Real-time Intermodalism for Airline Schedule Perturbation Recovery and Airport Congestion Mitigation under Collaborative Decision Making

Yu Zhang
University of South Florida

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AGENDA

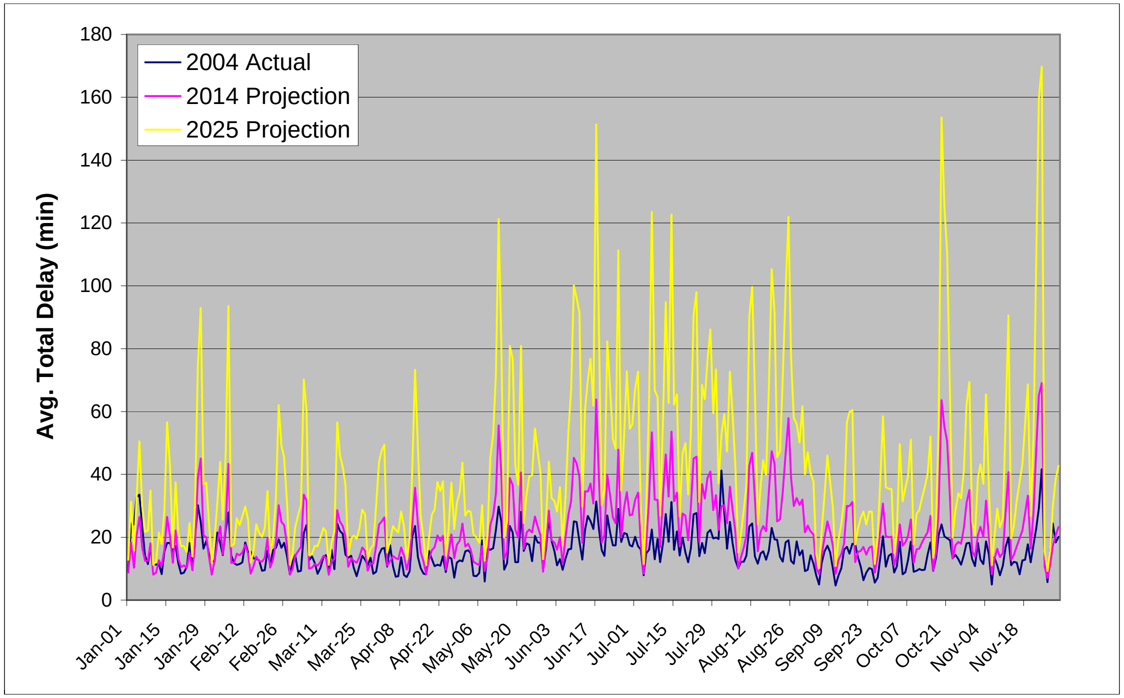
- Airline Schedule Perturbation
  - Causes and Consequences
  - Delay Projection
- Motivations and Proposed Strategies
- Real-time Intermodalism Strategies
  - Short-haul Substitution in an One Stage Hub-and-Spoke System
  - Short-haul Substitution and Flight Diversion in Metroplex System
- Ideas to Tackle Implementation Challenges
- Conclusions

Airline Schedule Perturbation

- **Causes**
  - Airline Internal Reasons
  - Adverse Weather
  - Airport Equipment Outages
  - Terrorism Threats
  - Natural Catastrophes
  - Etc.

- **Consequences**
  - Direct cost of air transportation delay in 2007 was over **32 billion** dollars (Ball, M. et al, 2010)

