

An Integrated Framework to Analyze Interactions between Air and Road Modes in a Regional Transportation System

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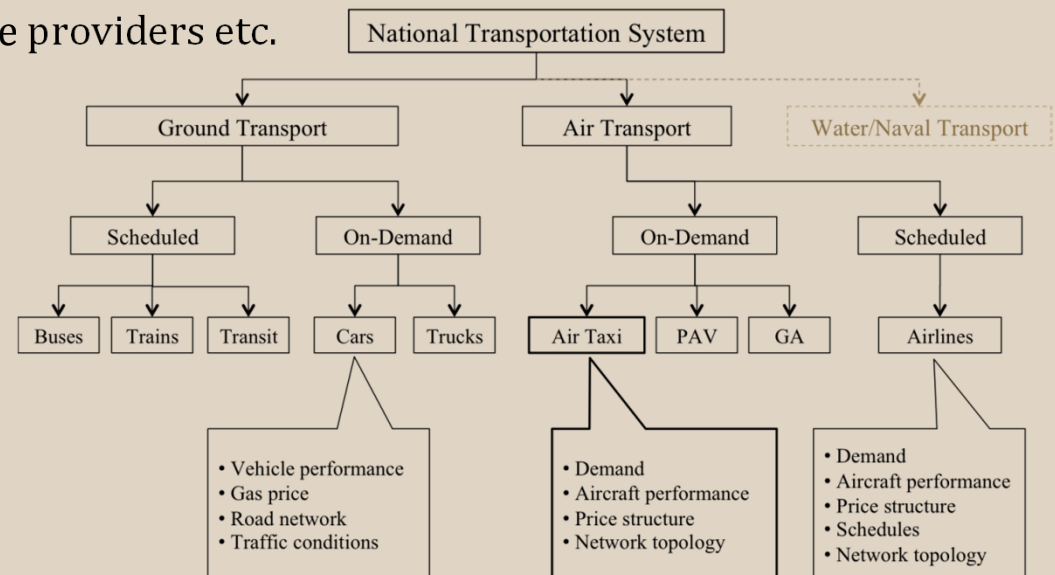
2011 TSL Asilomar Workshop

Acknowledgment: NEXTRANS Center, the USDOT Region V Regional University Transportation Center, for sponsoring this research (grant number 100612).

National Transportation System (NTS)

- **NTS is a System-of-systems**
 - Independently managed modes, independently operated users
 - No single entity has control
 - Geographically distributed systems
 - Emergent behavior
- **Evolving Constituents**
 - Infrastructure resources: roads, rails, airports etc.
 - Vehicle resources: auto, aircraft etc.
 - Layered policies: DOT, FAA, service providers etc.
 - Demand: passengers and goods

**Holistic, system-oriented
solutions required**



On-Demand Air Service (ODAS)

“Widely distributed, point-to-point air mobility, utilizing public-use general aviation airports and advanced aircraft navigation technology that enables operations in nearly all weather conditions without the assistance of control towers or ground infrastructure”

- According to NASA SATS program (Holmes and Durham 2003)

- **Very Light Jet (VLJ) aircraft**

- Driven by advances in efficient, low-maintenance small turbofan engines
- 3-8 passengers, cruise speed ~400 ktas, range ~1200 nmi
- GTOW not more than 10,000 lbs
- Advanced avionics technology (glass cockpits)
- Low acquisition and maintenance costs (\$1-3 million, compared to \$5-8 million for business jets)



- **Diverse business models**

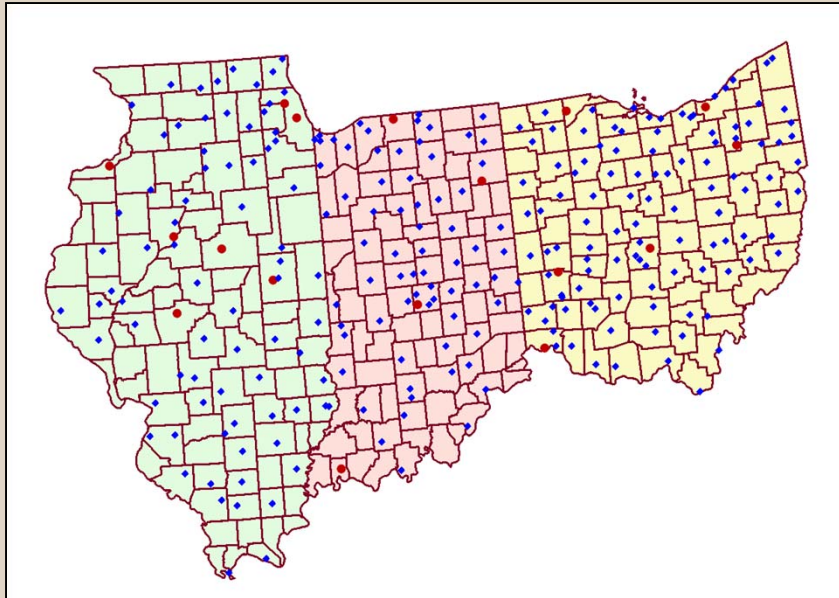
- Chartered aircraft
- Fractional ownership
- Per-seat, per-leg air taxi service



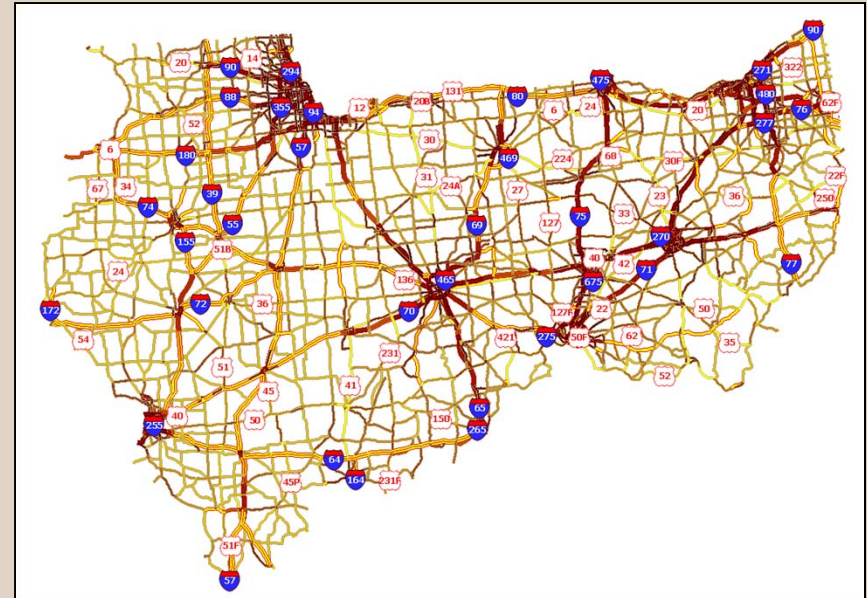
Research Goals and Objectives

- Overarching Goal: Create framework for regional planning that exploits mode synergy in producing more efficient and affordable intercity transport for people and goods
- Objective 1: Establish a composite model for a RTS with road transport, commercial air transport and a hypothetical ODAS mode
 - Characterize the demand for each mode
 - Capture multi-modal interactions in composite network
- Objective 2: Compare different models for ODAS mode
 - Different aircraft performance, cost structures, network size/topologies
- Objective 3: Evaluate ODAS in context of regional transportation demand
 - Is the mode economically viable? Will it attract sufficient demand?
 - What inefficiencies of existing modes can be overcome by the new mode?
 - Does it divert sufficient demand from commercial air transportation to claim that it can relieve pressure on commercial airports?

Model Description – Geographic Extent



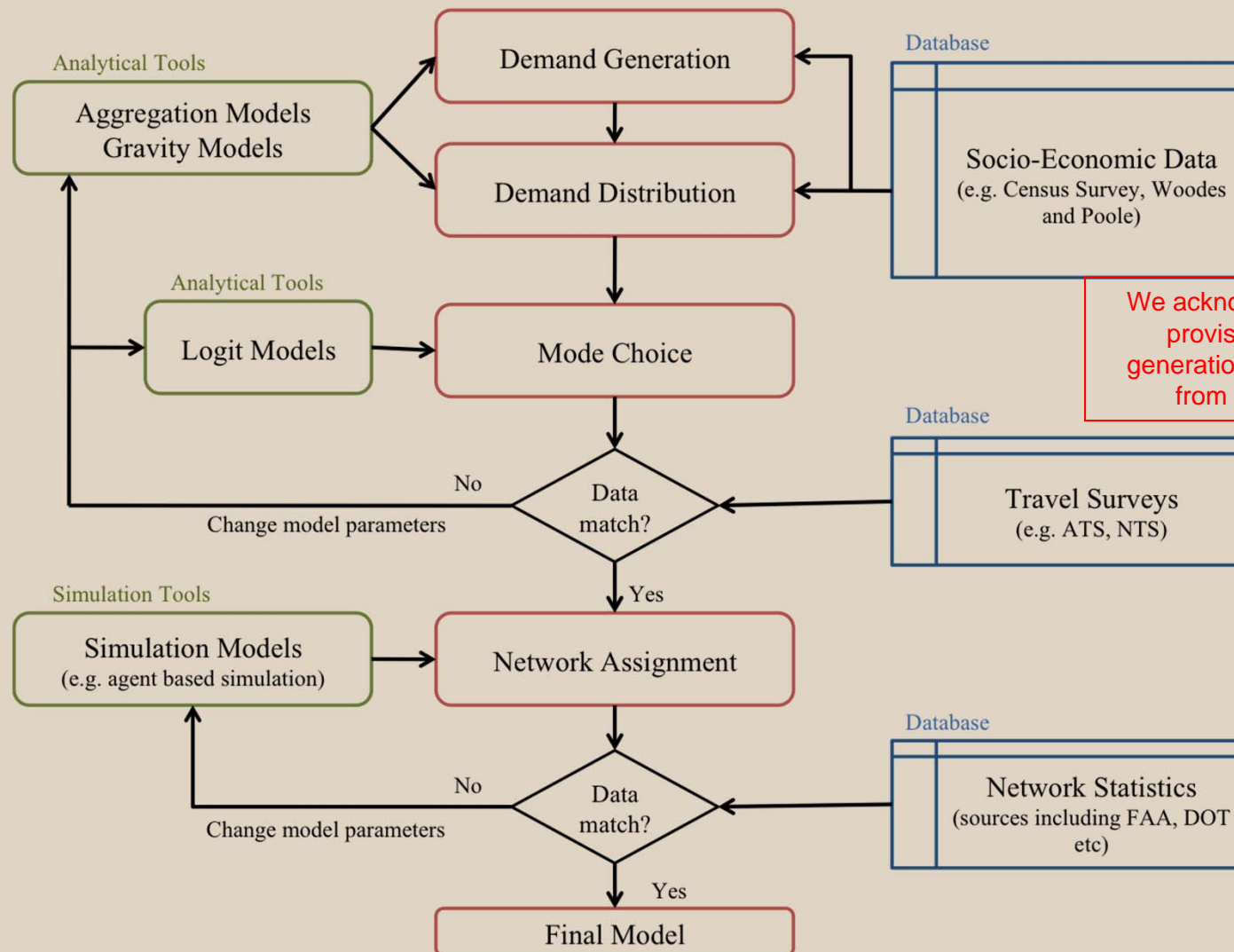
3 states (IL, IN, OH),
282 counties, 357
public use VLJ ready
airports



Highway network
consisting of interstate,
US highways and state
highways

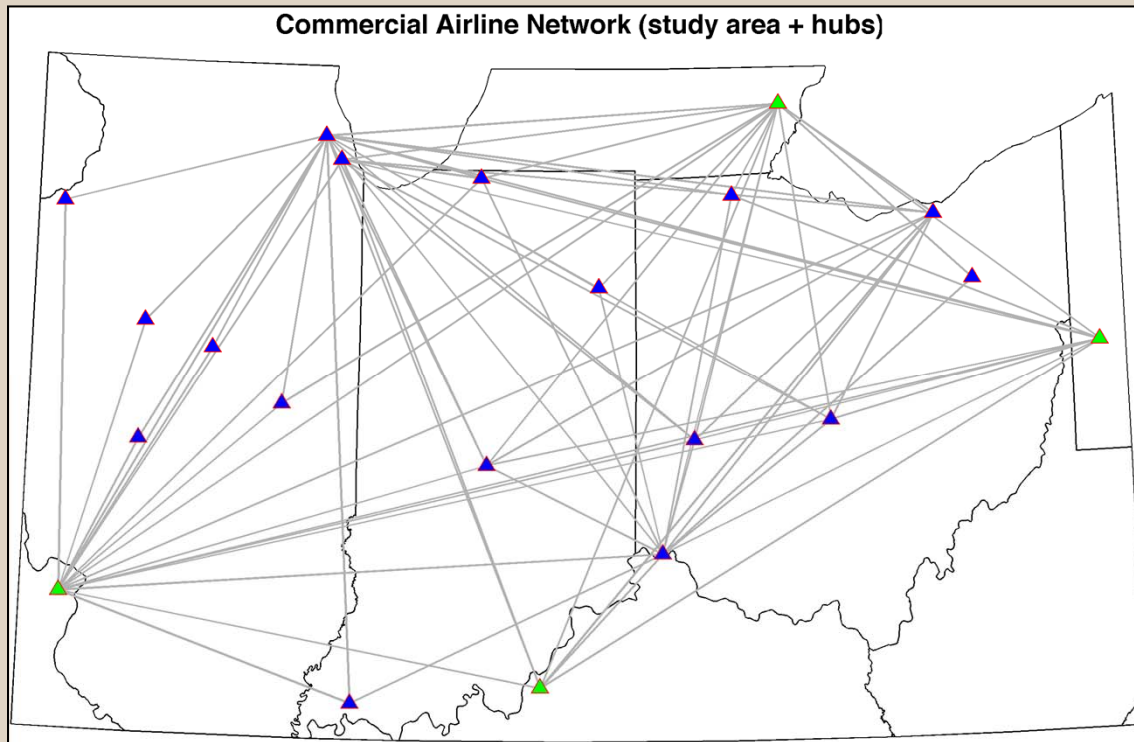
3145 nodes
5070 links

Demand Forecasting Model - Summary



We acknowledge NASA for provision of demand generation and distribution, from TSAM model.

