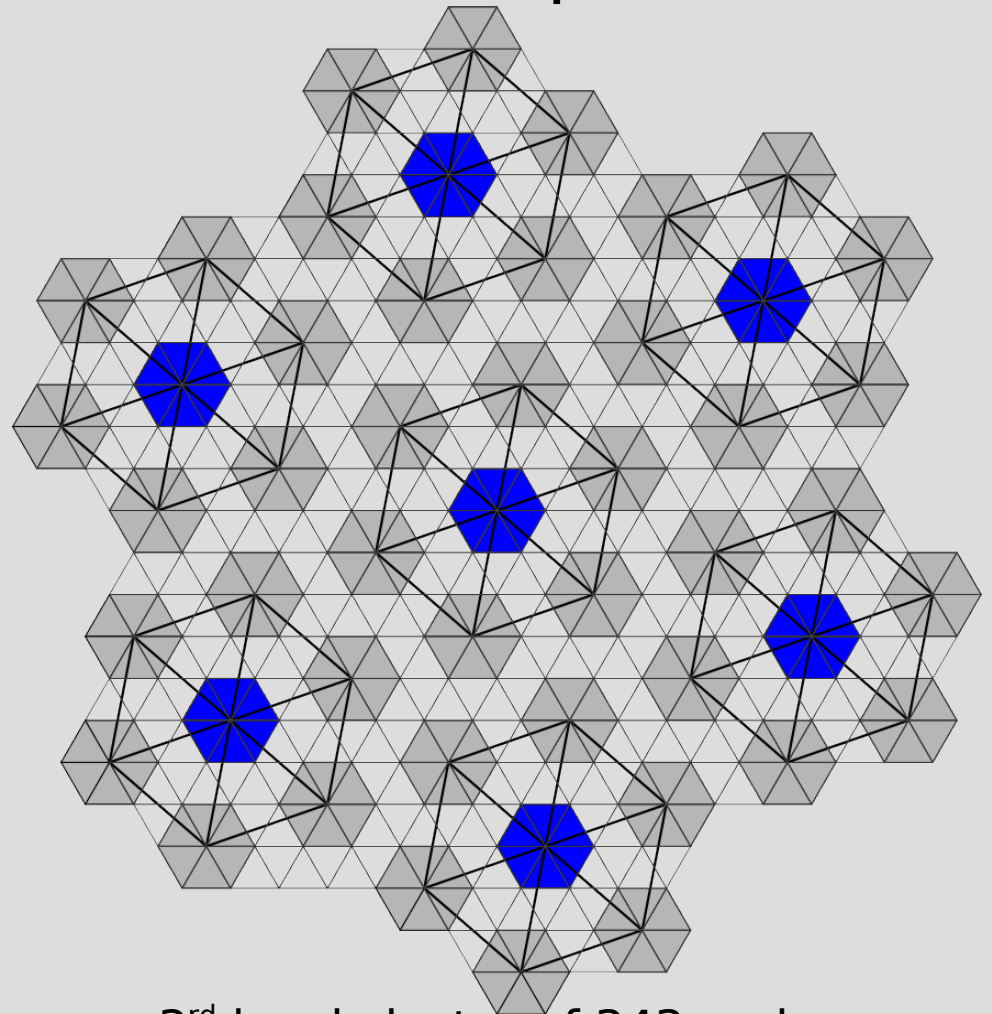
- Recursive Self-similar Hierarchical Space-Filling Structures



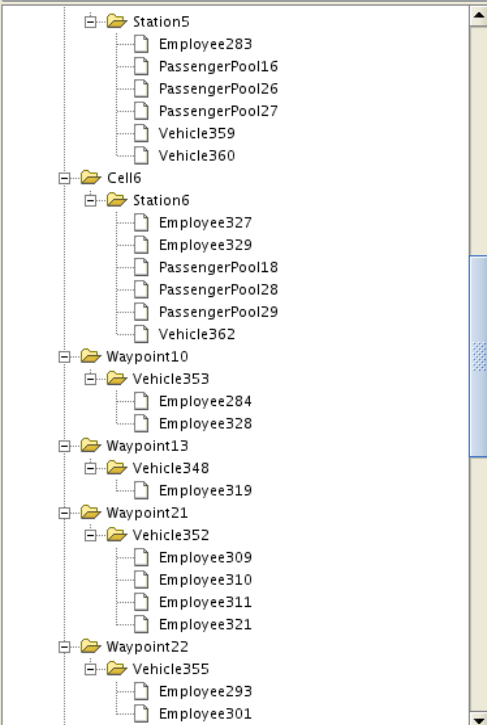
Basic 7-node unit



2nd level cluster of 49 nodes



3rd level cluster of 343 nodes



Arcology Simulation Framework

Rowin Andruscavage

University of Maryland
Systems Engineering
Master of Science Thesis

June 4, 2007

First a bit of personal background:

- While BS is in M&AE from CU,
- hobby and professional experiences revolved around tinkering with computers

Kept ending up in systems engineering roles: hence enrollment at ISR to figure out what the heck an SE does

- First job during tech bubble: supercomputing cluster architect – much thought on distributed redundant network topologies that shaped my approach to design
- Moved on to Boeing ATM: drag ATC into the information age

First class at UMCP: ENCE667 w/ Steve Gabriel: introduced computational methodology for OR

- Intrigued by ability to formulate problems in such a way that computers could return meaningful results
- Used to generate first attempt at aircraft transit scheduler
- Conc. in wireless comm: answer “why” not “how”

This project constitutes a desperate attempt to weave the various threads of my life into a coherent story. Here goes...

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”?

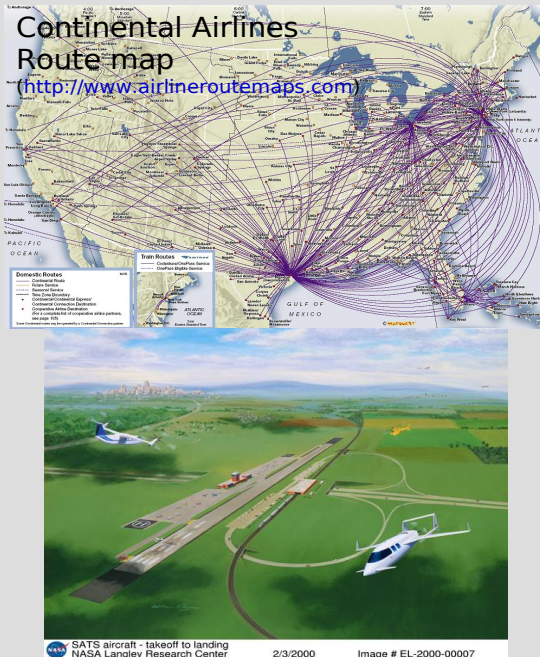
What do arcologies have to do with TOD?