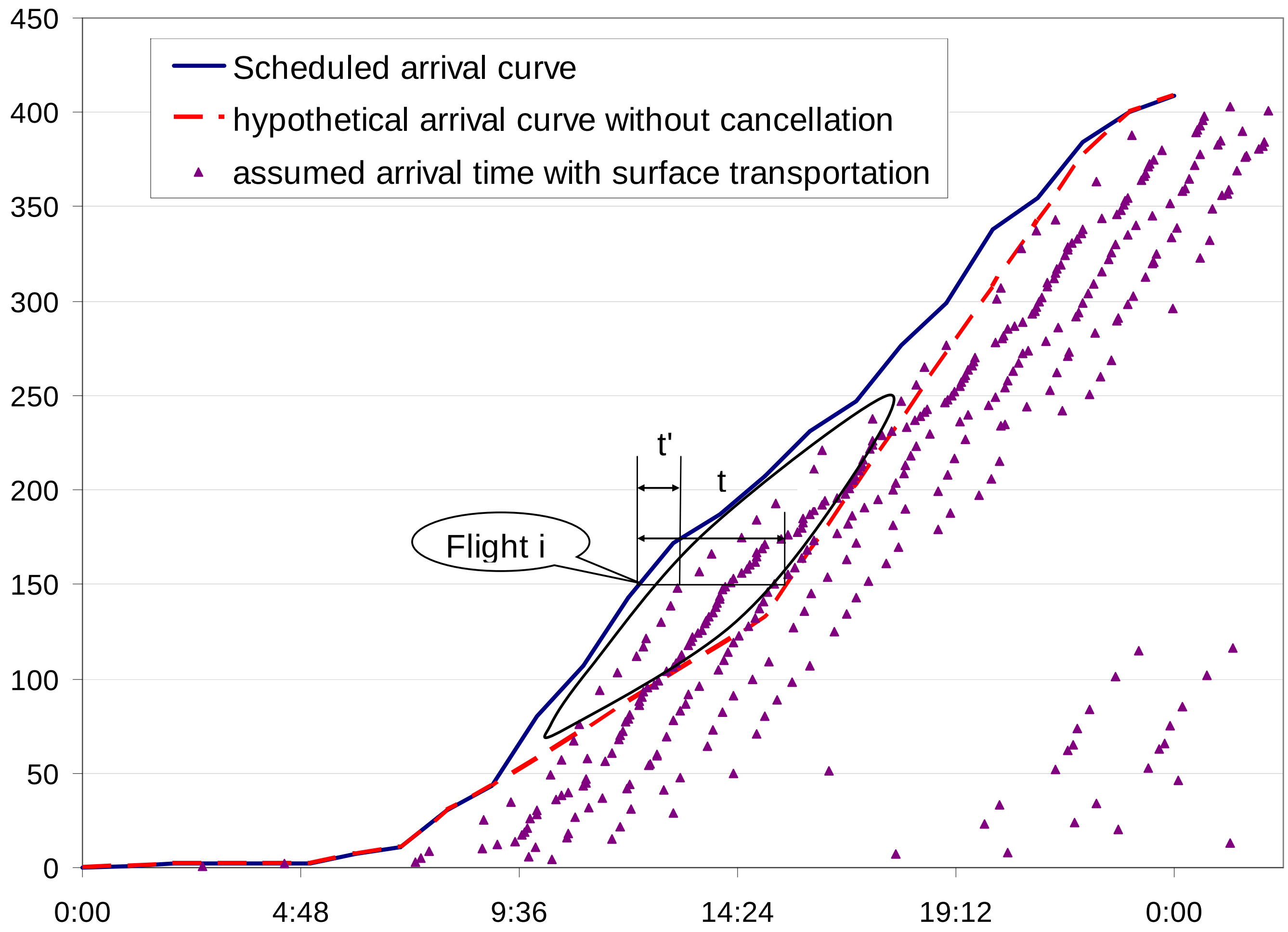

DELAY PROJECTION

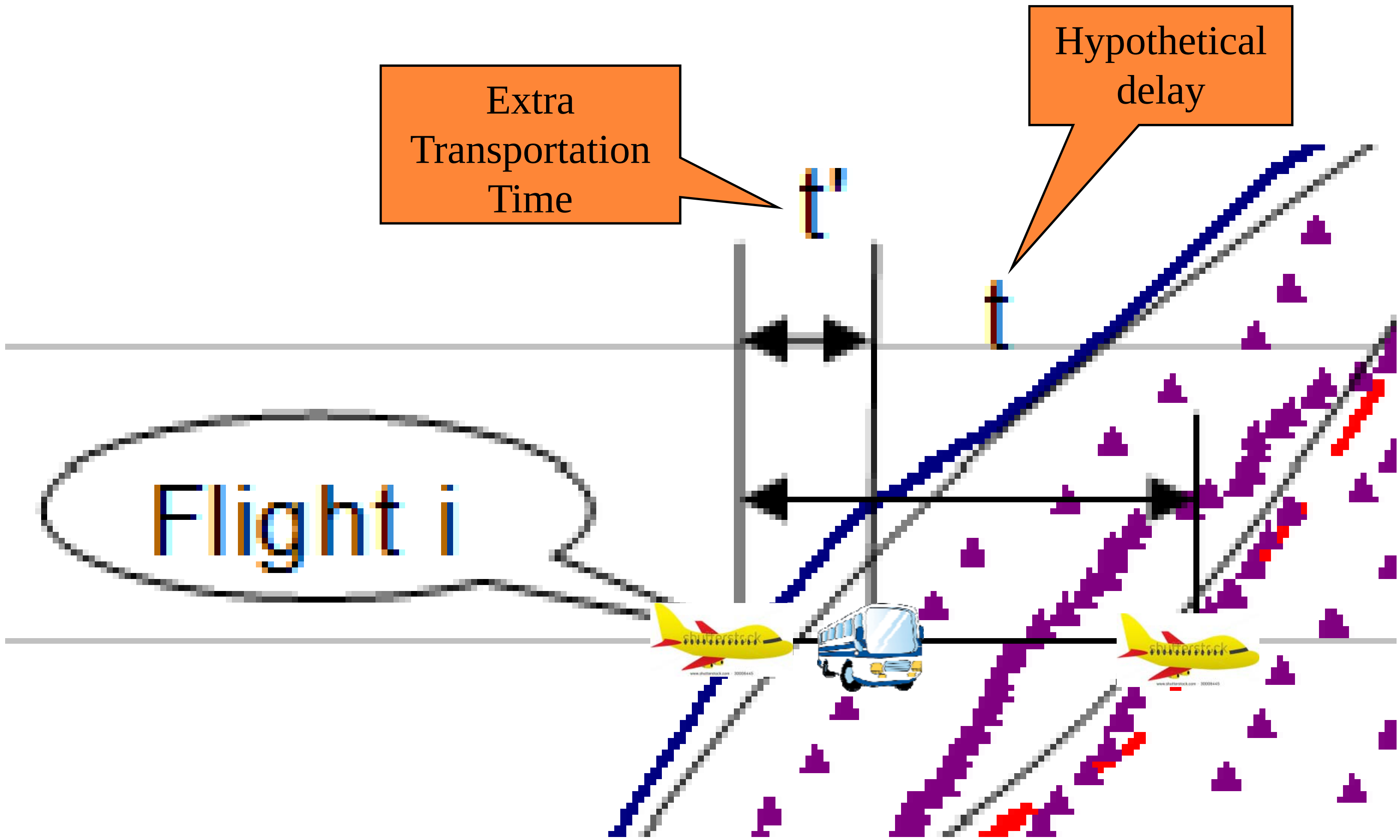


Delays projected using JPDO feasible schedules
Assumes weather in 2014 and 2025 the same as 2004*