Model Description – Commercial Air Network



4 airports are included from outside the three state region:

- Detroit, MI (DTW)
- St Louis, MO (STL)
- Louisville, KY (SDF)
- Pittsburgh, PA (PIT)

Model Description – Mode Choice Model

- MNL
- Alternatives: Road, commercial air, (hypothetical) ODAS

$$\Pi(\text{road}) = \frac{e^{U_{\text{road}}}}{e^{U_{\text{road}}} + e^{U_{\text{air}}} + e^{U_{\text{ODAS}}}}$$

Utility of mode m ,
from origin i to
destination j , for
person p

$$U_{m,i,j}^p = \alpha_t^p \cdot t_{m,i,j} + \alpha_c^p \cdot c_{m,i,j}$$

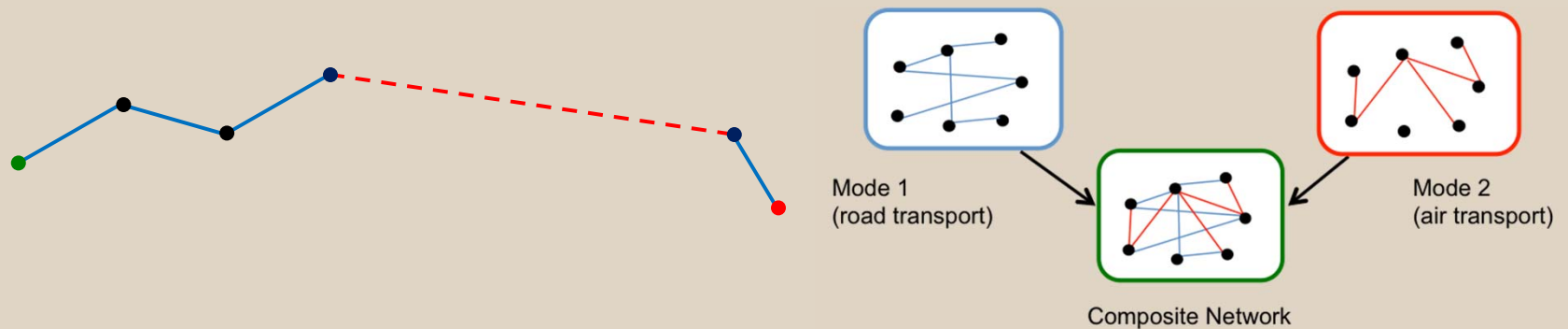
Time (minutes) → $t_{m,i,j}$

Cost (\$) → $c_{m,i,j}$

Attributes of mode → $t_{m,i,j}$ and $c_{m,i,j}$

Attributes of traveler → α_t^p and α_c^p

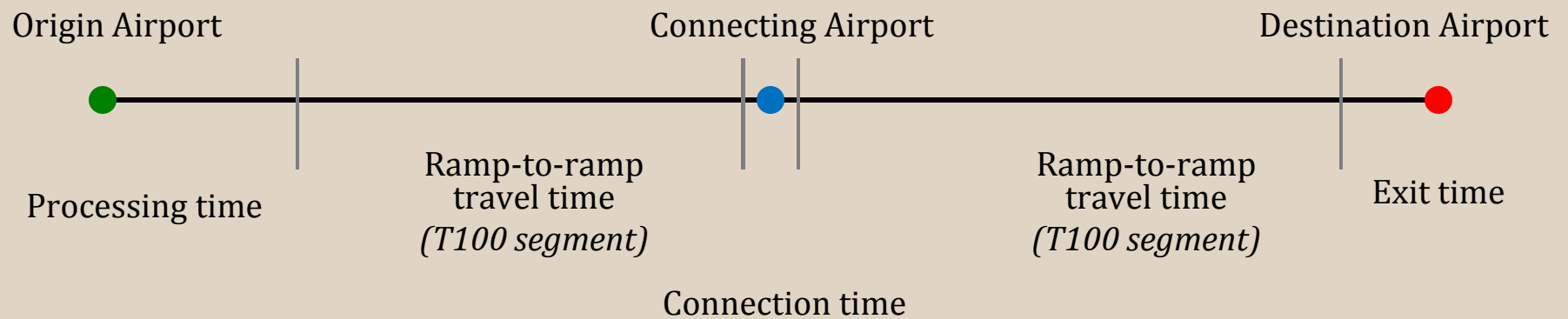
Composite Network Model Description – Utility Calculation



- Utility for a path = sum of utilities for all links involved in the path
- Utility for a mode = utility for the best path involving that mode
- If time taken for road transport is less than that for commercial air or ODAS transport, those modes are not considered in the choice set, thus automatically choosing road transport

Model Description – Utility Calculation

Commercial Air Links



Airport type	Processing time	Connection time	Exit time
Large hub	45	30	20
Medium hub	30	45	15
Non hub	20	N/A	15

Simulation Experiments

- **Each experiment starts with a definition of ODAS service mode:**
 - Service airports (from among the public use VLJ ready airports)
 - Price per passenger seat mile
 - Aircraft performance – cruise speed, rate of climb, cruise altitude
- **Experiment 1**
 - Full ODAS network: all airports served
 - Purpose: to investigate maximum possible demand and its distribution
- **Experiments 2 & 3**
 - Candidate regional network
 - Purpose: to investigate if a network serving urban areas can relieve pressure on the commercial air network
- **Experiment 4**
 - Candidate metropolitan area network
 - Purpose: to investigate if a network serving a high-density metropolitan area, with small geographic extent, can be sustained given right aircraft characteristics and price structure
- Nominal characteristics of Eclipse 500 are used as default, except in Experiment 4

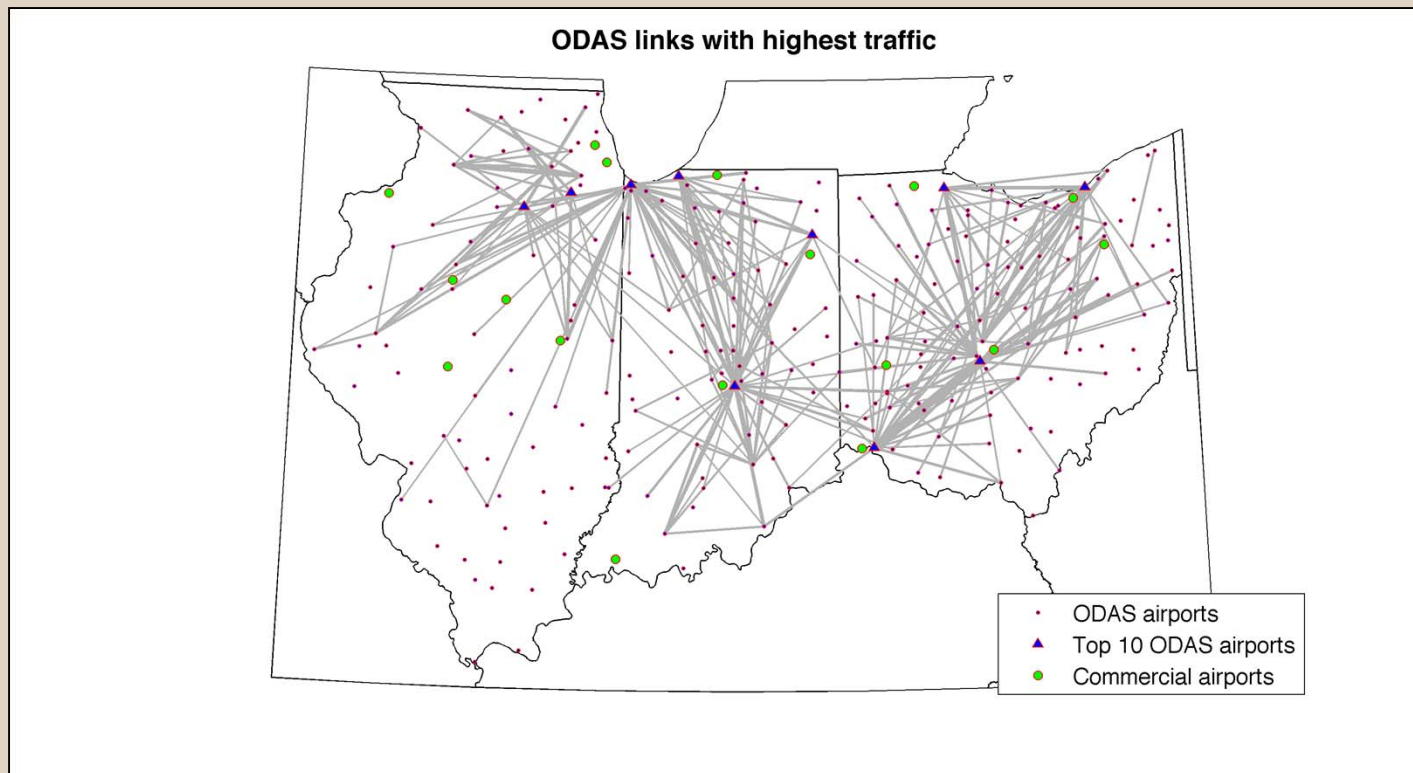
ODAS Parameters

Performance parameters of Eclipse 500 jet were used, as a representative of VLJ class aircraft. Following values of parameters were used:

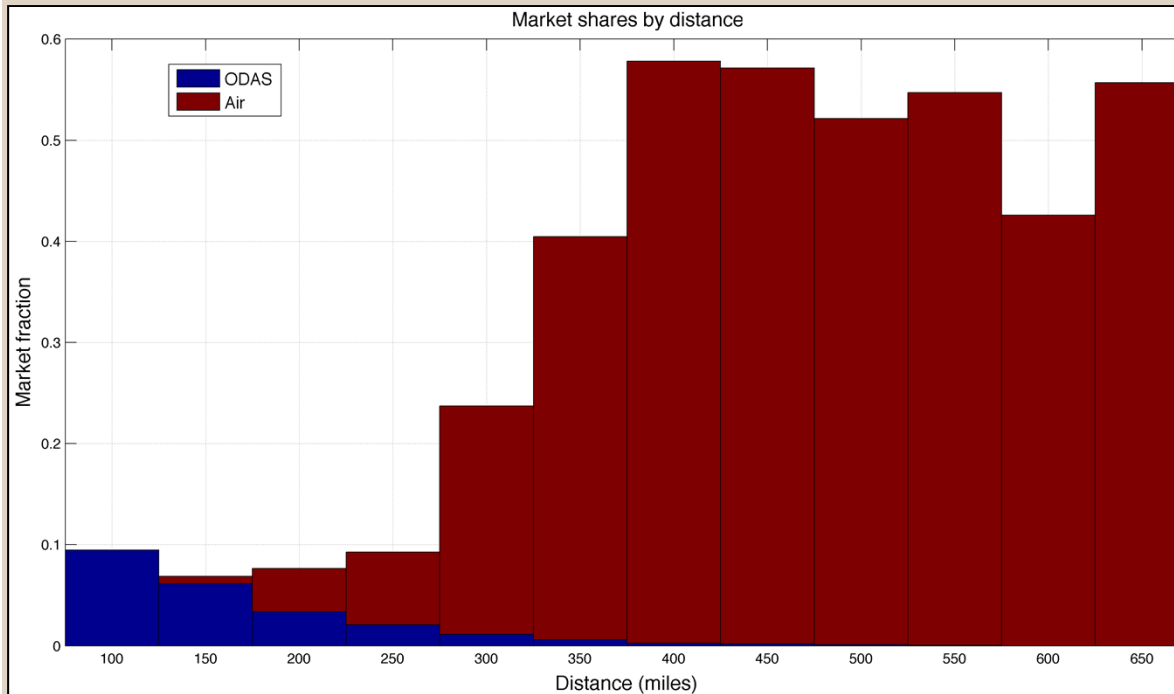
- Price per passenger seat mile (ppm) = \$2.25
- Maximum cruise speed = 425 mph
- Rate of climb = 3314 feet per minute
- Cruise altitude = 10,000 ft for distances up to 100 miles
= 24,000 ft for distances greater than 100 miles
- Trip price = $100 \times \text{ppm}$ for distances up to 100 miles
= $\text{distance} \times \text{ppm}$ for distances greater than 100 miles