- Futurism – the apogee of TOD
- Approach to design and SysArch: start with ideal and scale back to something realistic and pragmatic (with additional baggage that entails). Good systems architecture will accomodate.
- Few serious visioneering works on arcology design, compared to e.g. space colonization

1. What does a city do? Must **define measures**

2. After measures are defined, we can **optimize!** Let's take a brief tour of transit paradigms of the past century in 4 slides

Mass Transit Paradigms: Commercial Aviation



- 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

767 & 757 offered airlines

- a common flight deck certification for large and medium sized aircraft to ease crew management
- Operations along minimum spanning trees
- Good for high network coverage & low throughput

P to P

- More distributed megahubs: fewer points of system-wide failure and delay propagation
- More ideal for higher system traffic
- Less transfers means faster and less energy spend on takeoffs & landings

NASA's Small Aircraft Transportation System

- research lab right here at UCMP
- built off of emerging market for relatively affordable small jets (Honda & Toyota)
- ENSE626 cost estimation project

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

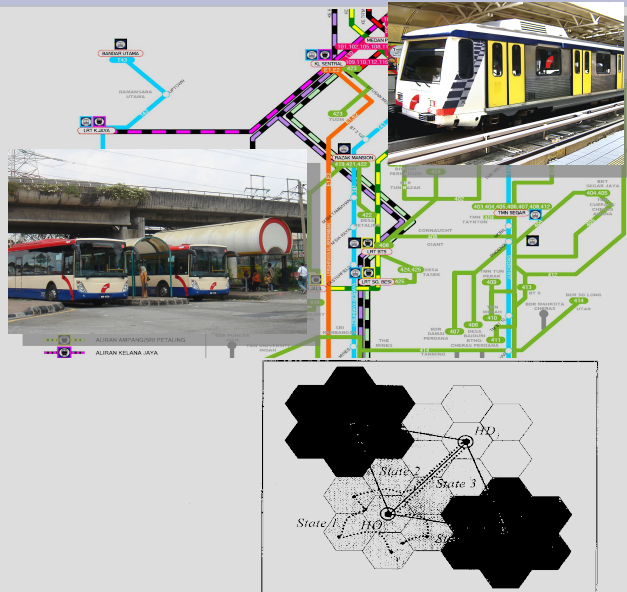


Figure 4.9 Vehicle schedule representation

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

Like hub-and-spoke system, if you don't live off of a trunk line station, you need to make several transfers to go most places

Many cities have legal barriers to prevent commercial competition with public transit systems

Cristian Cortes 2003: High Coverage Point-to-Point Transit

- distributed vanpool service
- looking for deployment in South America

Vehicle Sharing Options and Concepts



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

Decades of Eisenhower Interstate Highway System development have made automobiles unimodal transit

- Population pays for vehicle capital and maintenance
- Many attempts to turn cars into a mass transit system

Investments to promote carpooling

Micropayment-based car rentals good for quick errands

Taxis effective in third world countries (low cost of living)

In first world countries

- cabs are expensive
- operators/dispatchers not motivated to provide high levels of customer service (make money from leasing cabs to drivers)
- Awaiting fully autonomous vehicles

Winner of BusinessWeek IDEA 2006 design competition

- Fusion of CNS tech with mass transit

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

Back in the 70s, PRT considered the future of transit: driverless trams easier than driverless cars

CabinTaxi system slated for Detroit and Hamburg

Technology rolled into Raytheon 1996-1999, later disassociated into Taxi2000 SkyWeb Express

Boeing also working on people movers, deployed only operational system in 1975; software and maintenance handed over to local staff in 2003

ULTra system in UK winning near-term contracts for parking-lot people movers

Major failing in economics: very expensive infrastructure per mile; cannot compete on medium density suburban landscape designed for cars

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
- 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



Advances in transportation revolve around search for more efficient technologies

- “silver bullet” solutions to high energy needs, including: hybrids, hydrogen fuel cells, nuclear power
- Much simpler to reduce need for movement

On futurism: need to start with ideal reference designs to establish systems architecture, then strip away elements to reach a practical design.

More serious works on advanced space colonization than advanced earth colonization

Cities should offer incentives for staggered work schedules, tolls for telecommuters, etc. to protect their infrastructure investments.

Denser cities are more efficient per capita

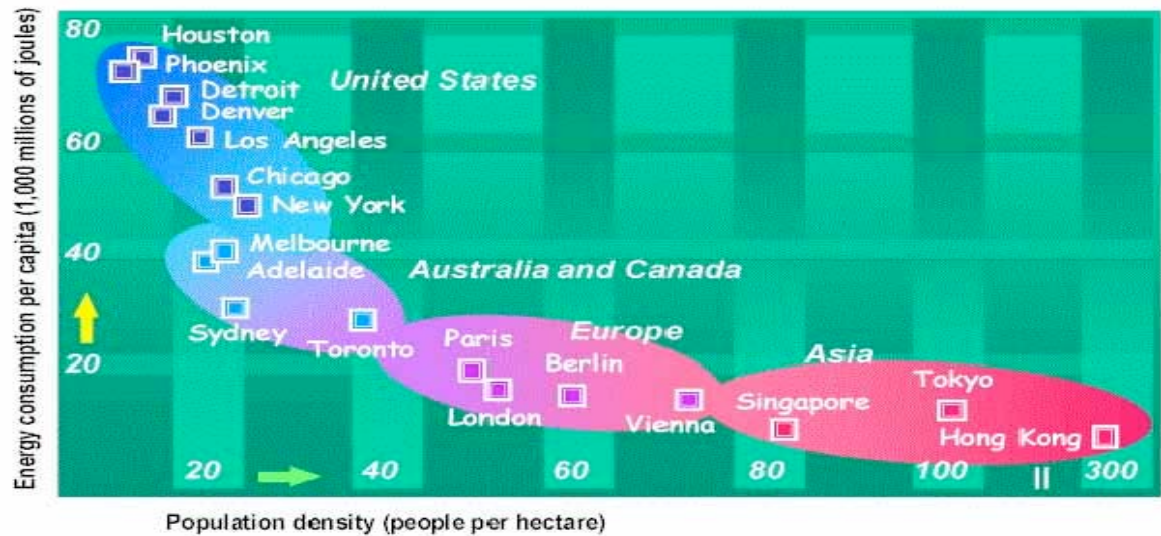


Figure 2. The relationship between population density and energy consumption in cities.

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

There is value in solving the complexities introduced by higher density

Promote efficiency and elimination of waste

Arcologies and Compact Cities pack functionality



Soleri's *Arcology*

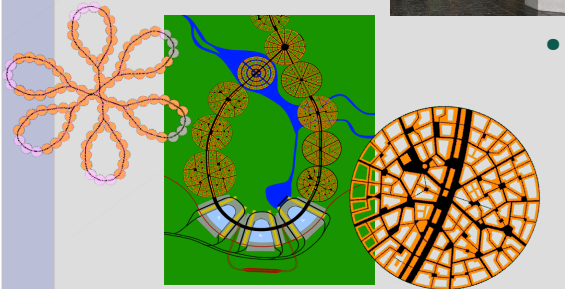
- Architectural implosion of cities
- Form a human relationship to the environment

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



Implosion of cities driven by economics: dense cities must be cheaper and offer much more functionality than surrounding suburbia