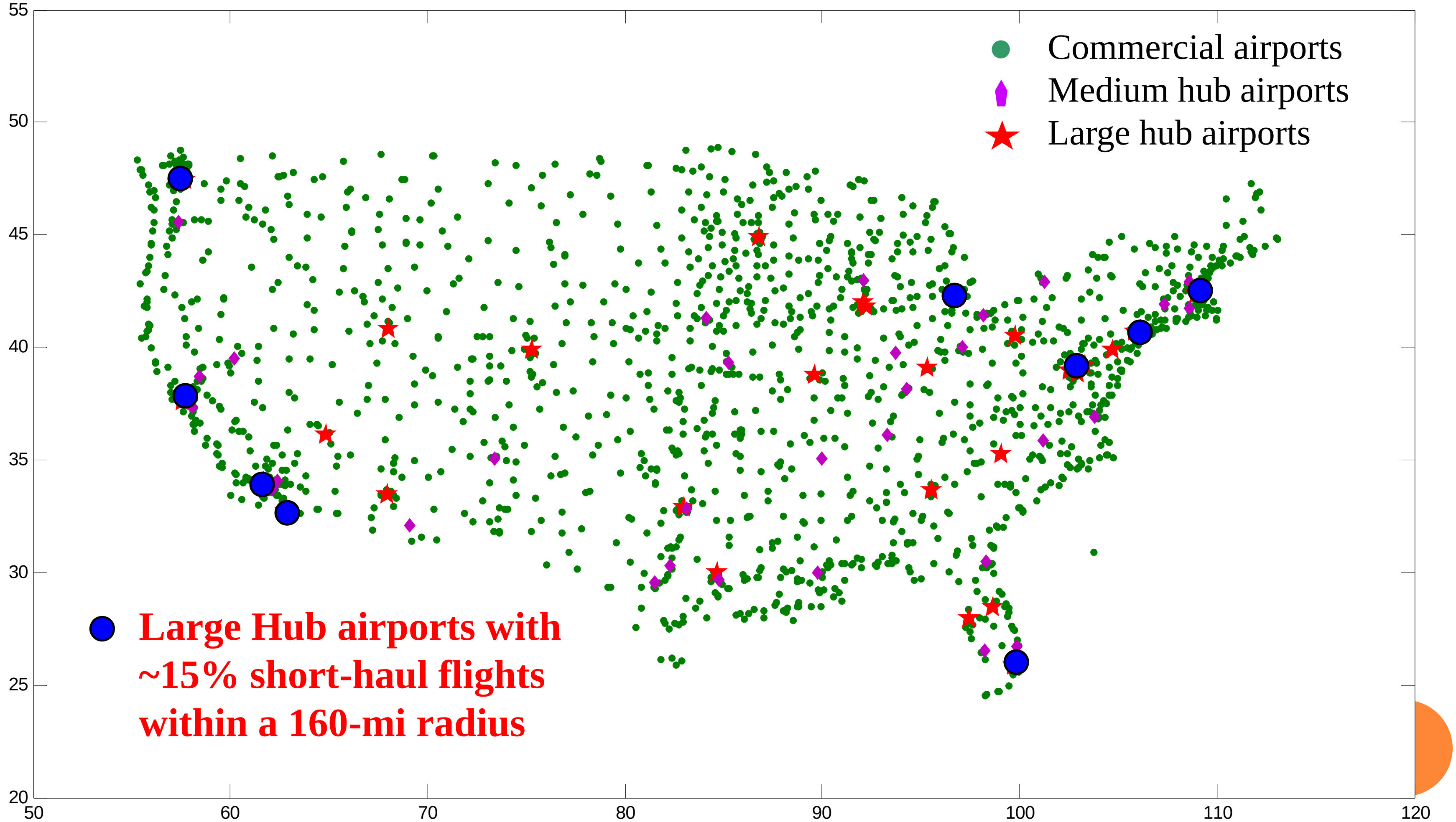
*FAA Strategy office

Motivation-- Benefits of Substituting Ground Transportation Modes for Short-Haul Flights