Experiment 1

- Demand on ODAS links

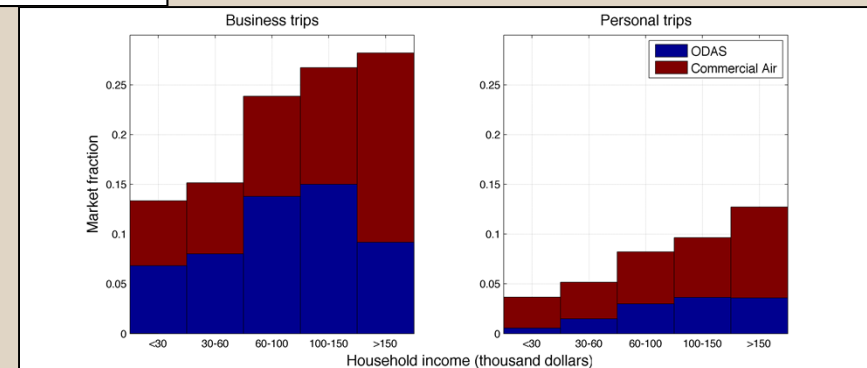


Experiment 1- Ubiquitous ODAS Availability



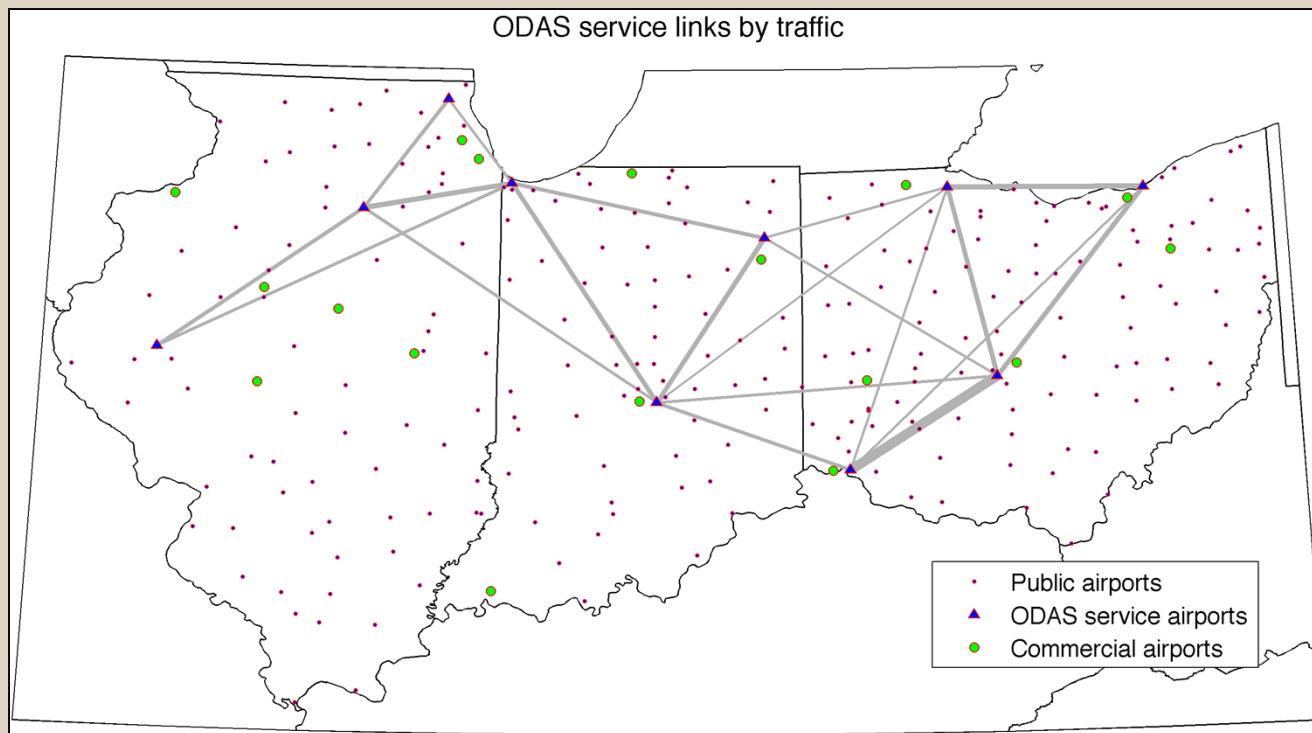
- Most of the demand for ODAS lies in short-range trips
- ODAS cost of \$2.25 *ppm* is prohibitive for long-range trips
- Commercial air travel is still dominant in the medium range trips
- Overall ODAS market share is 3.5%
- With an extensive ODAS network, commercial air market fraction decreases from 11.6% to 10.6%

- High income groups are more likely to switch to ODAS
- ODAS is likelier to be used for business trips than personal trips



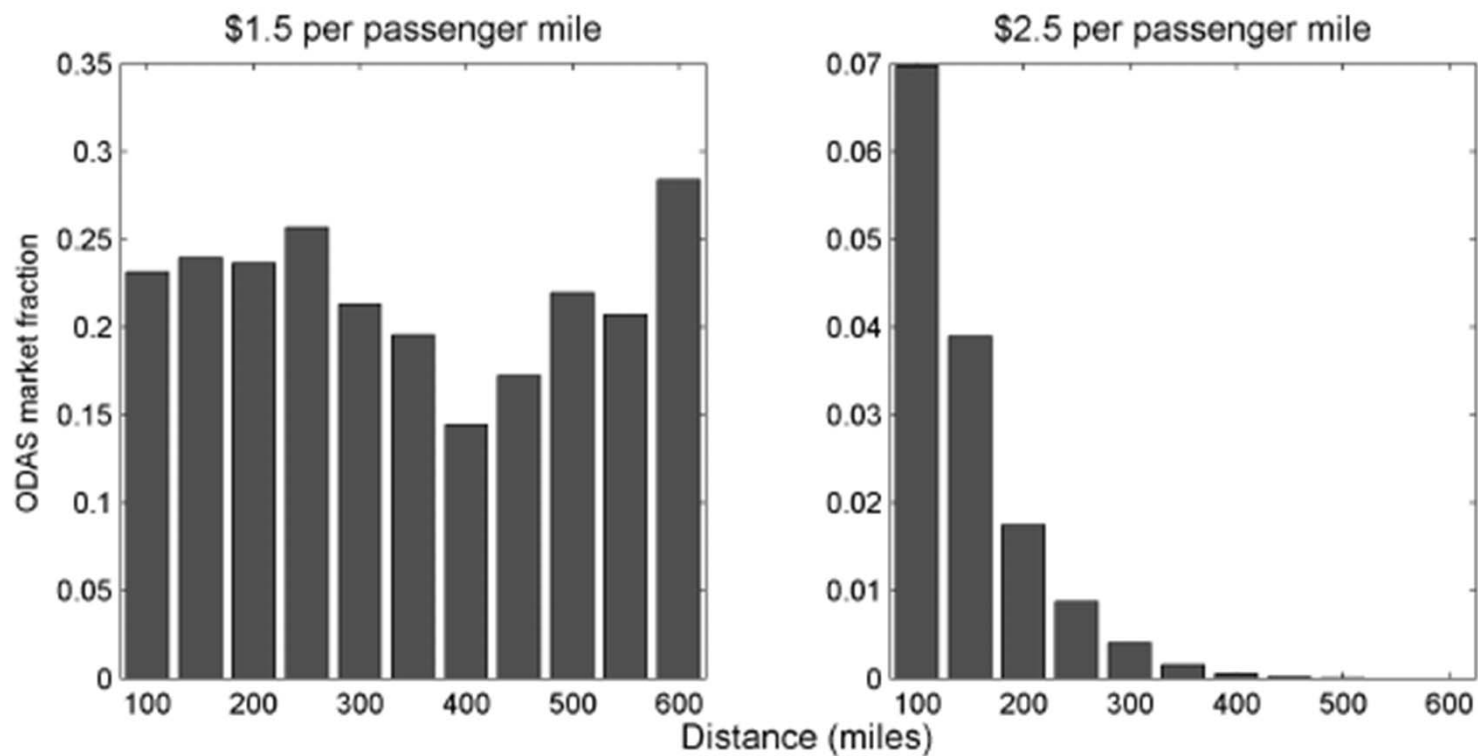
Experiments 2 & 3

- Experiment 1 shows top 10 airports situated in urban areas
- If these airports together form an ODAS service network, this network may act as reliever for commercial air network



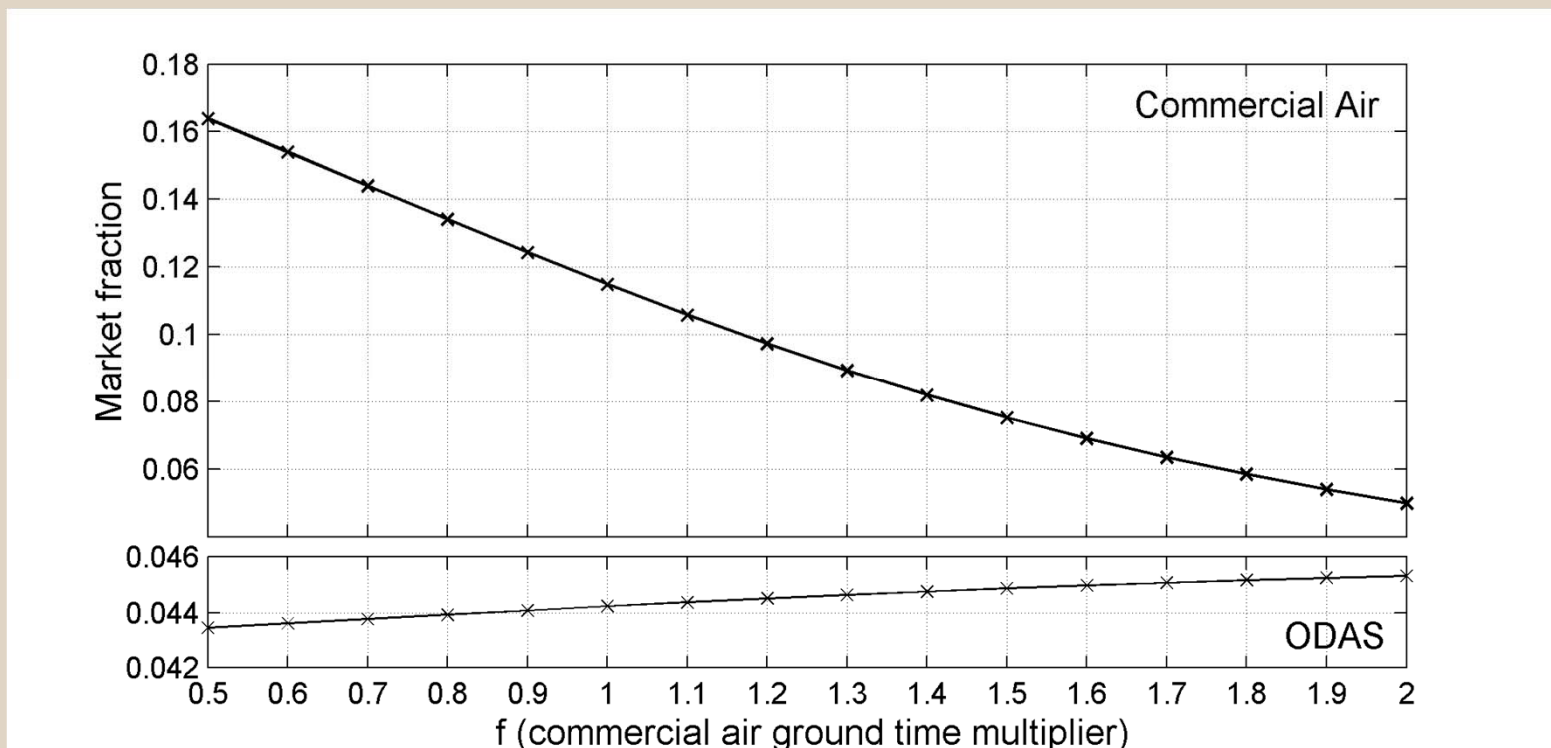
Experiment 2: Price Sensitivity Studies

- Sensitivity to ODAS price



Experiment 3: Time Sensitivity Studies

- Sensitivity to access & wait times at commercial airports

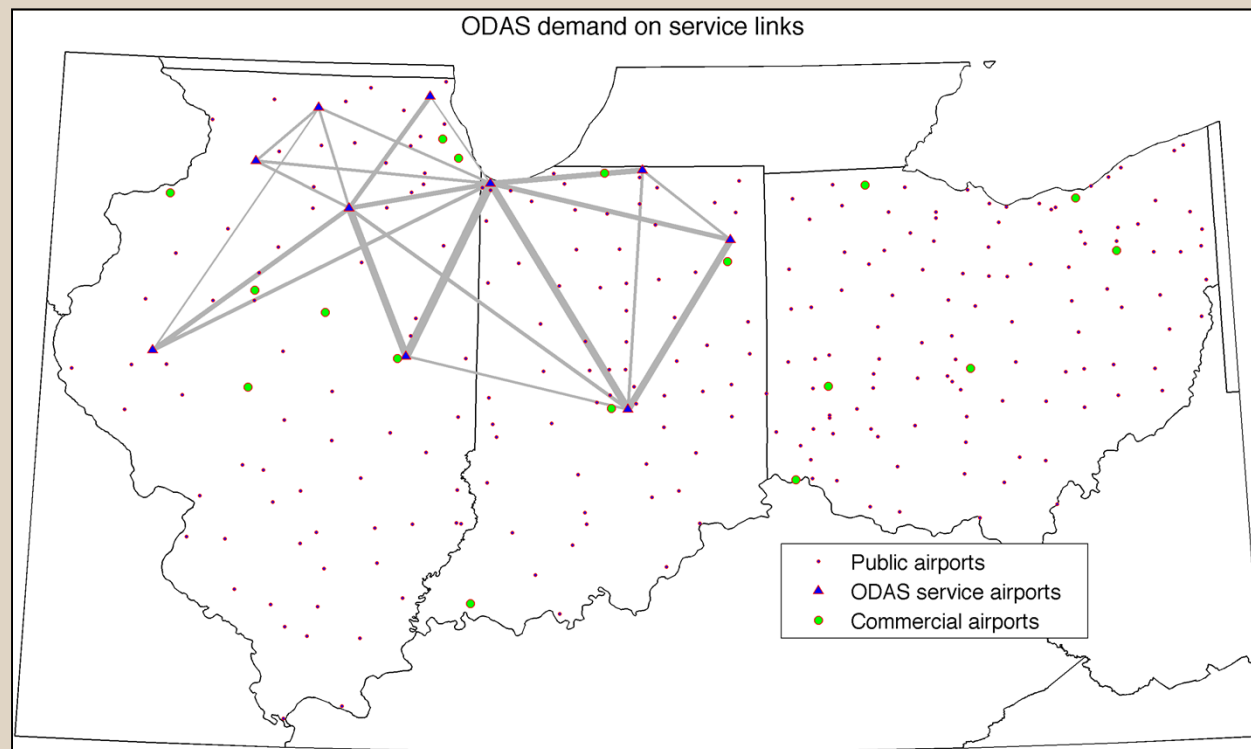


Experiment 4 – Finding well-suited ODAS vehicle

- Looking at average trip distances in earlier experiments, following conclusions can be drawn –
 - A big part of the range of a typical VLJ is not utilized. In fact, most of the trips are shorter than 200 miles
 - Time savings offered by ODAS mode are quite significant, however the cost is prohibitive for long range trips
 - In case of a specifically designed short-range aircraft (possibly slower than a typical VLJ), which has lower acquisition and maintenance costs, it may be possible to bring down the *ppm*
- ODAS parameters used in Experiment 4 –
 - *ppm* = \$1.5
 - Cruise speed = 250 mph