- TOD often accomplishes just the opposite: raises property values

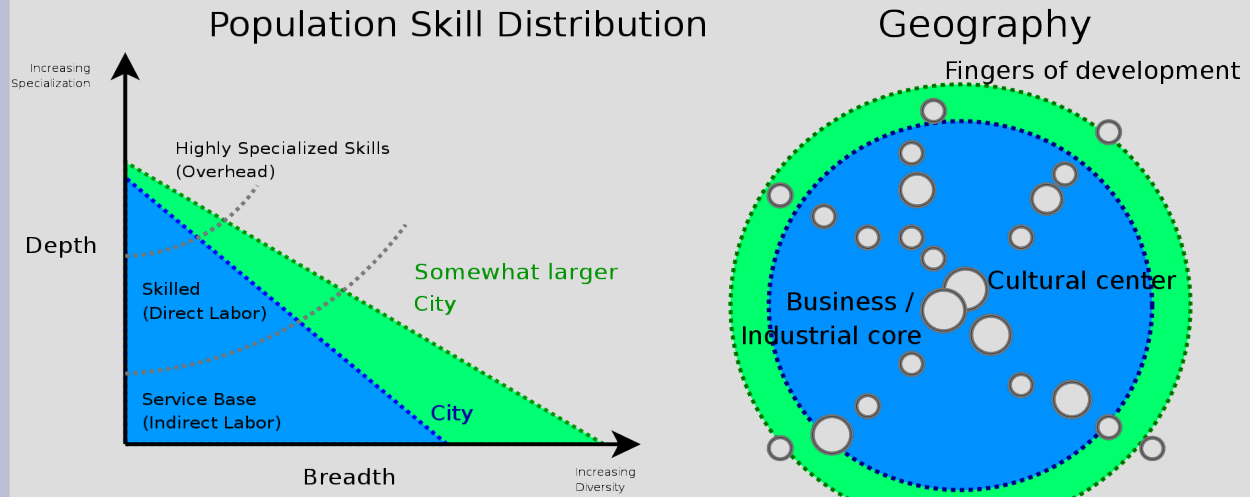
Soleri 1969 focuses on **form**, Dantzig & Saaty 1973 (fathers of linear programming and analytic hierarchy process, respectively) discussion details of **function**

Crawford 2002 reference designs focus on topologies and mechanisms

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



Graphical representation of thoughts published by Hans Blumenfeld (respected urban planner)

- What is the function of a metropolitan area?
- Maximize diversity of skills and jobs in a localized area
- **Diversity** represented in both **breadth** (ethnic restaurants, obscure specialty services, etc.) and **depth** (executive management, academia, R&D)

Notion of **locality** reflected by transportation – ruled by **temporal proximity** as opposed to **geographical**

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

“Framework” indicates that it's neither complete nor do we exercise all of its potential functionality

Similar prior works:

- SimCity: spent lots of time researching; ingrained with few common modes of transit, no vehicle persistence; difficult to collect full data

PRT analysis:

- John Lees-Miller 2003: SATURN (Simulation and Analysis Tools for Urban automated Rapid transit Networks): high school student's Java simulation
- SimPyTran 2004: continuous time comparison of station throughput of PRT vs. light rail

Mass transit: (Jayakrishna's students)

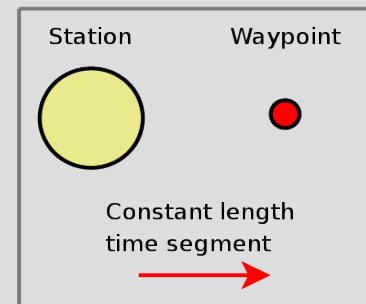
- Cristian Cortes 2003 HCPPT
- Louis Pages MTRVP 2006: paper in NAS's Transportation Research Board; similar formulation

Mass Transit Optimization Model Elements

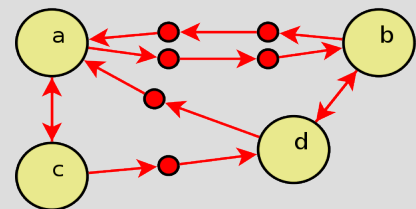
Modeled as an inventory problem

- **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



Very few modeling elements:

Inventory flow problem

- buckets of sand analogy – solves for how many buckets move to support desired flow of sand

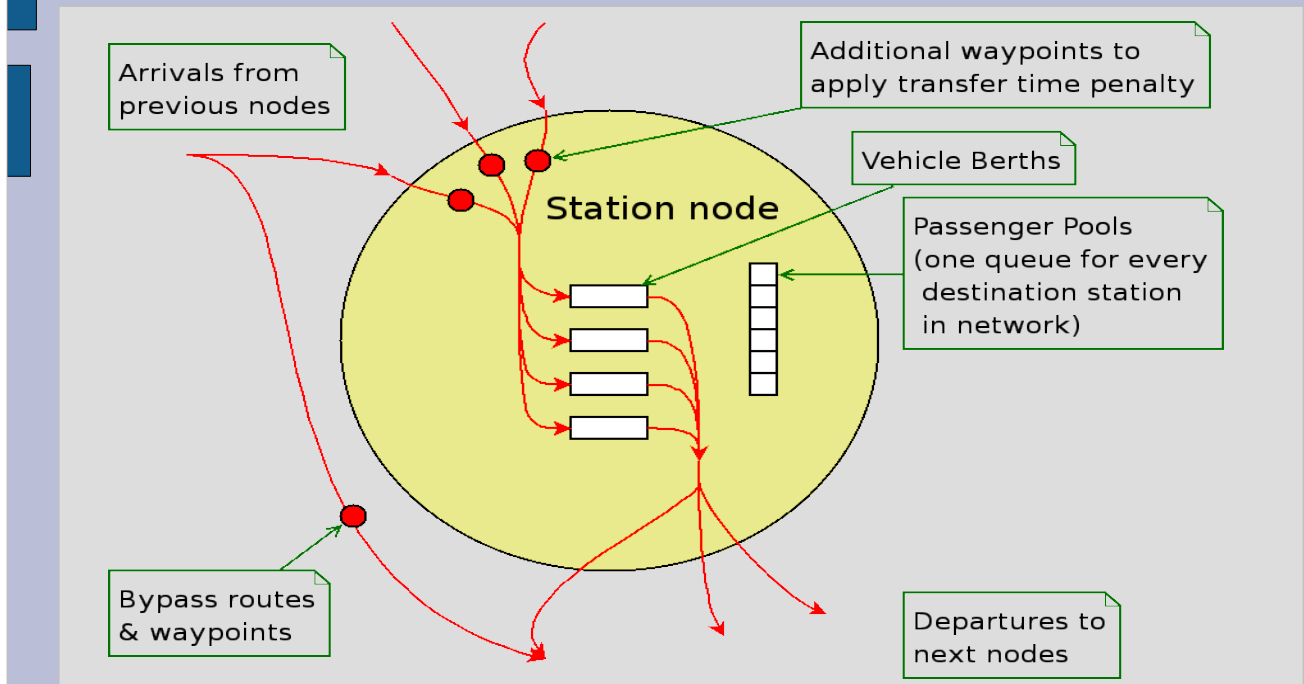
Passengers arrive and depart at stations; can flow freely through the network provided vehicles are there to carry them.