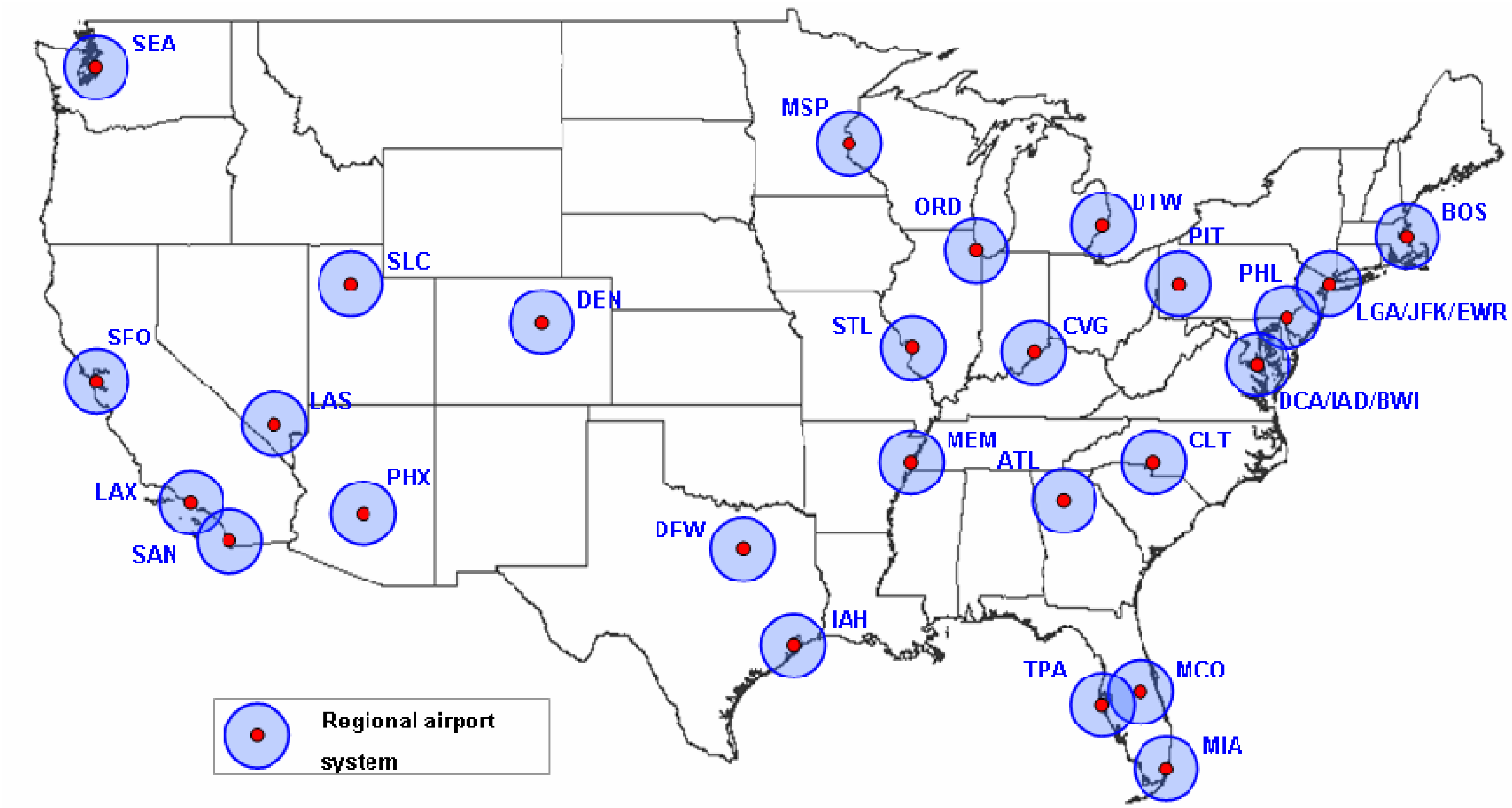



Extra Transportation Time
Hypothetical delay
t'
t
Flight i

GEOGRAPHIC DISTRIBUTION OF US AIRPORTS



Regional Airport System in the U.S.