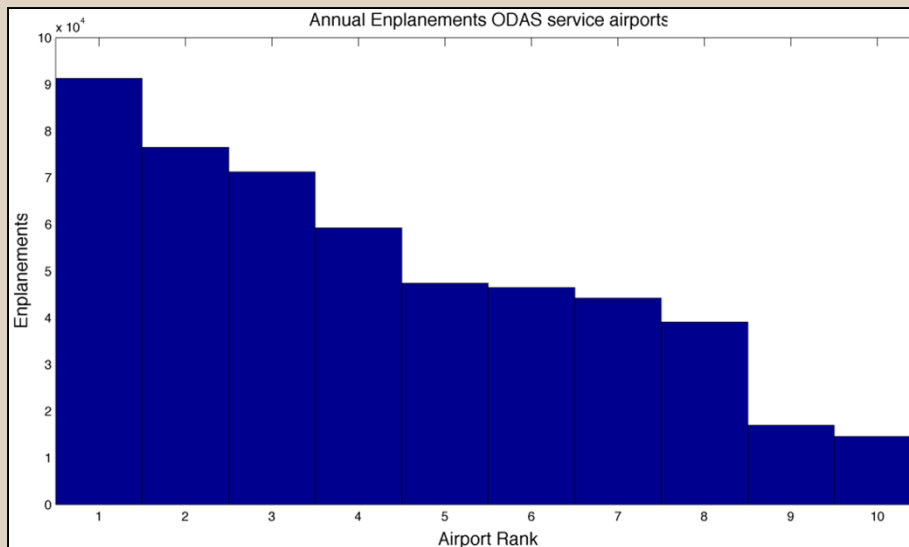
Experiment 4

- 10 airports in Chicago metropolitan area were selected to form the ODAS service network
- Demand on ODAS links is shown below

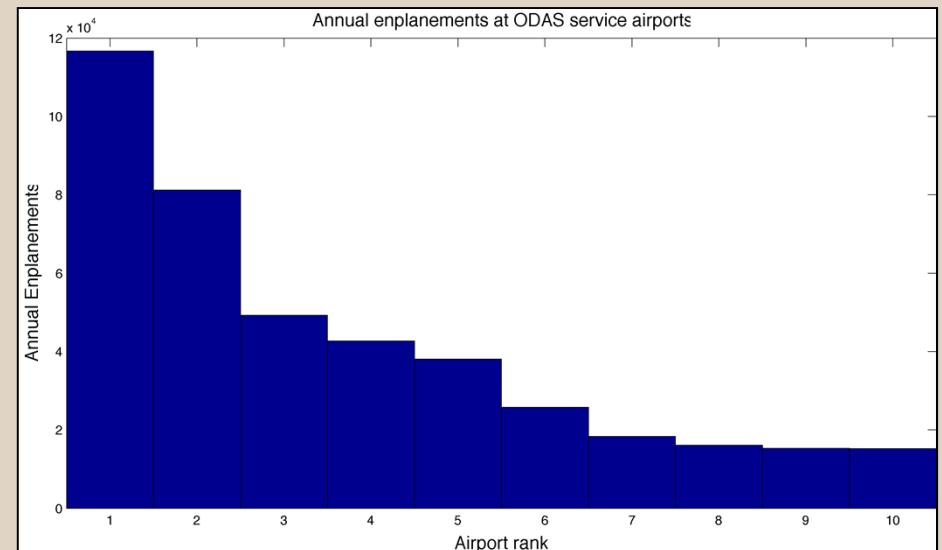


Experiment 4 – Lower ODAS speeds and prices

- Enplanements vs. ODAS Airport Rank
- As a result of lower prices, ODAS captures 80% demand volume compared to Experiment 2 network, even though it serves a much smaller area.
- An important characteristic of this network is that most of the trips involve Chicago as either origin or destination, which results in an airport near Chicago (Gary-Chicago International Airport) as a high volume ODAS airport



Experiment 3



Experiment 4

Conclusions

- ODAS can offer measurable mobility benefits for regional travel
 - However, its service cost as estimated by current available VLJ aircraft cost analysis, is still prohibitive for trips longer than ~200 miles
 - A regional ODAS service network can act as a reliever for the regional commercial air network
 - The design of VLJ aircraft can be tied to the regional demand analysis, in order to minimize the service costs once the aircraft enters service
- The method represents a viable analytical model for studying multi-modal transportation
 - Composite network method is advantageous (than the high-abstraction methods typically employed in demand forecast analysis) for capturing mode interactions.
 - Encapsulates all the modal networks; this addresses the multi-modal interactions directly and explicitly in the modeling



Intercity Demand Forecasting

Trip Generation

- Estimate total demand originating from a geographical unit in a given time interval

Trip Distribution

- Assign other geographical units as destinations to this demand

Mode Choice

- Divide the trips between each origin-destination pair by modes of transportation available

Network Assignment

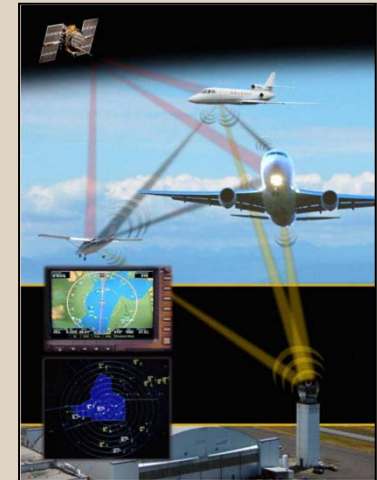
- Convert the demand into actual flow on the links and nodes of modal networks

Outline

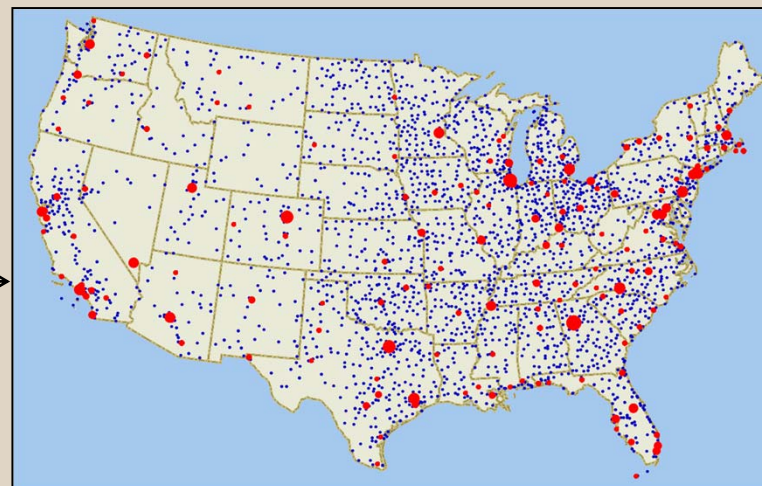
- **Introduction**
 - National & Regional Transportation Systems
 - On-Demand Air Service
 - Need for a new framework
 - Research objectives
- **Background**
 - Existing frameworks
 - Demand forecasting & Discrete Choice theory
- **Model Overview**
 - Model structure
 - Composite network model
 - Model calibration
- **Case studies**
 - Full ODAS network
 - Candidate regional network
 - Candidate metropolitan area network
- **Conclusions and Recommendations**

Solutions to increase NTS capacity

- **Infrastructure investment**
 - Slow, inefficient results
 - Environmental concerns
- **Advanced technology**
 - FAA NextGen
 - NASA Personal Air Vehicle Exploration (PAVE) study
 - High-speed rail
- **New service modes**
 - NASA Small Aircraft Transportation Systems (SATS) study

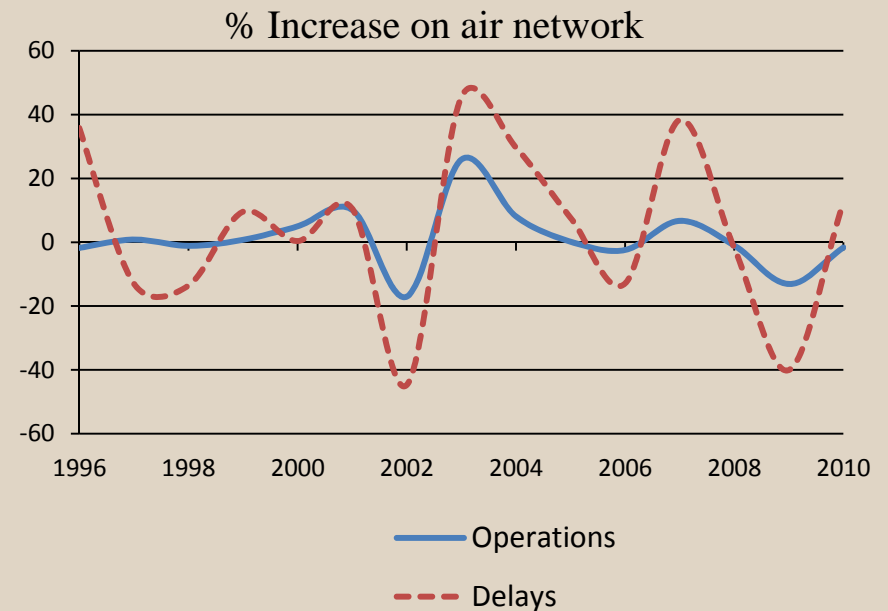
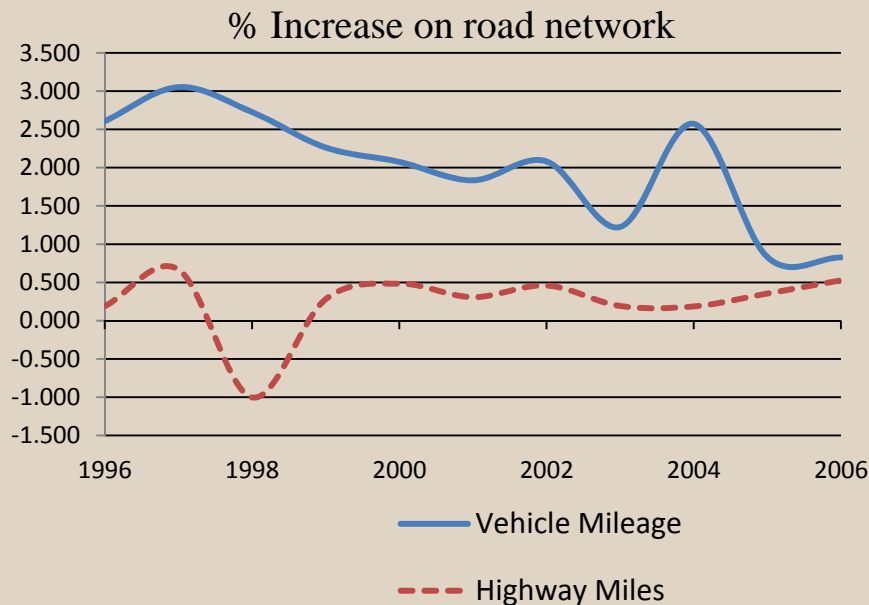


Number of public use GA airports far exceed the number of commercial airports



National Transportation System (NTS)

- **NTS is over-capacitated**
 - Increasing transportation demand
 - Saturated infrastructure
 - Environmental concerns



Research Motivation

- **Insufficient demand information for ODAS**
 - Service providers differ in revenue models, network topologies, type of aircraft
 - So far largely unsuccessful: DayJet, SATSAir, POGO Jets Inc
- **Hypotheses about ODAS benefits untested**
 - Economically viable mode
 - High mobility because of point-to-point access
 - Relieving pressure on existing systems such as hub airports
 - Can be integrated readily into NAS
- **Need to study multi-modal interactions**
 - Framework needed to study effects of changes in one mode on the RTS
 - Necessary to understand how ODAS fits into the existing system
- **Refine requirements for ODAS**
 - Evolution of systems engineering
 - Instead of developing single system (such as an aircraft), it is important to evaluate the system in the larger operational context

Transportation Network Modeling

- Tools to predict the utilization of transportation resources at any given time
- Microscopic Models
 - High degree of detail and complexity
 - Possibly low geographical extent
 - Agent based models: CORSIM, Jet:Wise, ACES
 - Used to study operational factors
- Macroscopic Models
 - High level of abstraction
 - Multi-modal
 - Used to study demand, resource investment and long-term evolution
 - TSAM, *Mi*
- Mesoscopic Models
 - Combination of the two
 - TSAM + ACES

TSAM & *Mi*

	TSAM	<i>Mi</i>
Purpose	Impact of SATS on the NAS, individual <i>what-if</i> scenarios for travelers	Evaluating different PAV concepts in the context of the NAS
Geographic Extent	Continental US	Continental US
Basic Unit	County	Metropolitan Statistical Areas (MSA), as defined by the Census Bureau
Intended Stakeholders	Policy makers, SATS providers, travelers	PAV designers, policy makers
Transportation modes	Automobile, commercial air, GA	Automobile, commercial air, GA, hypothetical PAV
Tools	System dynamics, discrete choice theory	Agent based modeling, system dynamics
Output	Demand distribution by counties and modes, GIS format, demand forecasting up to year 2050, input to ACES for aircraft trajectory generation in NAS	Demand distribution (in terms of fraction of total demand) by modes and distances

Intercity Demand Forecasting

Trip Generation

- Estimate total demand originating from a geographical unit in a given time interval