Segments indicate time and not distance; transit graphs do not indicate geophysical layout of network

Multimodal: each vehicle type gets a completely new transit layer and network

- Different size vehicles
- Separate tracks/roads
- Different operating costs

Conceptual Model of a Station



Vehicles travel in from source nodes

Limited berthing space (just a number per vehicle type)

Passengers organized by common destination

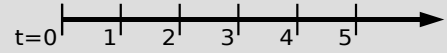
Waypoints added

- to give passengers and vehicles a state while in transit
- to add penalties for stopping at stations for transfers

Transit Optimization

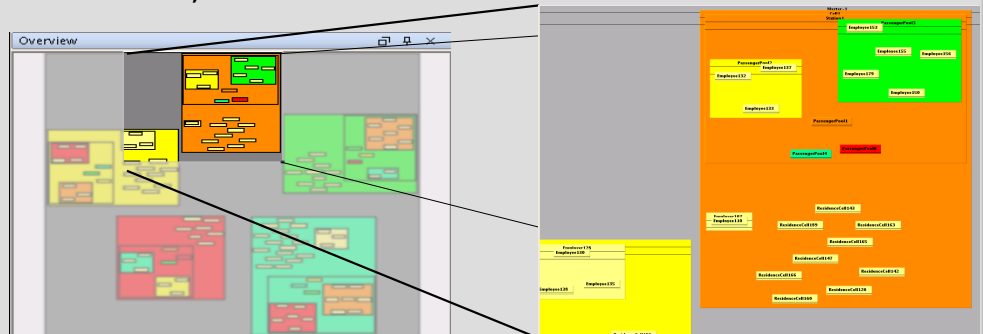
Input / Output Variables

- 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



Emphasis on coordination between vehicles for transfers means that time must be synchronized

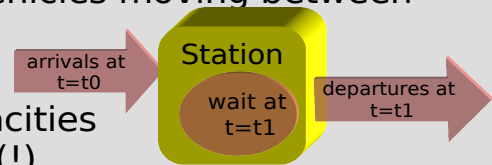
- Continuous time aliased to integer time steps.
- At each time step, all vehicles must be at a station or waypoint. Currently not allowed to be caught in-between

Outputs schedule decision variables for all time steps under consideration

- must be enough to traverse diameter of network (and then some extra for schedule flexibility)

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”

Vehicle capacities are constant per layer

- different max occupancies must be represented by separate layers.

Station / infrastructure constraints provided by input tables

Multiple Objectives

prioritized by weights:

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

1: Throughput

- Maximize passengers sent to final destination

2: Latency

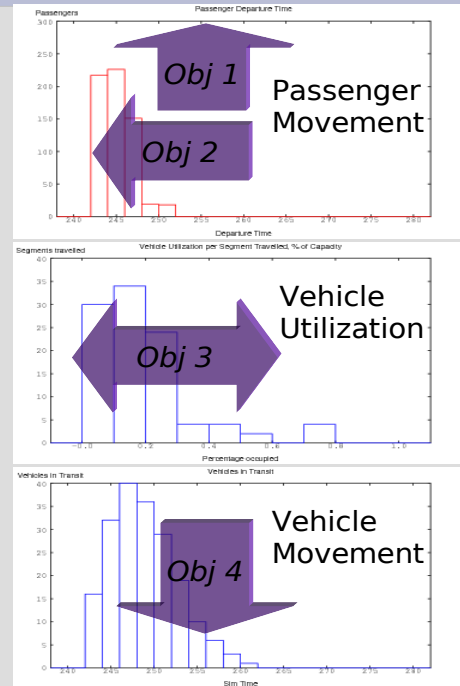
- Reward scheduler for delivering passengers earlier

3: Fleet Size (Optional)

- Minimize deviation from desired vehicle fleet size

4: Operating Cost

- Minimize vehicle movements



Results shaped by objective functions

Graph 1: passengers arriving at destination over time

Graph 2: how “full” vehicles are as they travel

- optionally set to use more or less than nominal to improve passenger service or reduce operating costs

Graph 3: vehicles in motion over time

Transit Modes:

timing, capacity, and optimization
parameters tuned to represent:



Aircraft



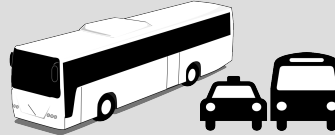
(original intent)



Subway / Rail (high capacity trunks)



Buses / Vanpools



Personal Rapid Transit networks



Elevators (!)



Automated Package Transport

Emphasis on making connections and transfers between vehicles, but allow time/cost savings for avoiding transfer stops

Optimized Schedule Verified by Simulation

(the second half)

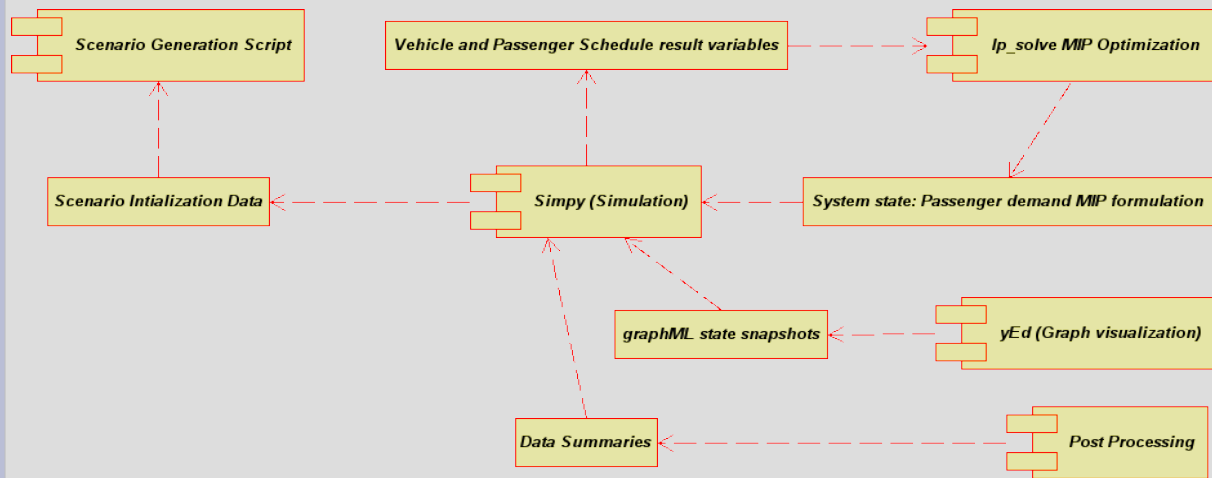
- Collects detailed performance metrics
 - Feasibility assurance
 - Continuous time execution of transit model based on integer time steps
 - Inspection & analysis of track logs from individual passengers and vehicles
- State persistence
 - Evolve system state with all known data
 - Reformulate and re-optimize 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 to execute the aggregate schedule using and tracking individual entities