IDEAS

Real-time Intermodalism in Passenger-Centric Recovery for Schedule Perturbation

- Hub-and-Spoke Network: Substitute short-haul flights with ground transport

- MetroPlex System: Substitute short-haul flights, divert flights to alternative airport(s) and provide ground transport between the hub and alternative hubs

A **passenger-centric solution** based on information sharing and exchange among passengers, airports, air navigation service providers, and stakeholders of different transportation modes (air, rail, highway, public transit, for-hire vehicles, car rental agencies).

Coach Service Outsourcing Feasibility Study

	Range of Seating	San Francisco	Los Angeles	New York	Chicago	Miami	Texas
All Type		100	188	260	153	88	114
Deluxe Motorcoach	36-68	63	113	189	83	59	80
Executive Coach	18-30	1	5	11	9	4	6
Limo Bus	18-30	10	9	34	15	10	13

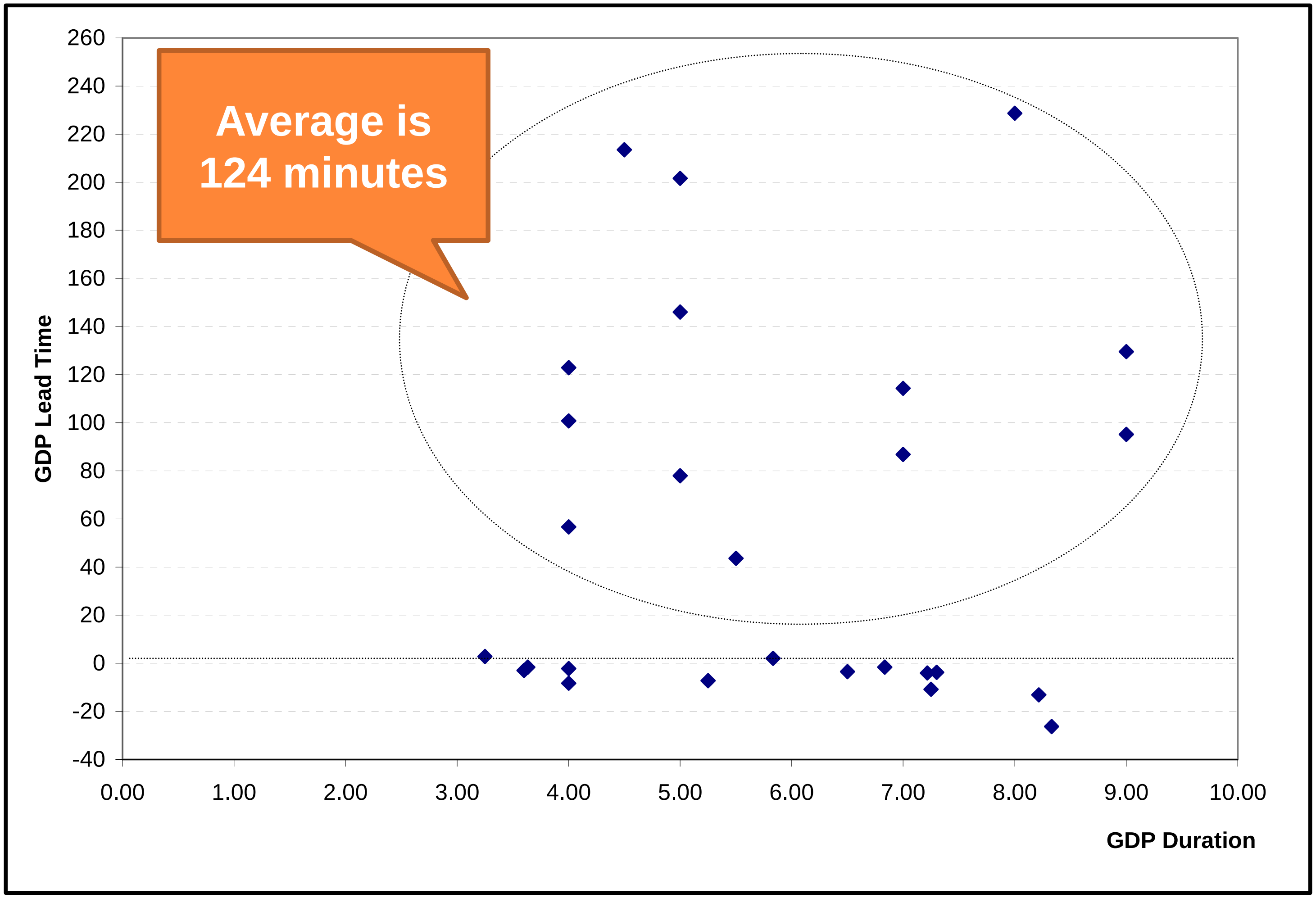
Source: BusRates.com, accessed in May 2008.

Charter Company's Response to Urgent Service Request

	San Francisco	Los Angeles	New York	Chicago	Miami	Texas
	SFO	LAX	JFK	ORD	MIA	DFW
Not available	3	2	3	5	4	4
1-1.5 hours	2	3	4	2	3	2
3-4 hours	4	5	3	3	3	4
Total	9	10	10	10	10	10

The unavailability or long lead time for some coach service companies to respond to urgent service requests are mainly caused by the lack of drivers.