Trip Distribution

- Assign other geographical units as destinations to this demand

Mode Choice

- Divide the trips between each origin-destination pair by modes of transportation available

Network Assignment

- Convert the demand into actual flow on the links and nodes of modal networks

Discrete Choice Theory

Fundamental Axioms:

- When presented with alternatives, human beings act rationally to arrive at an estimate of relative utility of each alternative, and choose an alternative that maximizes their utility under given circumstances
- **Independence of Irrelevant Alternatives:** If A is preferred over B in a choice set $\{A, B\}$, then introducing a third alternative C does not change the preference order between A and B. Moreover, *relative odds between A and B do not change with the addition of C.*

These two axioms cover a variety of cases of individual behavior while choosing alternatives, however the second axiom is too strong in some cases

Discrete Choice Theory

$$U_x(A_i) = f(a_{i1}(x), a_{i2}(x), \dots, a_{in}(x))$$

Utility of alternative A_i
to the individual x

Attributes of the alternative (time, cost,
accessibility etc) and individual (income,
age, gender etc)

$$U_x(A_i) = V_x(A_i) + \varepsilon_x(A_i)$$

Deterministic utility
(given by an analytical
function)

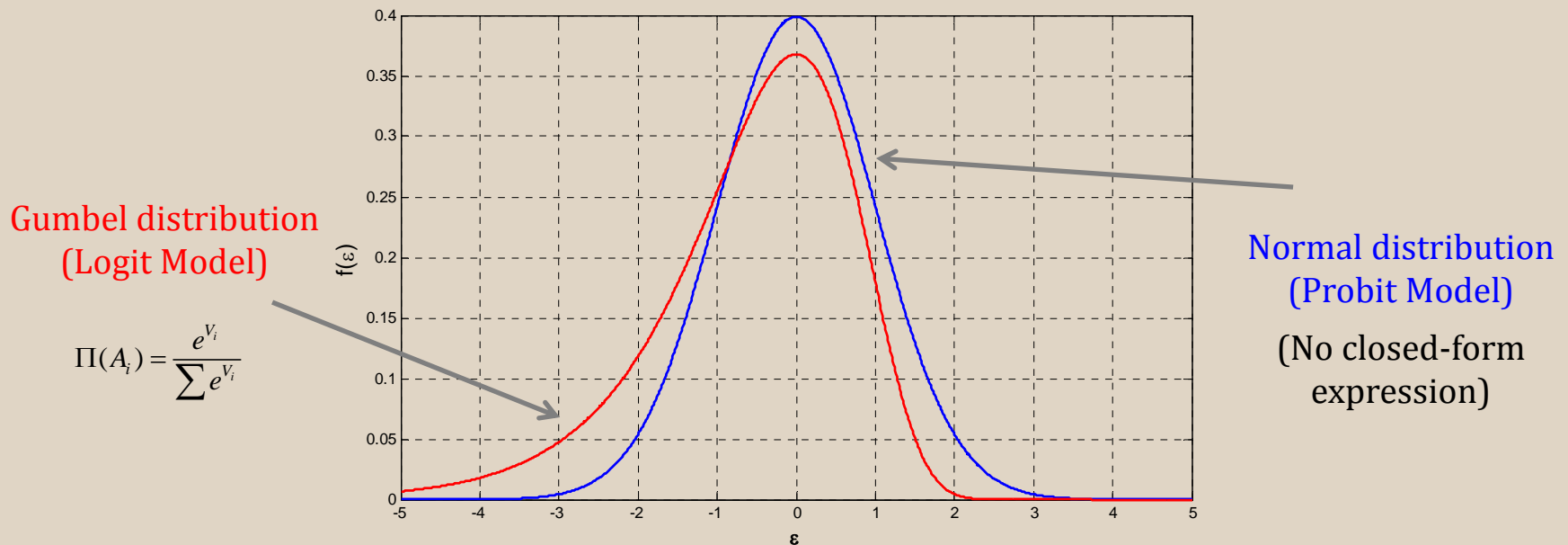
Random utility (given by a
probability distribution)

Discrete Choice Theory

Probability of alternative A_i being chosen over all other alternatives,

$$\Pi_x(A_i) = P(V_m - V_i \leq \varepsilon_i - \varepsilon_m \quad \forall m \neq i)$$

Assume a probability density function $f(\varepsilon_i)$ for all alternatives



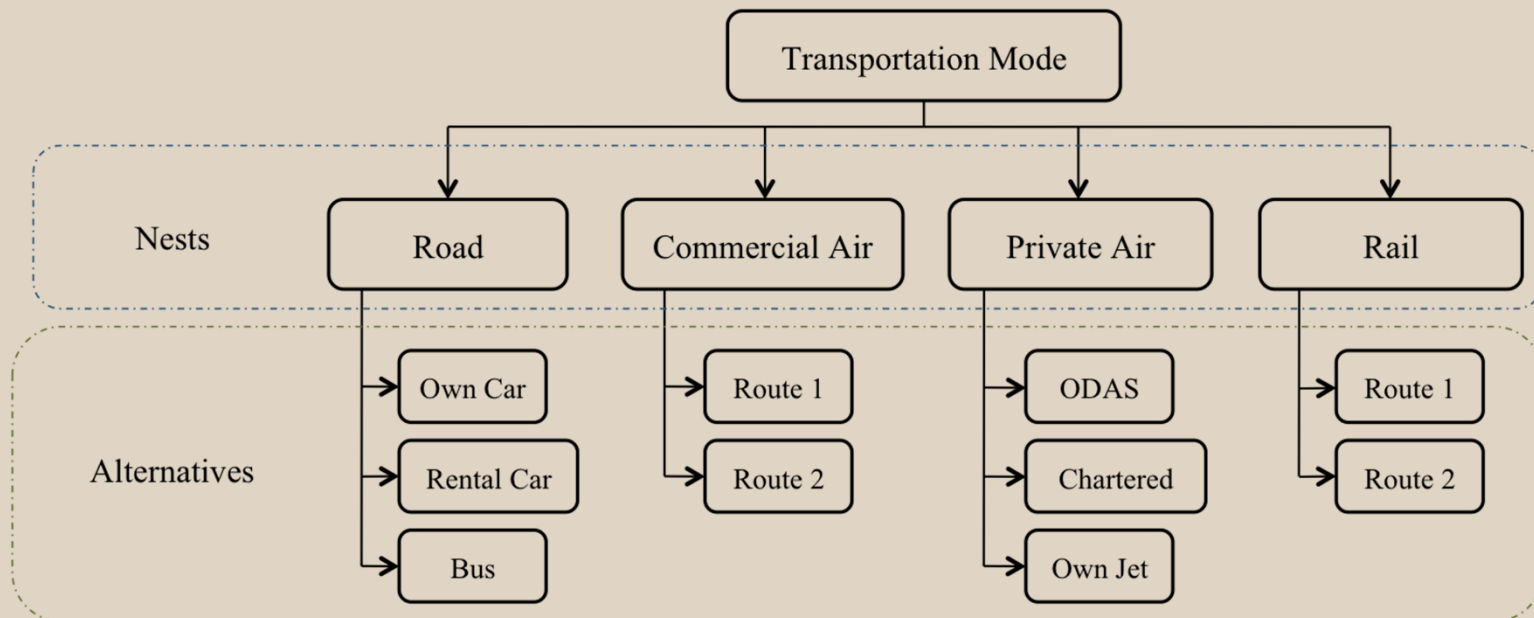
Discrete Choice Theory

In multinomial logit model (MNL), the IIA axiom is sometimes too strong

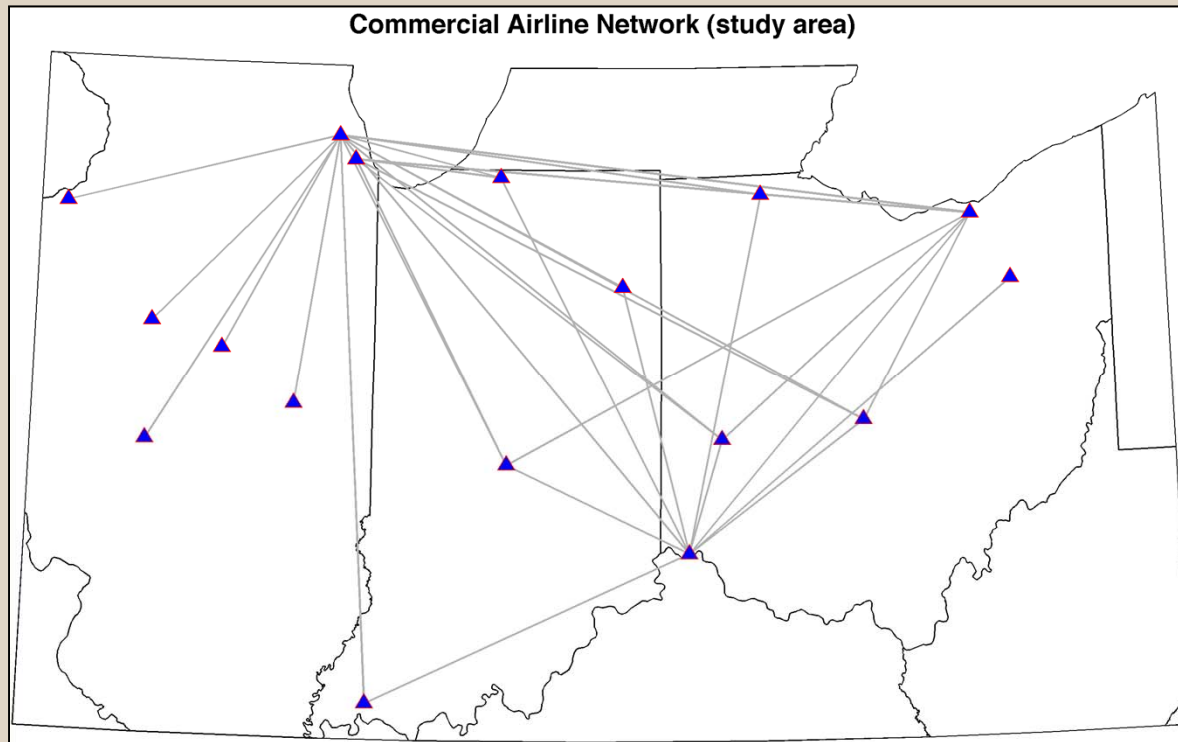


Nested Logit Model

$$\Pi(A_j) = \Pi(N_k) \times \Pi(A_j | N_k)$$

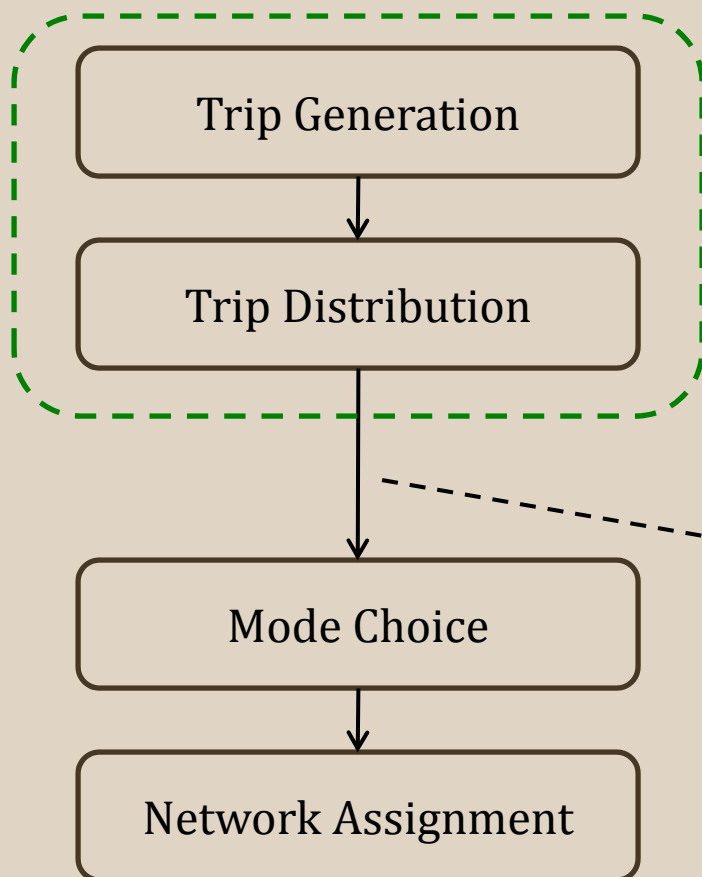


Model Description – Commercial Air Network



- Network created using T100 segment data
- Hub-and-spoke nature
- Does not truly represent the network available to travelers
- Need to include nearby hub airports