Simulation Component Diagram



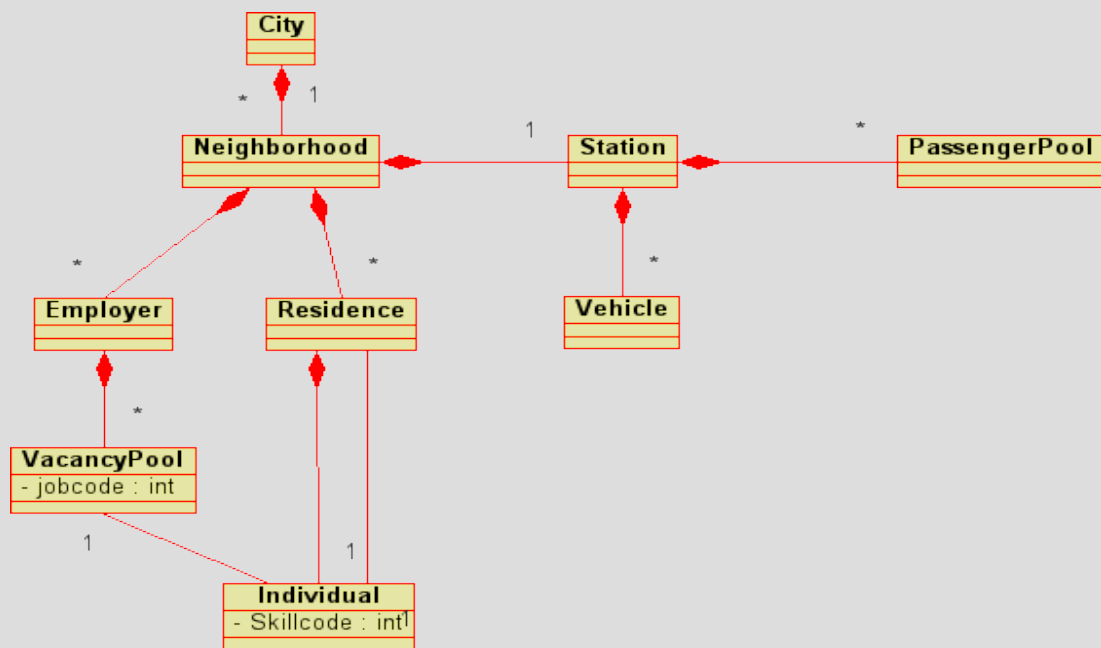
Main loop between simulation dumping state of requests to optimization

Optimization takes majority of CPU time and returns a schedule for execution

Post processing tools followup

Commuter Transit Model

Class Structure



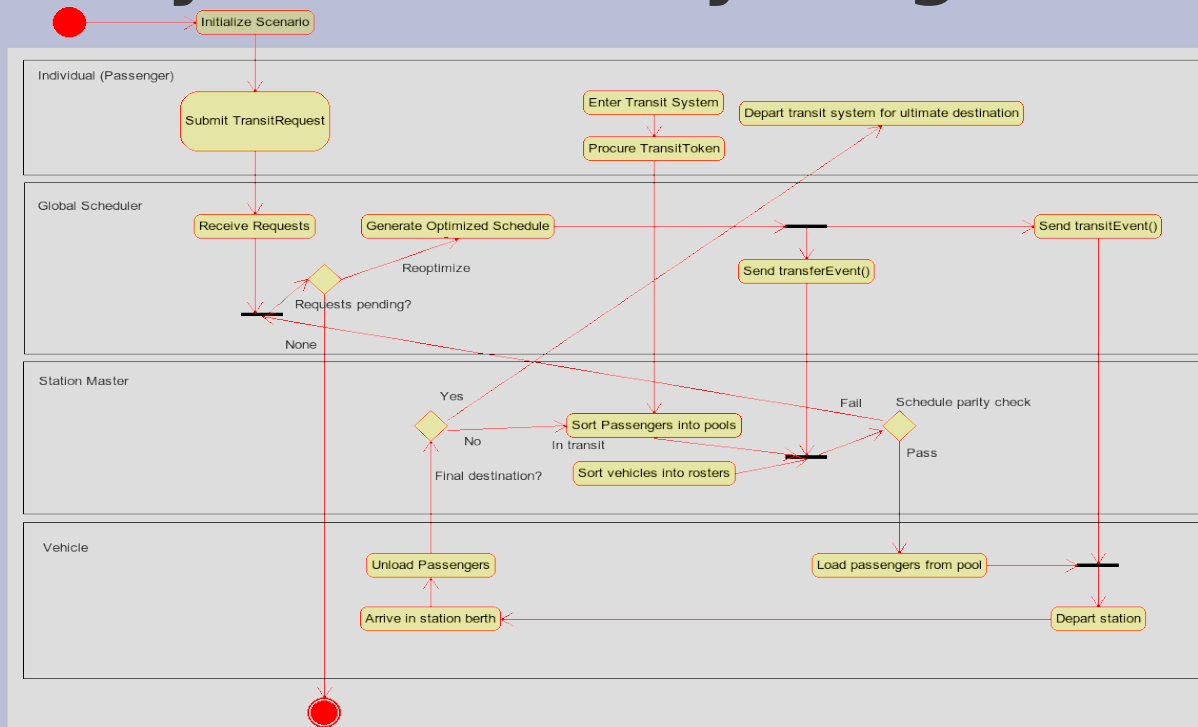
Commuting accounts for over 60-80% of use of urban transit networks

A city is formed by several neighborhoods sharing a common transit station

Distribution of employers and residences created in each neighborhood, with commuters creating transit requests between their residence and employer stations

“Individual” commuter unit hops between Residence, PassengerPool, Vehicle, and Employer cells.

Commuter Transit Model System Activity Diagram



Swimlane activity diagram shows:

Passengers request transit at some point in the future

Global scheduler dispatches to optimizer to create a schedule, then beats the drum to synchronize the shuffling of passengers among **stations** and **vehicles**