GROUND DELAY PROGRAM LEAD TIME



PROBLEM DEFINITION

- Scenario:
  - An airline with a hub-and-spoke network
  - Capacity reduction at this major hub airport
- Strategy:
  - Delay, cancel, substitute arrival and departure flights
  - Allow passenger reassignment at the hub airport
  - Allow aircraft swapping at the hub airport
- Input data:
  - Original flight schedule
  - Hub airport capacity profile
  - Passengers' purchased itinerary
  - Airborne and surface transportation time
  - Original fleet assignment

Mathematical Programming

- Decision Variables

xf_t^a =1 if aircraft i should be flown and landed during time t period, 0 otherwise.

xs_t^a =1 if aircraft i should be substituted with buses and arrive at the hub airport during time t period, 0 otherwise.

yf_t^f =1 if aircraft j should take off during time t period, 0 otherwise.

ys_t^f =1 if aircraft j should be substituted with buses and depart from the hub airport during time t period, 0 otherwise.

Flight decision variables

P_f The number of passengers on a departure aircraft f

Passenger decision variables

Where:

$a \in \mathrm{A}$ A set of inbound flights scheduled to arrive at the major hub airport

$f \in \Phi$ A set of outbound flights scheduled to take-off from the major hub airport

$t \in \Gamma$ A set of discrete time unit

MATHEMATICAL PROGRAMMING

- Objective Function (Airline disruption cost)
  - Passenger delay (flying delay, ground transportation time, and waiting for connection)
  - Flight delay and Cancellation penalty
  - Operating cost of coach service
  - Disrupted passenger penalty

$$Min \quad \left(\sum_a AD_a \cdot AHPax_a + \sum_f DD_f \cdot P_f \right) \cdot Cost_P + IO_s \cdot CostP'$$

$$+ \left(\sum_a AD_a + \sum_f DD_f \right) \cdot Cost_F + BO + DP \cdot Cost_D$$

Where:

$Cost_P$	Passenger time value of delaying
$Cost_P{}'$	Passenger time value of waiting at terminal
$Cost_F$	Flight delay cost of a discrete time unit
$Cost_D$	Penalty cost of one disrupted passenger

OBJECTIVE FUNCTION COMPONENTS (1)

Passenger Waiting Time at Airport Terminal

$$IO_s = \sum_{s} \sum_{\tau}^{T-1} \left(IPax_s^{\tau} - OPax_s^{\tau} \right)$$

Where:

The cumulated in-flow at time τ

$$IPax_s^{\tau} = IPax_s^{o} + \sum_{t=1}^{\tau} \sum_{a} \sum_{f} \left(xf_a^{\,t} + xs_a^{t} \right) \cdot Pax_{af} \cdot SpokeF_{fs}$$

The cumulated out-flow at time τ

$$OPax_s^{\tau} = OPax_s^{o} + \sum_{t=1}^{\tau} \sum_{f} \left(yf_f^{\,t} + ys_f^{t} \right) \cdot \left(P_f - DHPax_f \right) \cdot SpokeF_{fs}$$

Pax_{af} The connecting passengers take arrival aircraft i and departure aircraft j

$Spoke_{fs}$ The indicator of departure flight j and destination s, =1 if j goes to s, 0 otherwise

Objective Function Components (2)

Flight Arrival Delay

$$AD_a = \sum_t (t - AT_a) \cdot (xf_a^t + xs_a^t) + \left(1 - \sum_t (xf_a^t + xs_a^t)\right) \cdot ACanT_a$$

Flight Departure Delay

$$DD_f = \sum_t (t - DT_f) \cdot (yf_f^t + ys_f^t) + \left(1 - \sum_t (yf_f^t + ys_f^t)\right) \cdot DCanT_f$$

Where:

$ACanT_a$	Cancellation penalty of arrival flight a
$DCanT_f$	Cancellation penalty of departure flight f
AT_a	is the scheduled arrival time of aircraft a at the original hub airport
DT_f	is the scheduled departure time of aircraft f at the original hub airport

Objective Function Components (3)

Bus Operating Cost

$$BO = \left(\sum_a APax_a \cdot ABT_a \cdot \sum_t xs_a^t + \sum_f P_f \cdot DBT_f \cdot \sum_t ys_f^t \right) \cdot CostBP$$

$$+ \left(\sum_a \sum_t xs_a^t + \sum_f \sum_t ys_f^t \right) \cdot CostB$$

Where:

$APax_a$	is the number of passengers who purchased their itinerary to take arrival flight a
ABT_a	is the bus driving time for substituting an arrival flight a
DBT_f	is the bus driving time for substituting a departure flight f
$CostBP$	is the unit passenger cost on taking bus
$CostB$	is the fixed cost of substituting one cancelled flight