Model Description – Demand Matrix

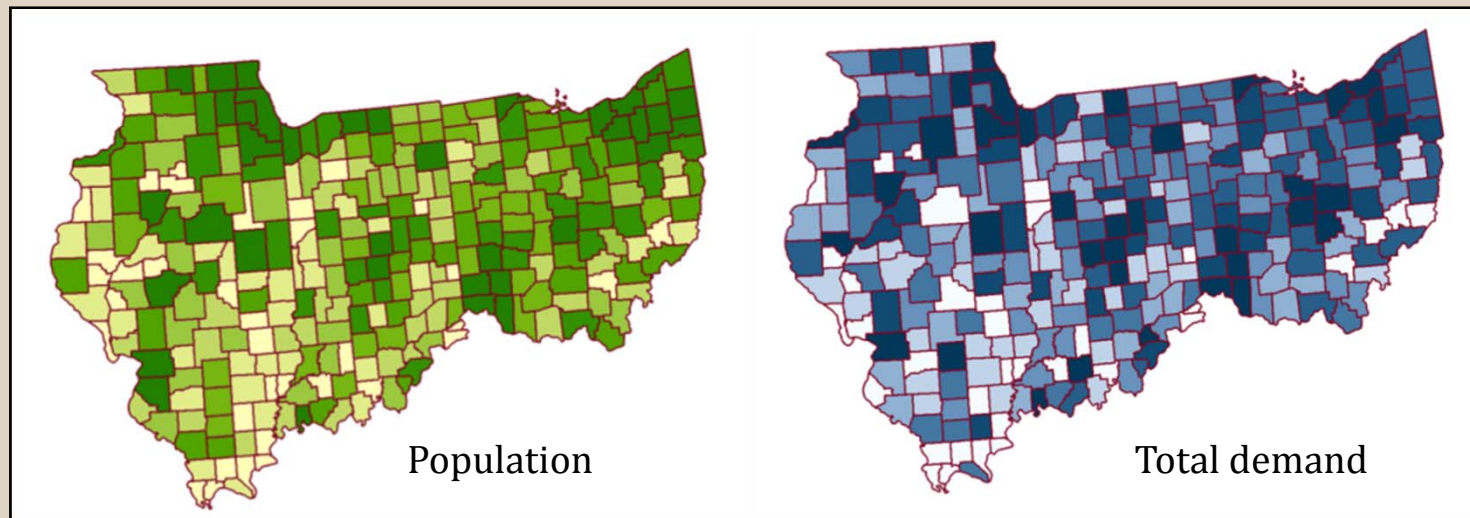


Data collaboration with TSAM

$$T_{ij}(k) = \begin{bmatrix} n_{12}(k) & \cdot & \cdot & \cdot & n_{1M}(k) \\ \cdot & \cdot & & & \cdot \\ \cdot & & \cdot & & \cdot \\ \cdot & & & \cdot & \cdot \\ n_{MM}(k) & \cdot & \cdot & \cdot & n_{MM}(k) \end{bmatrix}$$

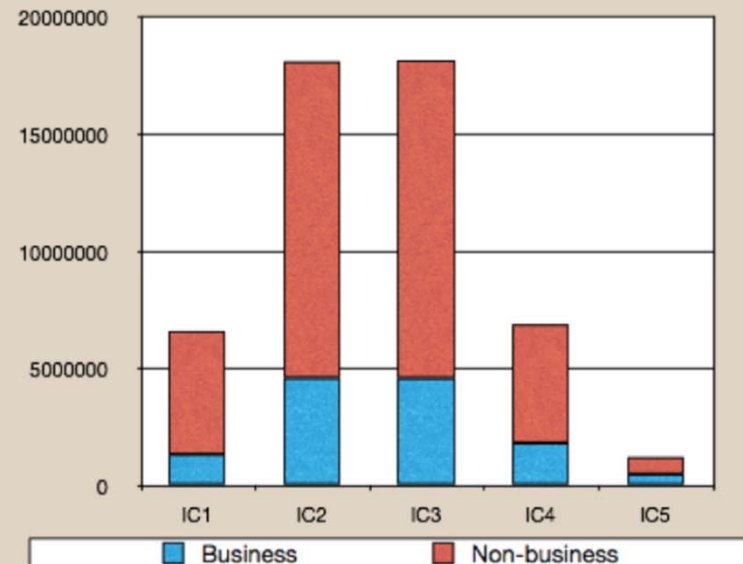
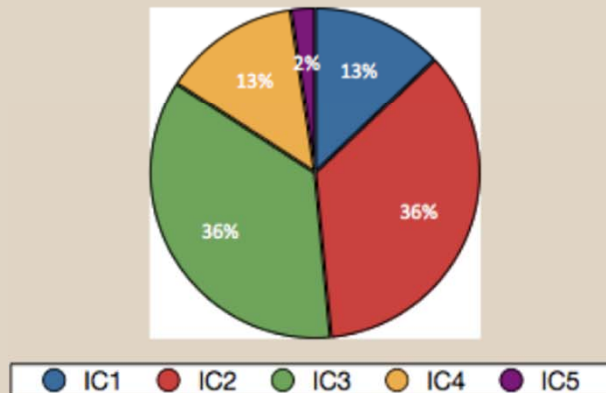
Model Description – Demand Matrix

- 282 X 282 origin-destination trip matrix
- Total ~50 million annual person trips for year 2002
- ~4 trips per household
- Demand distribution follows population trends



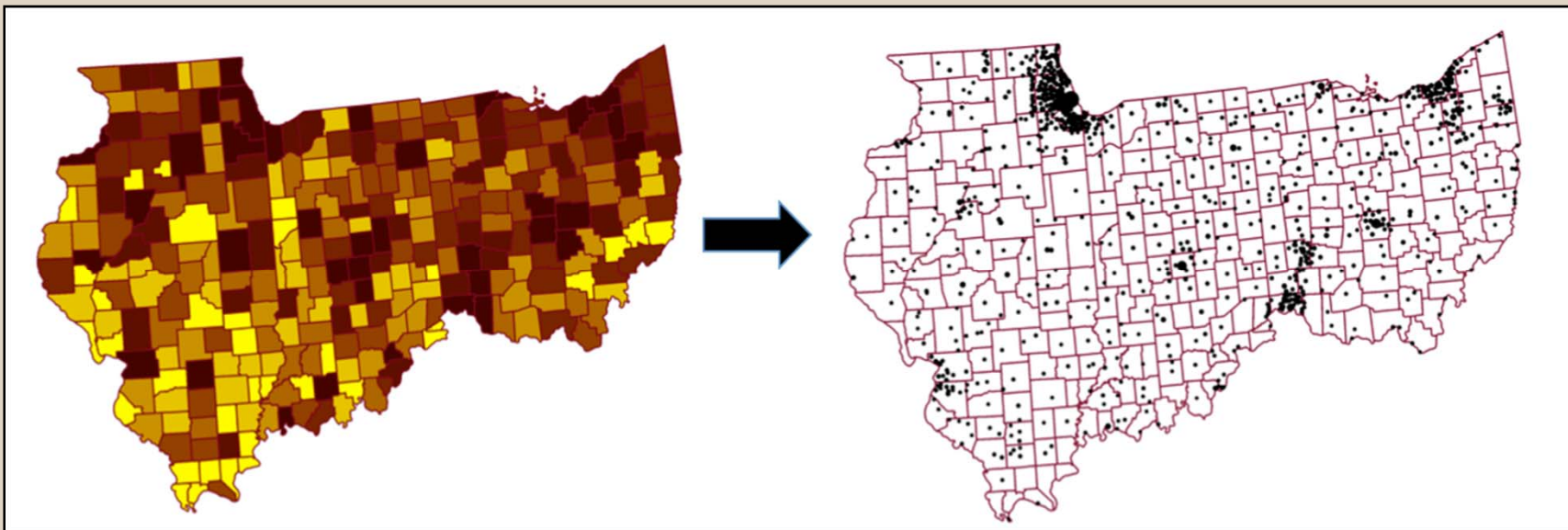
Model Description – Demand Matrix

- **Traveler Household Income**
 - <\$30K, \$30K-\$60K, \$60K-\$100K, \$100K-\$150K, >\$150K
 - Referred to as IC1 to IC5
- **Trip Type**
 - Business
 - Non-business



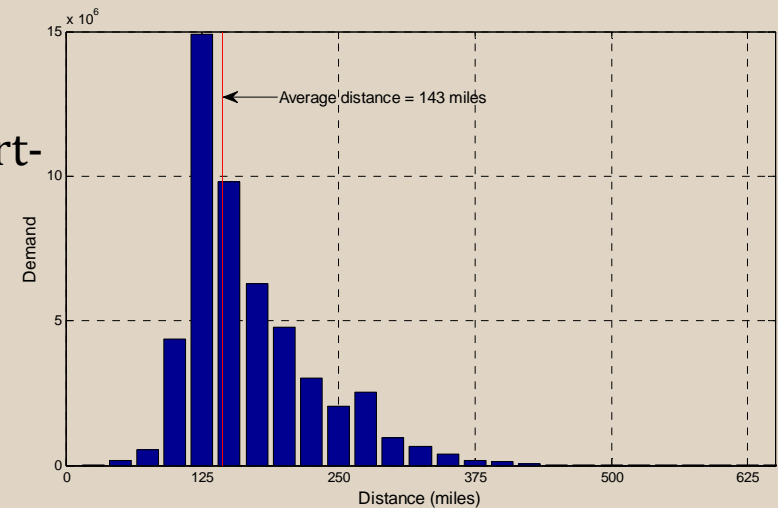
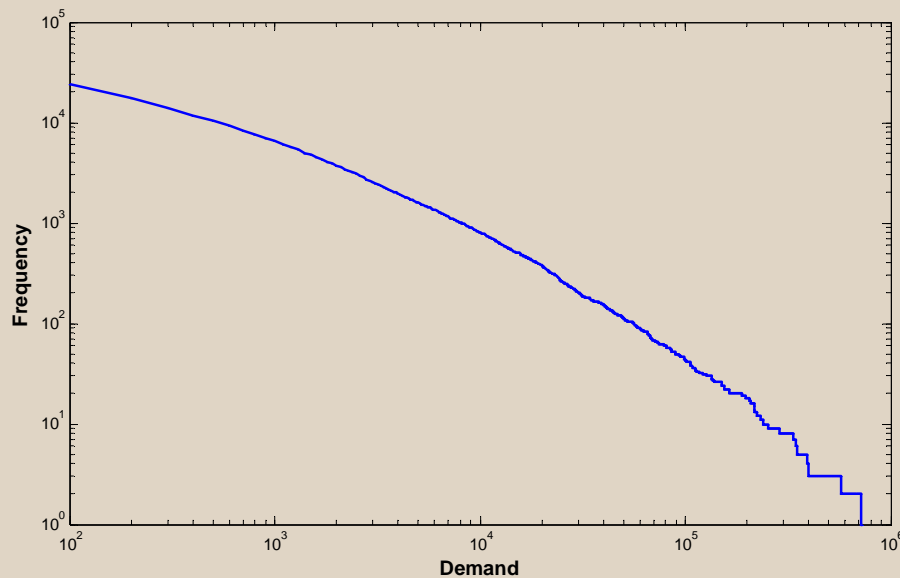
Model Description – Demand Matrix

- Expansion of demand matrix
- Distribution of demand in a county by population centroids
- 282 points => 1015 points
- Resultant points are nodes on highway network



Model Description – Demand Matrix

- Majority of the demand for short-range trips



- Cumulative distribution plot
- Each point represents an O-D pair
- Scale-free nature

Model Description – Utility Calculation

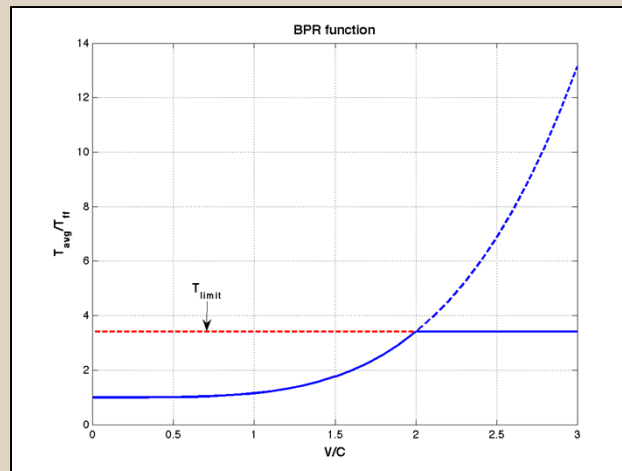
Highway Links

For each highway link, following data is obtained from HPMS:

- Length (l)
- Functional class
- Annual Average Daily Traffic (AADT)
- Number of lanes (N_l)

$$T_{avg} = T_{ff} \left(1 + \alpha \left(\frac{V}{C} \right)^\beta \right)$$

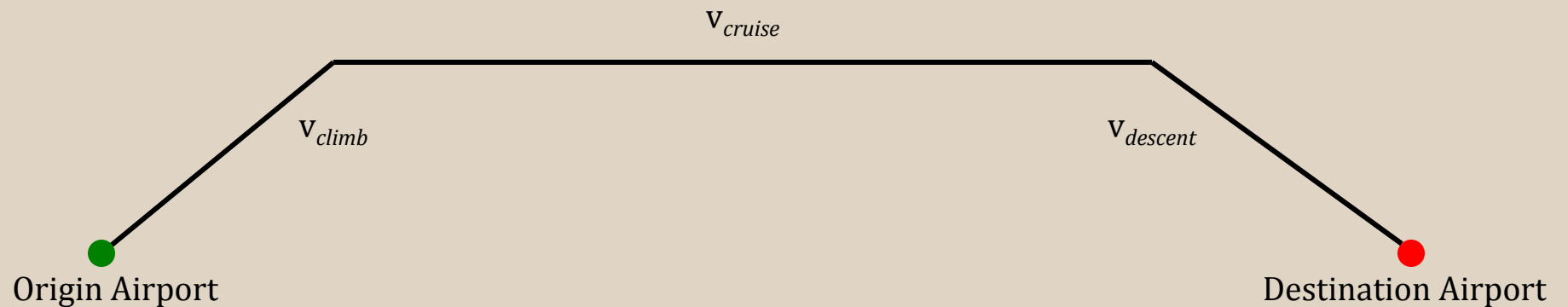
Free-flow travel time T_{ff}
 Average travel time for link T_{avg}
 0.15 α
 Peak traffic volume (pc/hr/lane) V
 Peak traffic capacity (pc/hr/lane) C
 4 β