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

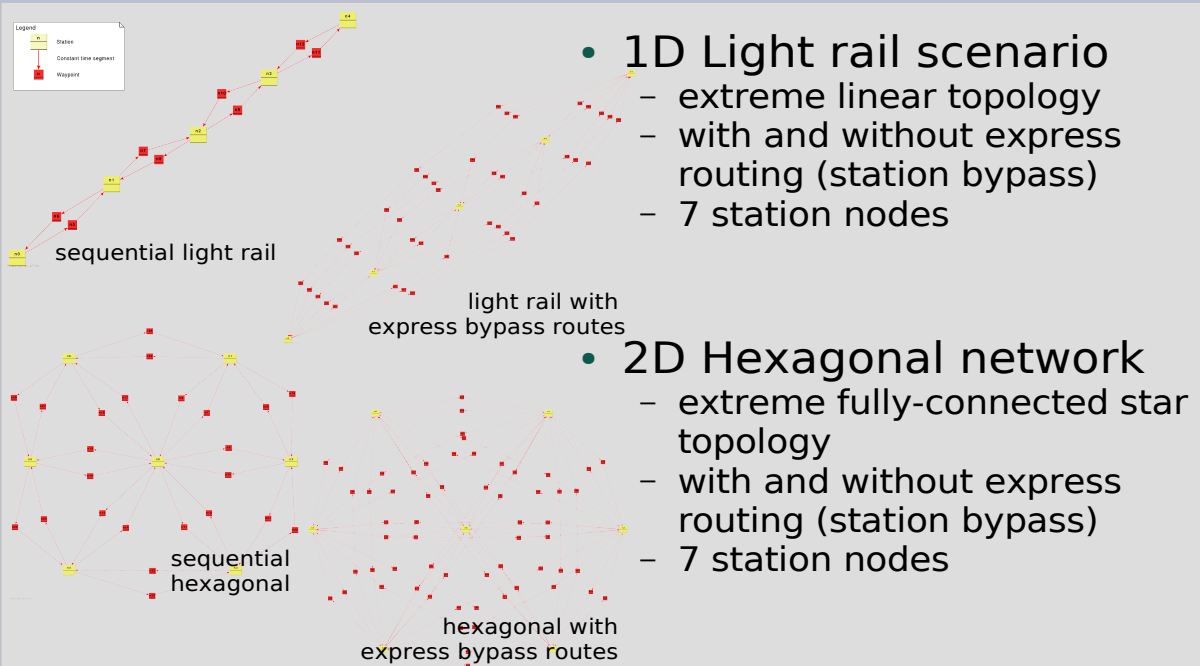
VNC / LiveCD walkthrough

Illustrate yEd autolayout

Demo of schedule generation with 30 sec timeout

gnnumeric view of schedule results

Parametric Analysis Scenarios



Step back and talk about network topologies

TSP scalability limitations reached around 7 station nodes

Simplest is linear

- On-line stations (sequential routing)
- Off-line stations (express bypass routing)

2D star topology simplest possible with 7 nodes

Create larger transit networks using combinations of these two forms that are piecewise optimal

1D Rail Passenger Metrics

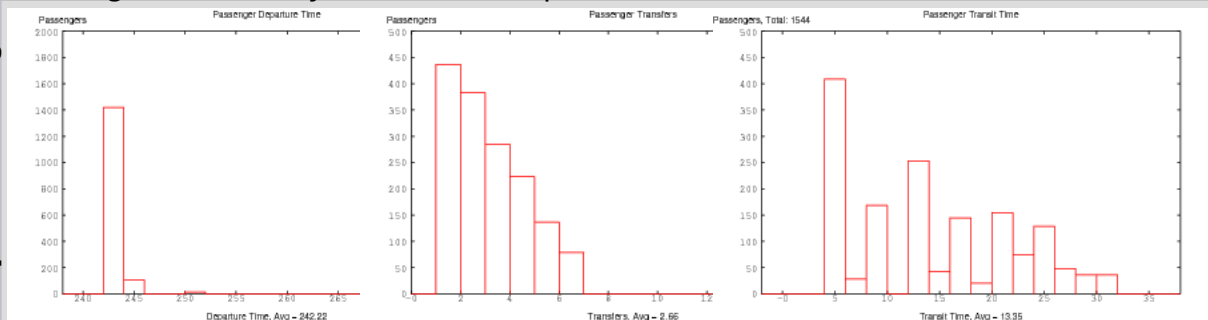
Response to uniform random demand pulse

waiting time (latency)

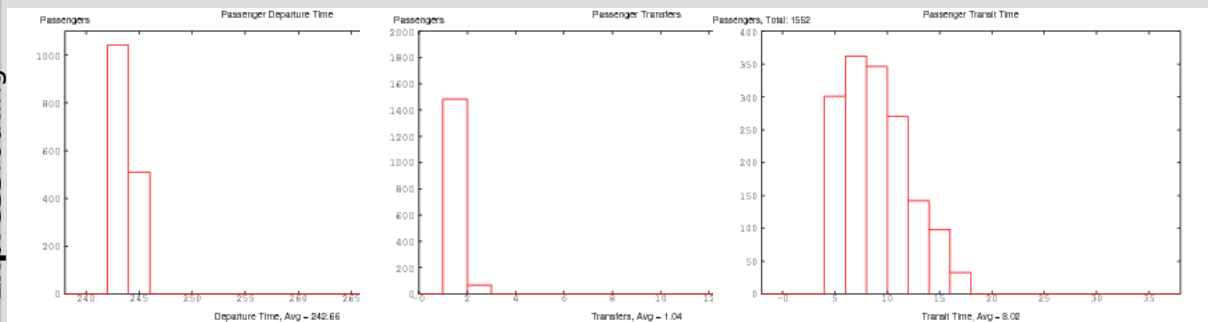
transfer stops (convenience)

travel time

Sequential routing



Express routing



Linear network system performance from the passenger point of view: sequential vs express routing

- Departure time delayed in express routing
- Much fewer transfers
- Much faster arrival times, mostly attributed to stop/transfer penalty : advantage could vary with lower transfer penalties.

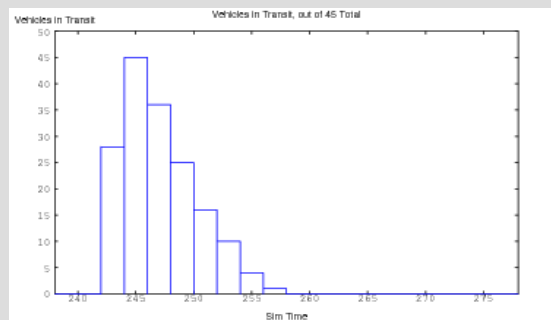
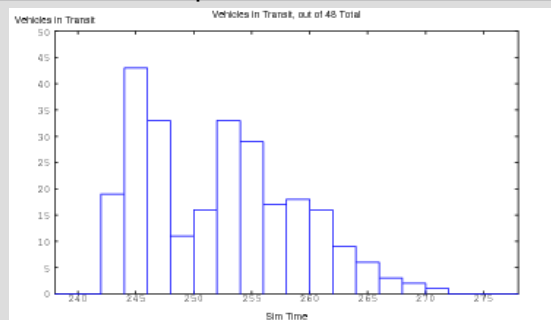
1D Rail Vehicle Metrics

Operating cost & efficiency

Sequential routing

Express routing

Vehicles in operation



Fleet operator performance perspective

- 3 fewer vehicles needed in express routing: due to congestion at the center “hub” nodes of sequentially routed network
- Vehicle utilization much more “balanced” with express routing :
 - Few vehicles running empty
 - Few vehicles running at capacity (indicates more schedule slack)

Backup:

Practical using 2 (4 with bypass) rail lines: fairness via 4 vehicle berths / station: all vehicles can leave in any direction in any order