Number of Disrupted Passengers

$$DP = \sum_a \left(1 - \sum_t \left(xf_a^t + xs_a^t \right) \right) \cdot APax_a + \sum_s \left(IPax_s^T - OPax_s^T \right)$$

CONSTRAINTS (1)

1. Aircraft capacity constraint: $P_f \leq DCap_f \quad \forall f \in \Phi$
2. Passenger flow constraint: $IPax_s^{\tau} \geq OPax_s^{\tau+mpax} \quad \forall s \in \Theta \;\; \forall \tau \in \{1..(T-mpax)\}$
3. Arrival constraint: $\sum_t \left(xf_a^t + xs_a^t\right) <= 1 \quad \forall a \in \mathrm{A}$
4. Departure constraint: $\sum_t \left(yf_f^t + ys_f^t\right) <= 1 \quad \forall f \in \Phi$
5. Aircraft conservation:

$$TypeO_k + IAircraft_k^{\tau} \geq OAircraft_k^{\tau+maircraft} \quad \forall k \in \mathrm{K} \;\; \forall \tau \in \{1..(T-maircraft)\}$$

$$TypeO_k + IAircraft_k^{T} \geq OAircraft_k^{T} + TypeT_k \quad \forall k \in \mathrm{K}$$

Where:

$$IAircraft_k^{\tau} = \sum_{t=1}^{\tau} \sum_a xf_a^t \cdot TypeA_{ak}$$

$$OAircraft_k^{\tau} = \sum_{t=1}^{\tau} \sum_f yf_f^t \cdot TypeD_{fk}$$

CONSTRAINTS (2)

6. Airport capacity constraints:

$$\sum_{6(n-1)<t\le 6n} \sum_{a} xf_a^t \le AHCap_n \qquad \forall n \in N$$

$$\sum_{6(n-1)<t\le 6n} \sum_{a} yf_f^t \le DHCap_n$$

7. Arrival time constraint:

$$\sum_t t \cdot xf_a^t \ge AT_a \cdot \sum_t xf_a^t \qquad \forall a \in A$$

$$\sum_t t \cdot xs_a^t \ge \left(AT_a + \left(BAT_a - AAT_a\right)\right) \cdot \sum_t xs_a^t$$

8. Departure time constraint:

$$\sum_t t \cdot \left(yf_f^t + ys_f^t\right) \ge DT_f \cdot \sum_t \left(yf_f^t + ys_f^t\right) \qquad \forall f \in \Phi$$

9. Decision variable constraints:

$$xf_a^t, xs_a^t, yf_f^t, ys_f^t \qquad binary \qquad \forall a, f, t$$

$$P_f \qquad Integer \qquad \forall f \in \Phi$$

SOLUTION METHODOLOGY

- Iterative:
  - Arrival and departure banks

- Approximation:
  - Relaxation
  - Rounding
  - Finalization

NUMERICAL EXAMPLE

- Simplified Flight Schedules
  - 40 arrivals and 40 departures in 4 hours
  - 25 percent of short-haul flights
- Identical driving distances from short-haul spoke airports
- Identical number of transfer passengers
  - From short-haul to short-haul
  - From short-haul to long-haul and vice versa
  - From long-haul to long-haul
- Two types of aircraft
- Airline's slots according to the hub airport capacity
  - 4 arrivals and 4 departures per hour for 5 hours
  - 8 arrivals and 8 departures per hour afterwards

RESULTS AND COMPARISON (1)

Objective Function	w/o Substitution	w Substitution		
		Approximation		Lower bound
Total Cost ($)	411046	221575	220188	216250
Total Arrivals and Departures	80	80	80	
Inbound Cancellation		12	14	
Substitution		10	10	
Outbound Cancellation	2	14	16	
Substitution		10	10	
Longest Delay (hrs)	5.5	1.5	1.3	
Total Passengers	7360	7360	7360	
Disrupted Passengers	90	14	16	
Computation Time (secs)	$\sim 10^3$	10^1-10^2	$\sim 10^3$	10^1-10^2