Minimum speed = 35 mph

Model Description – Utility Calculation

ODAS Air Links



- Aircraft performance characteristics are a part of the design parameters

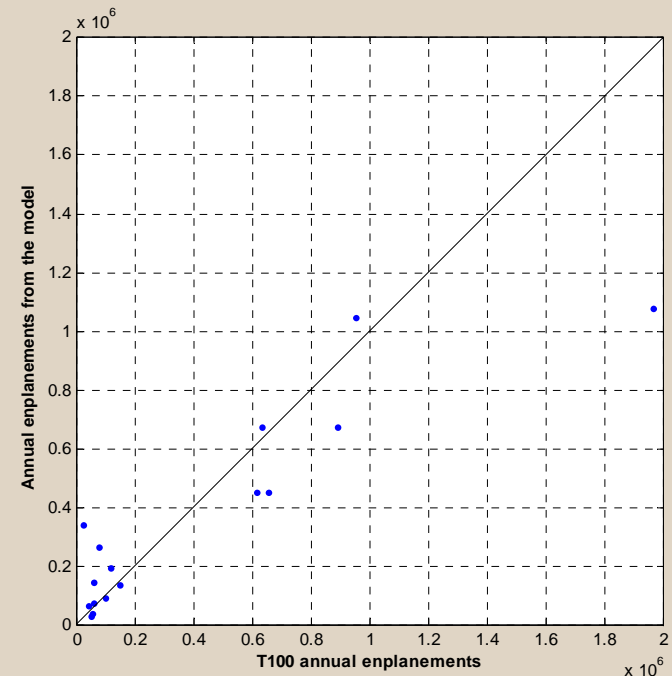
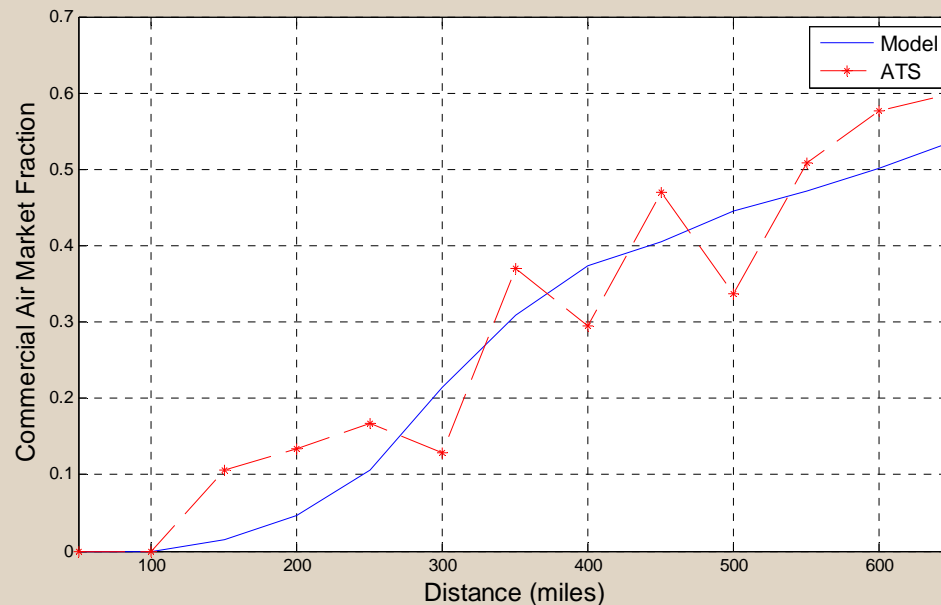
Model Description – Utility Calculation

Link Costs

- **Highway link**
 - Average cost of owning and operating a personal vehicle
 - 20 cents/mile in 2002 according to BTS
- **Commercial air link**
 - DB1B dataset
- **ODAS air link**
 - Price per passenger seat mile (*ppm*) multiplied by great circle distance
 - *ppm* is a design parameter
 - Typical values: \$1.5 - \$2.5

Model Calibration

- American Travel Survey 1995 – Largest individual travel preference survey
- Reports person household income, trip type, origin and destination (in terms of Metropolitan Statistical Area) and the mode of transportation chosen
- Used for calibrating the utility coefficients for 5 user types and 2 trip types

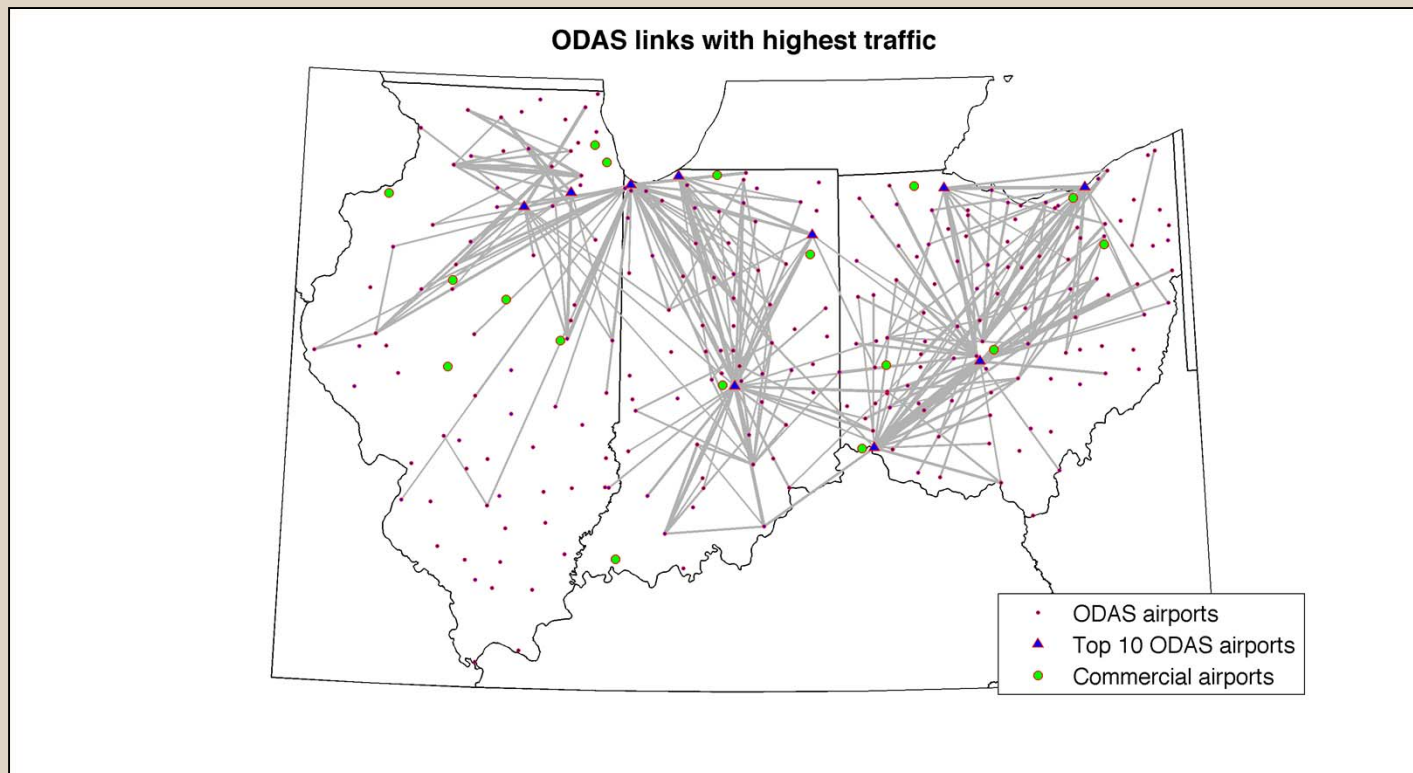


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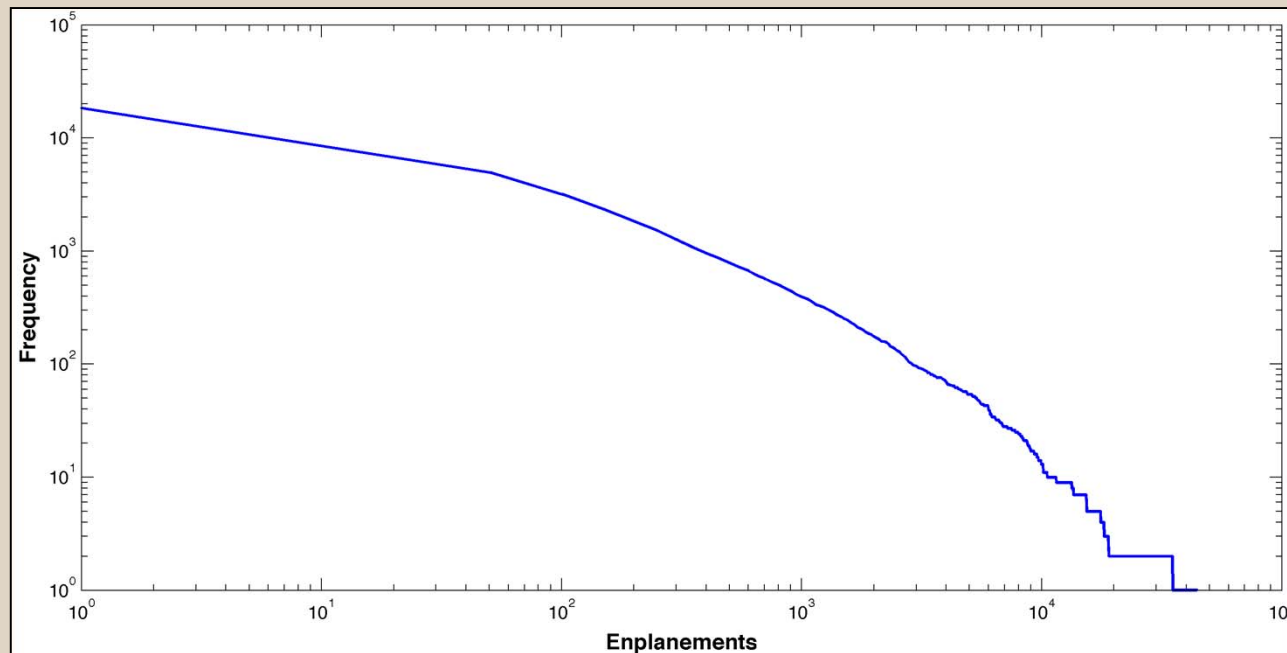
Experiment 1

- Demand on ODAS links is shown below



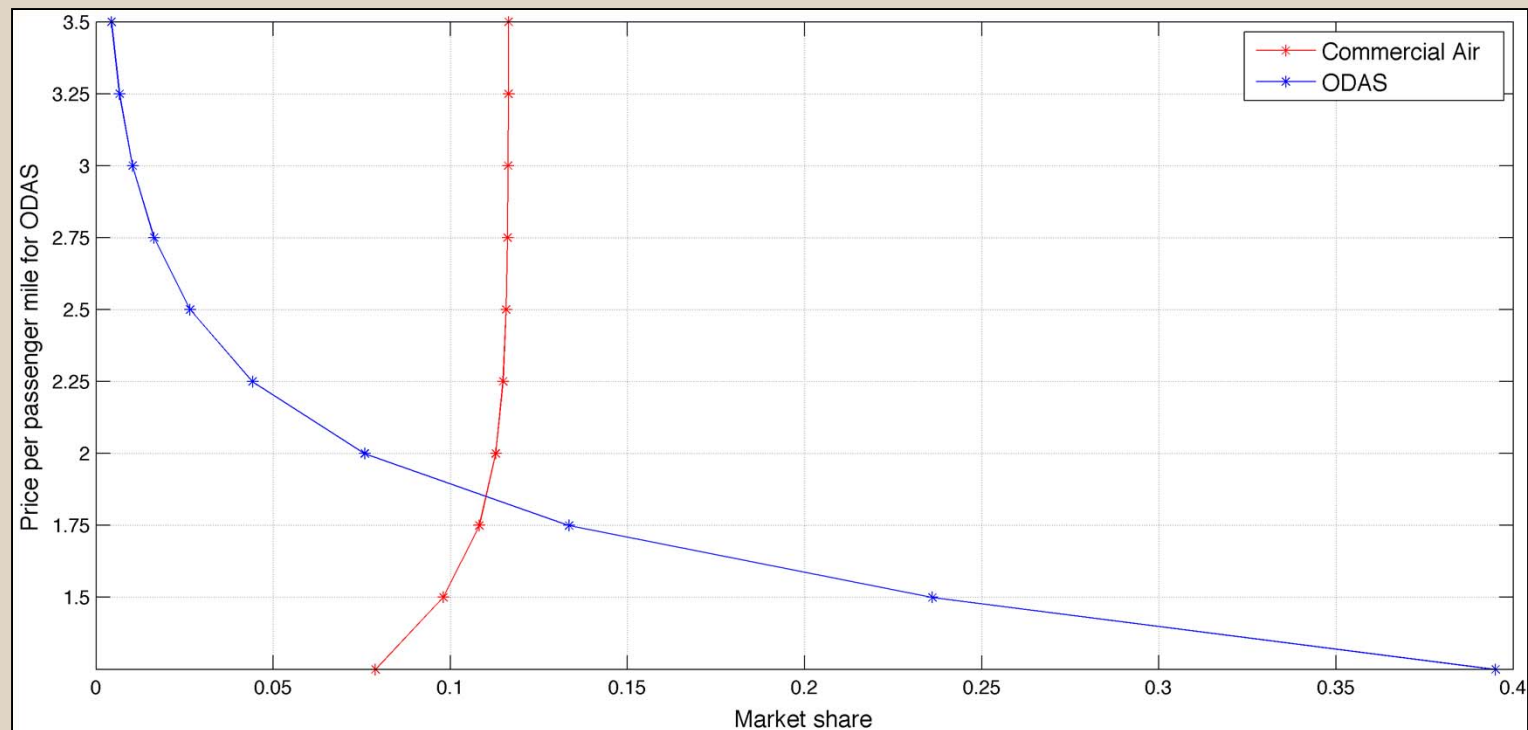
Experiment 1

- Cumulative demand distribution is shown below
- Each point represents an O-D pair
- Scale-free characteristics can be attributed to similar characteristics in the overall demand