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

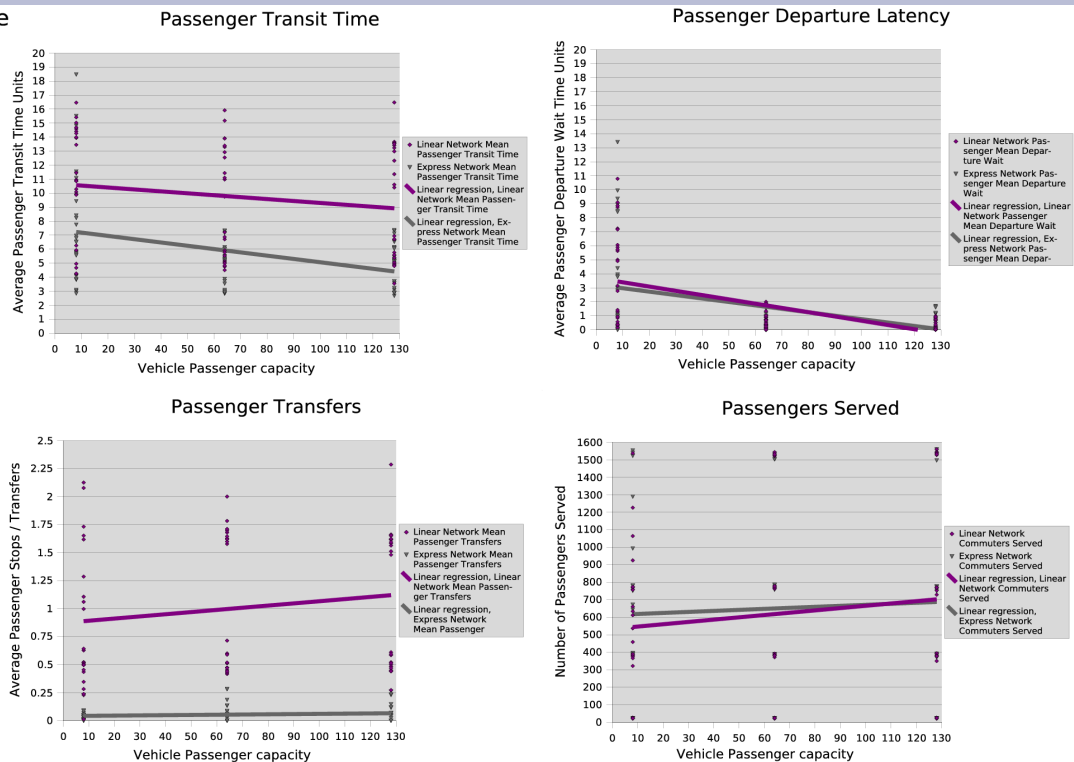
Uniform random passenger distribution for maximum vehicle utilization

- other distributions possible
 - e.g. population centers vs. job centers
 - Would result in more empty vehicles

Vehicles return to start configuration to make response to sustained loads repeatable and eliminate unfair advantage of vehicles miraculously appearing and disappearing when needed

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

Effect of Vehicle Capacity on Passenger Metrics



Magenta shows sequentially routed networks, grey shows express routed

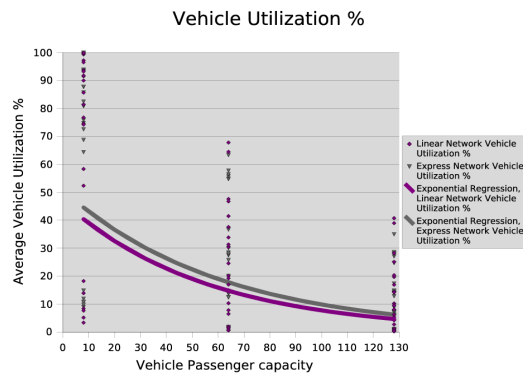
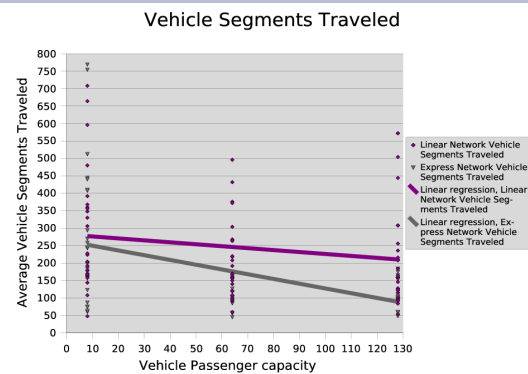
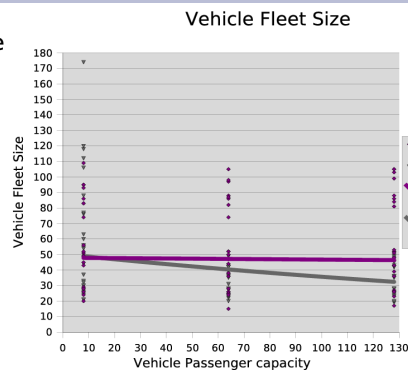
From passenger perspective
Routing is mostly independent across all vehicle capacities

Expect less transit time and number of stops / transfers logged

Can serve slightly more passengers using smaller vehicles

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

Effect of Vehicle Capacity on Vehicle Fleet Metrics



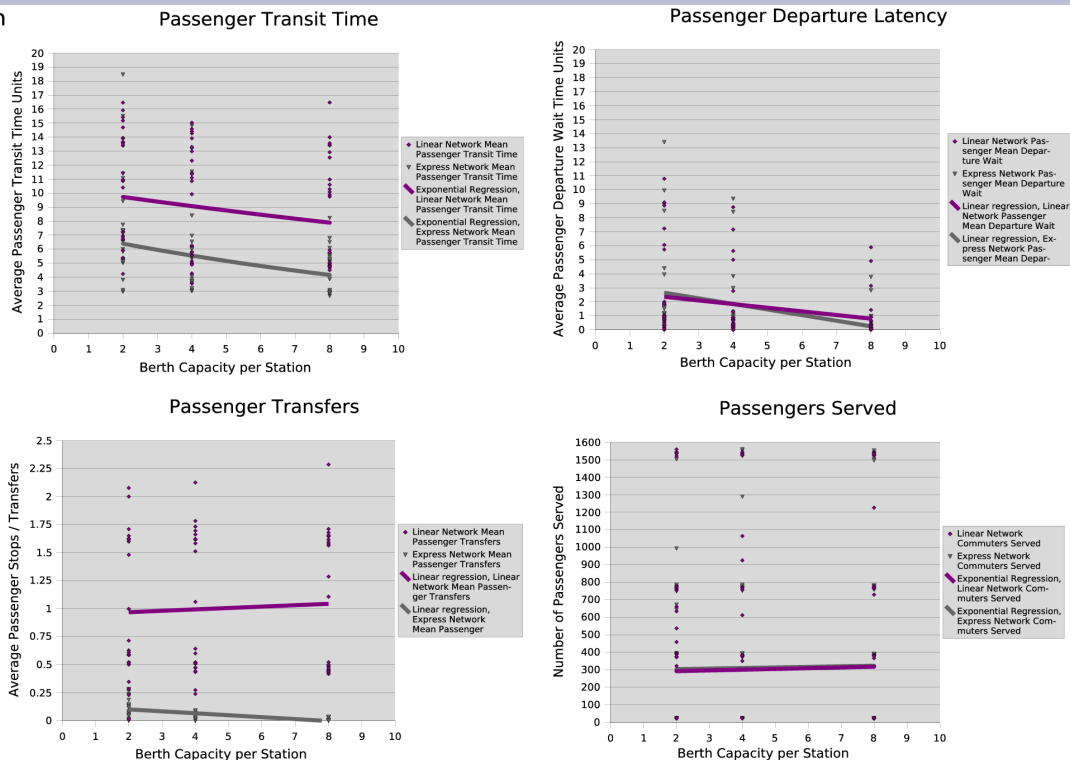
From fleet operator perspective, we see express routing requires fewer vehicles when vehicle size is large

express routing reduces vehicle movements / stops, especially with larger vehicles

express routing maintains slightly higher utilization, presumably because they spend less time running empty (empties can speed back to their initial location)

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

Effect of Station Size on Passenger Metrics

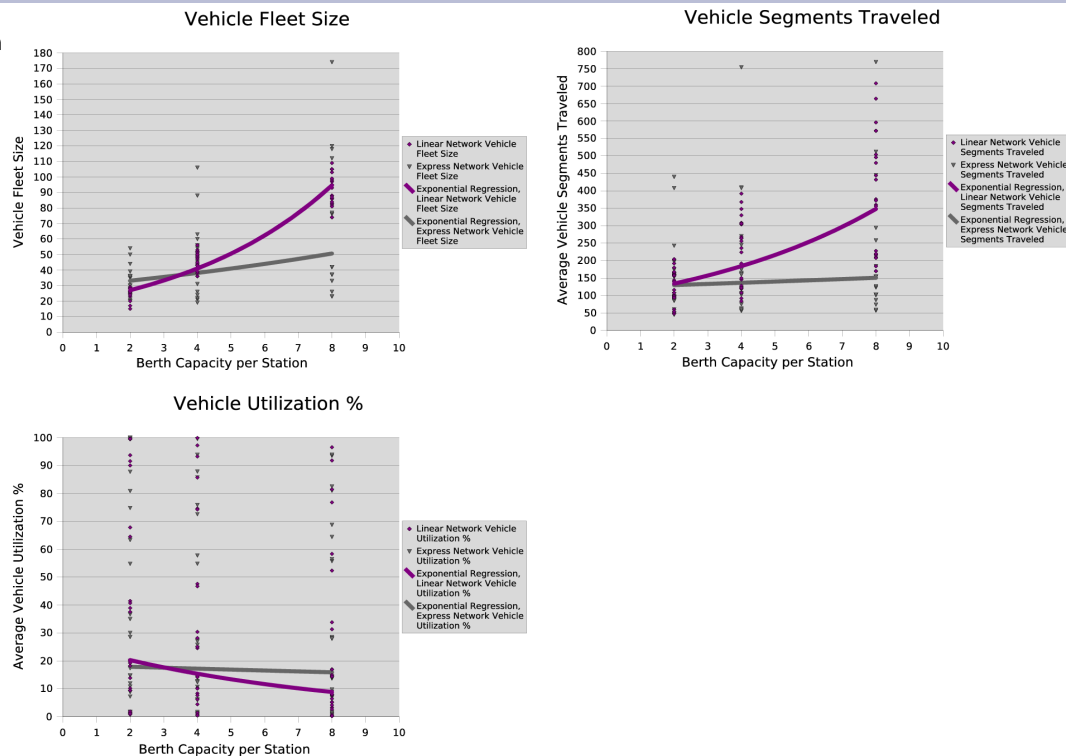


Exact same graphs from another variable: station capacity for total vehicles berthed simultaneously

Shows that more berthing space reduces passenger transit time and latency in all conditions

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

Effect of Station Size on Vehicle Fleet Metrics



More berthing space works much better with express routing: drastically reduces fleet necessary to sustain high throughput compared to sequential routing.

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

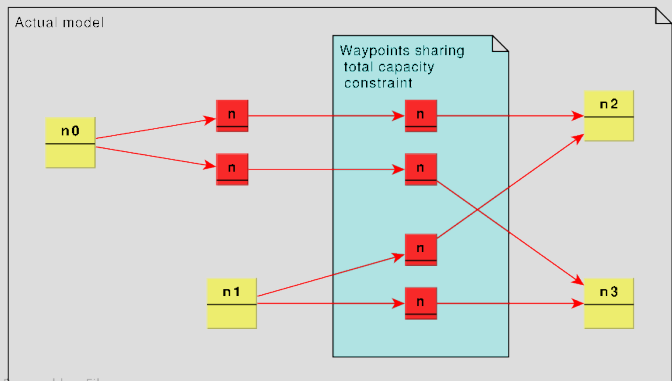
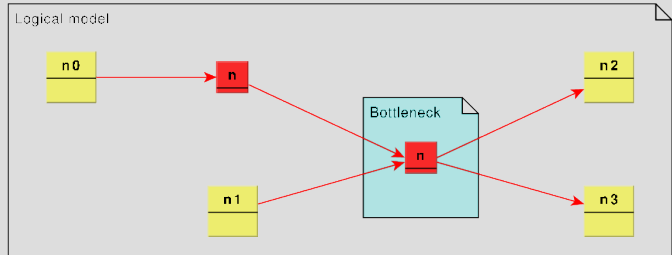
(for some definition of the word “interesting”)
good thing we're not testing a null hypothesis

From personal experience, public transit takes roughly twice as long as a rush hour drive. A 2x improvement will easily achieve parity

At this point, Continuous time gets aliased to the discrete time steps

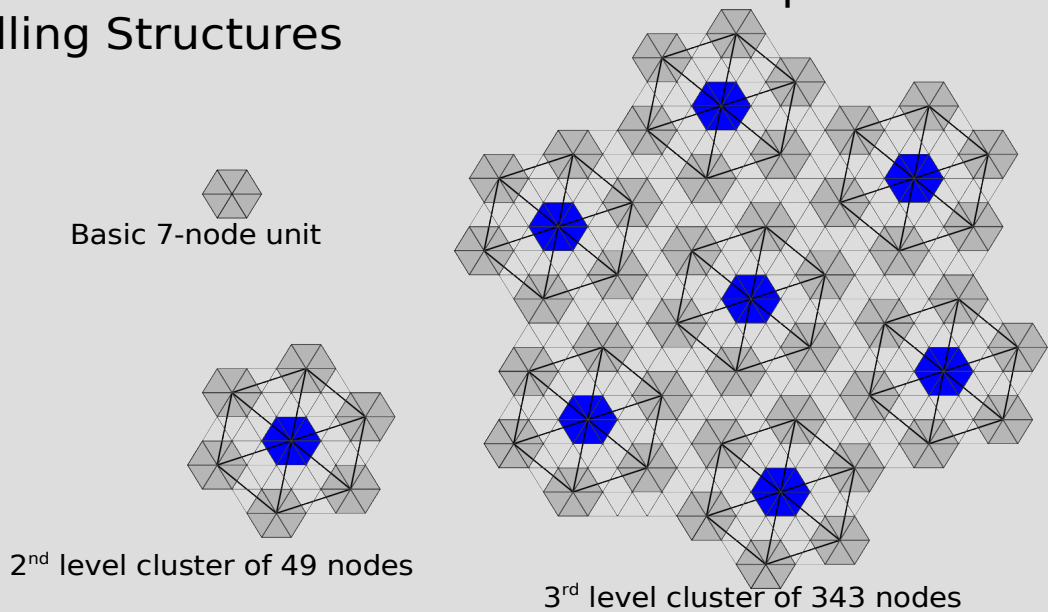
Future Work: Model feature completion

- 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



Clusters might be interfaced through:

- central hub links and/or
- distributed edge links

Neighborhoods with central facilities
Joined into clusters

Clusters form recursive tessellations of
central and satellite cities

Reference design framework represents
fully-populated framework; practical
applications would not utilize all links

Interstitial space size configurable and a
good opportunity to establish greenways