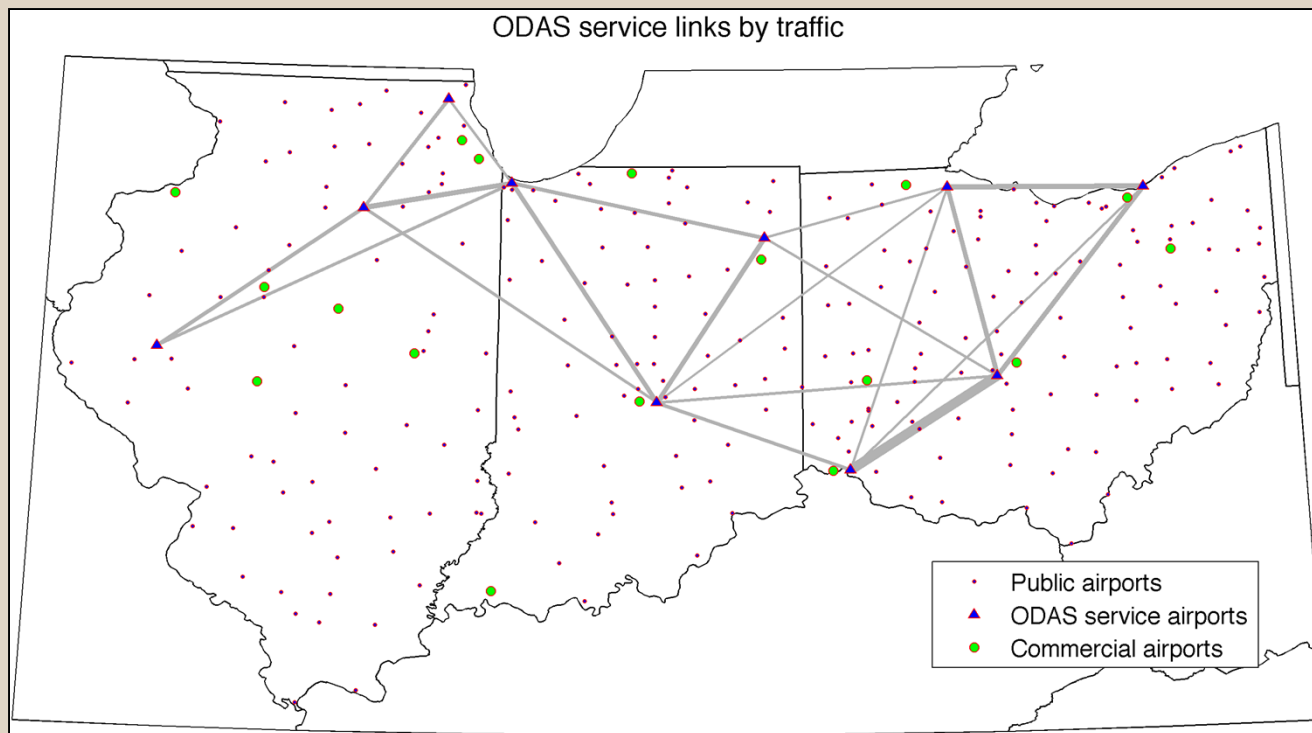
Experiment 1

- Price sensitivity of demand was examined by changing the *ppm* from \$1.25 to \$3.5 in increments of \$0.25
- Significant market share increase starts around \$2.00



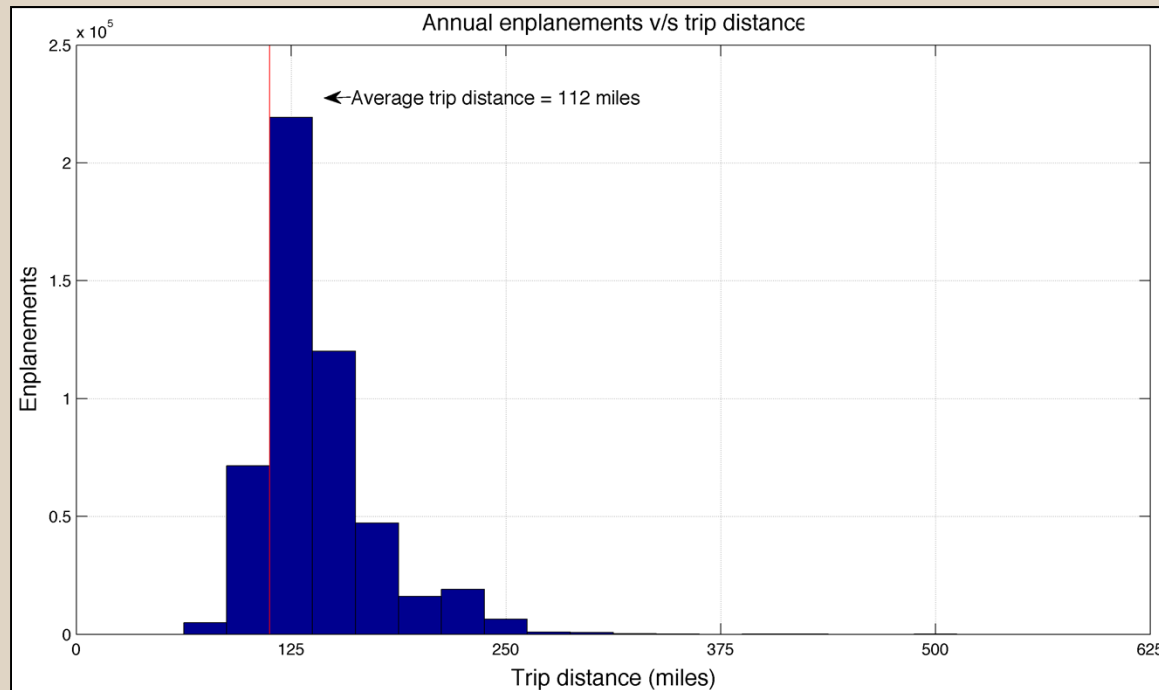
Experiment 2

- Experiment 1 shows top 10 airports situated in urban areas
- If these airports together form an ODAS service network, this network may act as reliever for commercial air network



Experiment 2

- Average trip distance is fairly short, keeping with the overall demand distribution and ODAS price effect



Experiment 3

- Looking at average trip distances in earlier experiments, following conclusions can be drawn –
 - A big part of the range of a typical VLJ is not utilized. In fact, most of the trips are shorter than 200 miles
 - Time savings offered by ODAS mode are quite significant, however the cost is prohibitive for long range trips
 - In case of a specifically designed short-range aircraft (possibly slower than a typical VLJ), which has lower acquisition and maintenance costs, it may be possible to bring down the *ppm*
- ODAS parameters used in Experiment 3 –
 - *ppm* = \$1.5
 - Cruise speed = 250 mph

Recommendations

- Commercial air network model needs higher fidelity, as suggested in the validation study
- Framework can be extended to include additional transportation modes such as high-speed rail, in order to study changes in overall RTS under this new scenario
- Current framework involves no feedback between transportation demand and supply. In reality, the supply capacity will be limited. These limitations can be included
- Additional studies such as overall demand forecast for future years, study of emission levels etc. can be included without changing the basic framework

Thank you!

Questions?

Back-up Slides

Trip Generation and Distribution

$$o_i(k) = f(p_1(i), p_2(i), \dots, p_r(i))$$

Number of trips
originating from i in
time interval k

Socioeconomic parameters associated with i
(population, average household income,
number of business enterprises, tourism
activity etc)

$$n_{ij}(k) = o_i(k) \frac{f(p_1(j), p_2(j), \dots, p_r(j))}{c_{ij}(k)^\gamma}$$

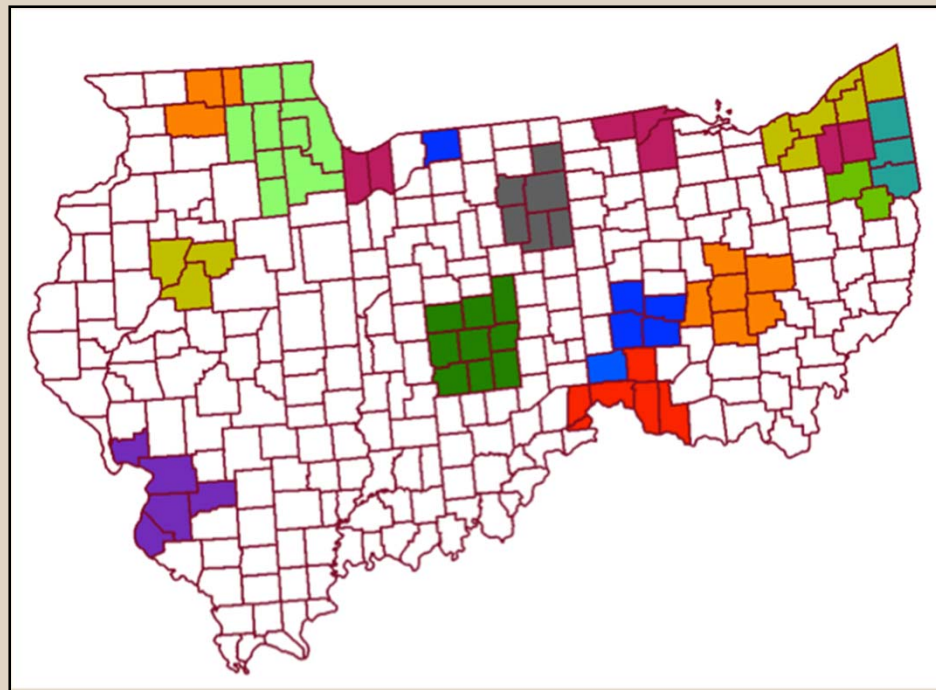
Number of trips
between i and j

Perceived impedance of a trip between i
and j (depends on the factors such as
distance, accessibility etc)

Exponent (>1)

Model Calibration

- Each color represents a MSA. White represents NMSA
- For each O-D pair in the ATS, the states and great circle distance is reported.
- Find out corresponding node pair on the network that has the closest distance



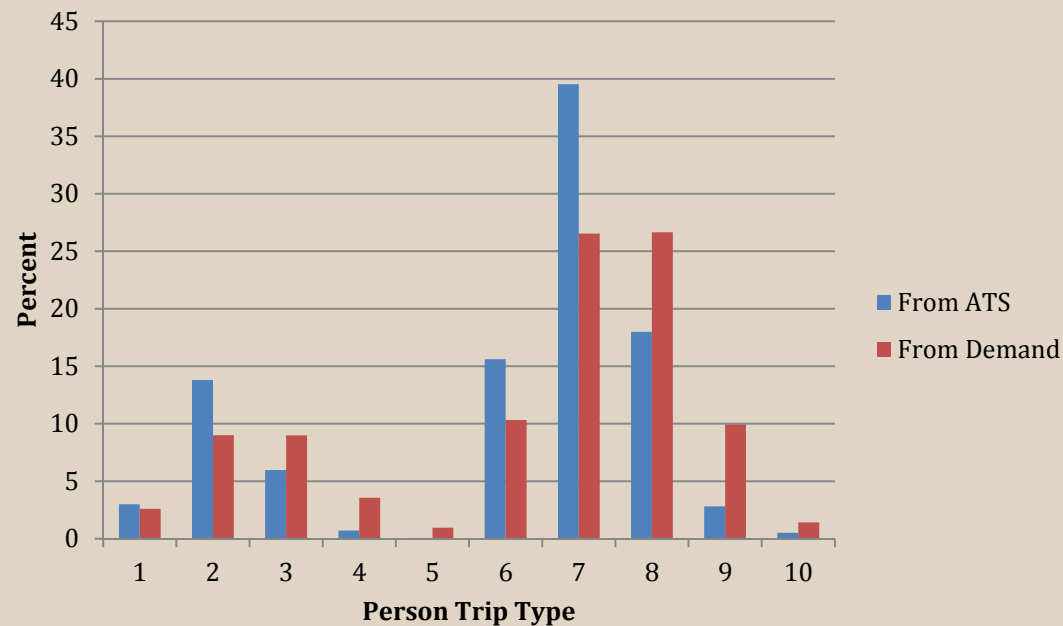
Model Calibration

- American Travel Survey 1995 – Largest individual travel choice preference survey
- Reports person household income, trip type, origin and destination (in terms of Metropolitan Statistical Area) and the mode of transportation chosen
- Used for calibrating the utility coefficients for 5 user types and 2 trip types

Coefficient	Value	Std Error	Value/Std Error	P (Z >Z)
Business Trips				
Time	-0.03513	0.00224	-15.68303	<0.0001
Cost (IC1)	-0.01182	0.00105	-11.25714	<0.0001
Cost (IC2)	-0.00755	0.00177	-4.26553	<0.0001
Cost (IC3)	-0.00563	0.00113	-4.98230	<0.0001
Cost (IC4)	-0.00494	0.00108	-4.57407	<0.0001
Cost (IC5)	-0.00448	0.00291	-1.53951	0.0003
Personal Trips				
	-0.04675	0.00282	-16.57801	<0.0001
Cost (IC1)	-0.01581	0.00128	-12.35156	<0.0001
Cost (IC2)	-0.01256	0.00105	-11.96190	<0.0001
Cost (IC3)	-0.00892	0.00267	-3.34082	<0.0001
Cost (IC4)	-0.00739	0.00172	-4.29651	<0.0001
Cost (IC5)	-0.00715	0.00343	-2.08454	0.0006

Model Calibration

- Insufficient data for high income groups
- Better/ more focused travel survey for high income groups, which are more likely to shift to ODAS, would increase the fidelity of the model



ODAS Parameters

Performance parameters of Eclipse 500 jet were used, as a representative of VLJ class aircraft. Following values of parameters were used:

- Price per passenger seat mile (ppm) = \$2.25
- Maximum cruise speed = 425 mph
- Rate of climb = 3314 feet per minute
- Cruise altitude = 10,000 ft for distances up to 100 miles
= 24,000 ft for distances greater than 100 miles
- Trip price = $100 \times \text{ppm}$ for distances up to 100 miles
= $\text{distance} \times \text{ppm}$ for distances greater than 100 miles