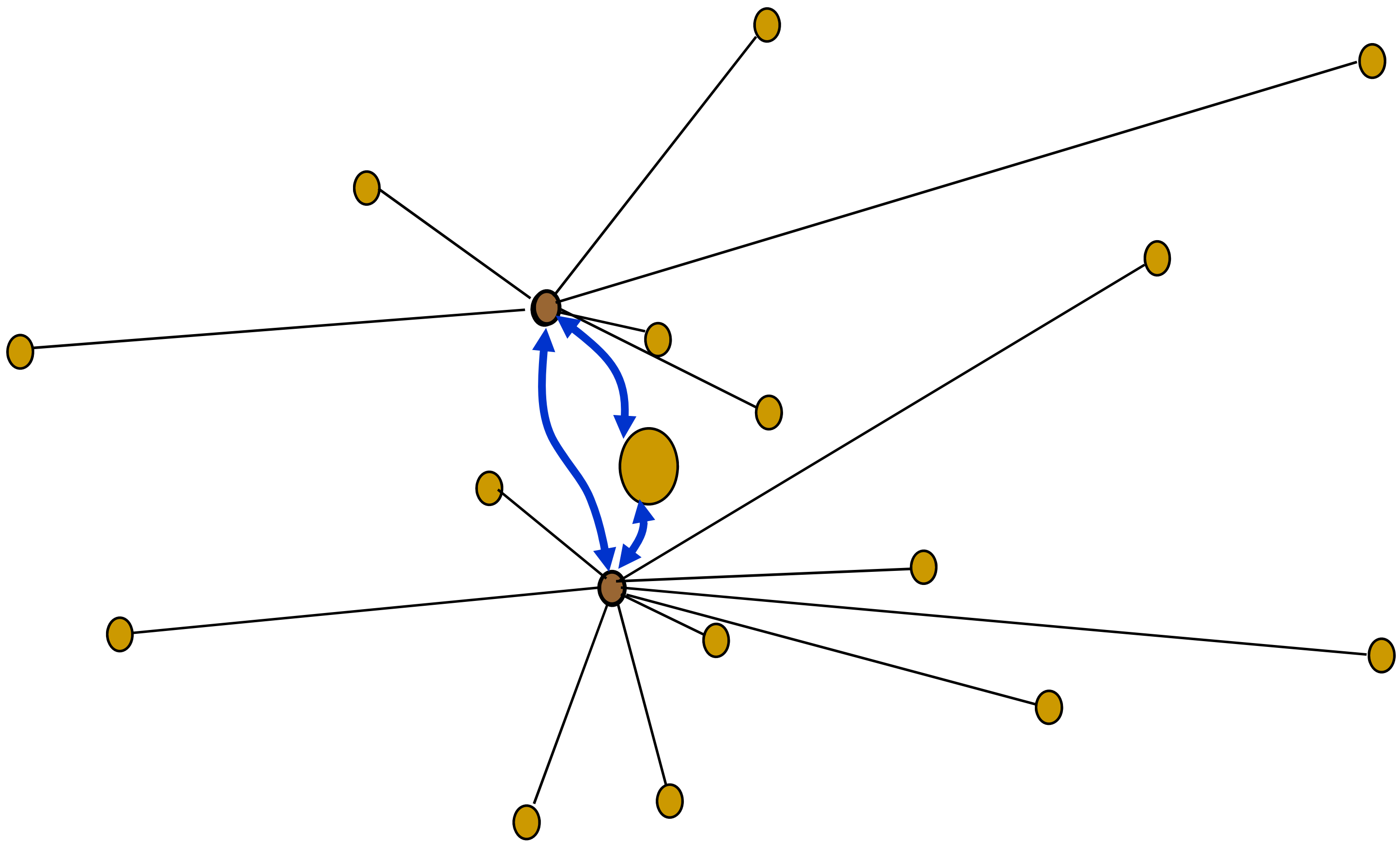
Sensitivity Analysis – Passenger Delay Cost

Objective Function	Passenger Delay Cost		
	CostP	1.5 CostP	2CostP
Total Cost ($)	220188	303898	348269
Total Arrivals and Departures	80	80	80
Inbound Cancellation	14	12	12
Substitution	10	10	10
Outbound Cancellation	16	12	10
Substitution	10	10	10
Total Passengers	7360	7360	7360
Disrupted Passengers	16	90	180

Sensitivity Analysis – Load Factor

	Load Factor (Aircraft Capacity)		
Objective Function	0.82	0.88	0.93
	0.70	0.80	0.89
Total Cost ($)	212141	220188	228084
Total Arrivals and Departures	80	80	80
Inbound Cancellation	12	14	12
Substitution	10	10	10
Outbound Cancellation	12	16	14
Substitution	10	10	10
Total Passengers	7360	7360	7360
Disrupted Passengers	0	16	43

Network with Regional Airport Systems



Substitution and Diversion for Metroplex Hub-and-Spoke System - Problem Definition

- Scenario:
  - An airline with a hub-and-spoke network
  - The hub airport is in a metroplex system
  - Capacity reduction at this major hub airport
- Strategy:
  - Delay, cancel, and substitute cancelled flights or divert flights to a nearby airport
  - Allow passenger reassignment at the hub and alternative airports
  - Allow aircraft swapping at the hub and alternative airports
- Input data:
  - Original flight schedule
  - Hub airport capacity profile
  - Excess capacity profile at the alternative airport
  - Passengers' purchased itinerary
  - Airborne and surface transportation time
  - Original fleet assignment

CASE STUDY

- A Metroplex system in the US with two hub airports located within 70 mile radius.
- Flight data
  - Official Airline Guide (OAG)
  - DOT Data Bank 1A
- Three Scenarios
  1. Capacity continuously reduced to half for 5 hours
  2. Airport closed for 3 hours and back to normal
  3. Airport closed for 5 hours and back to normal

COMPARISON OF STRATEGIES

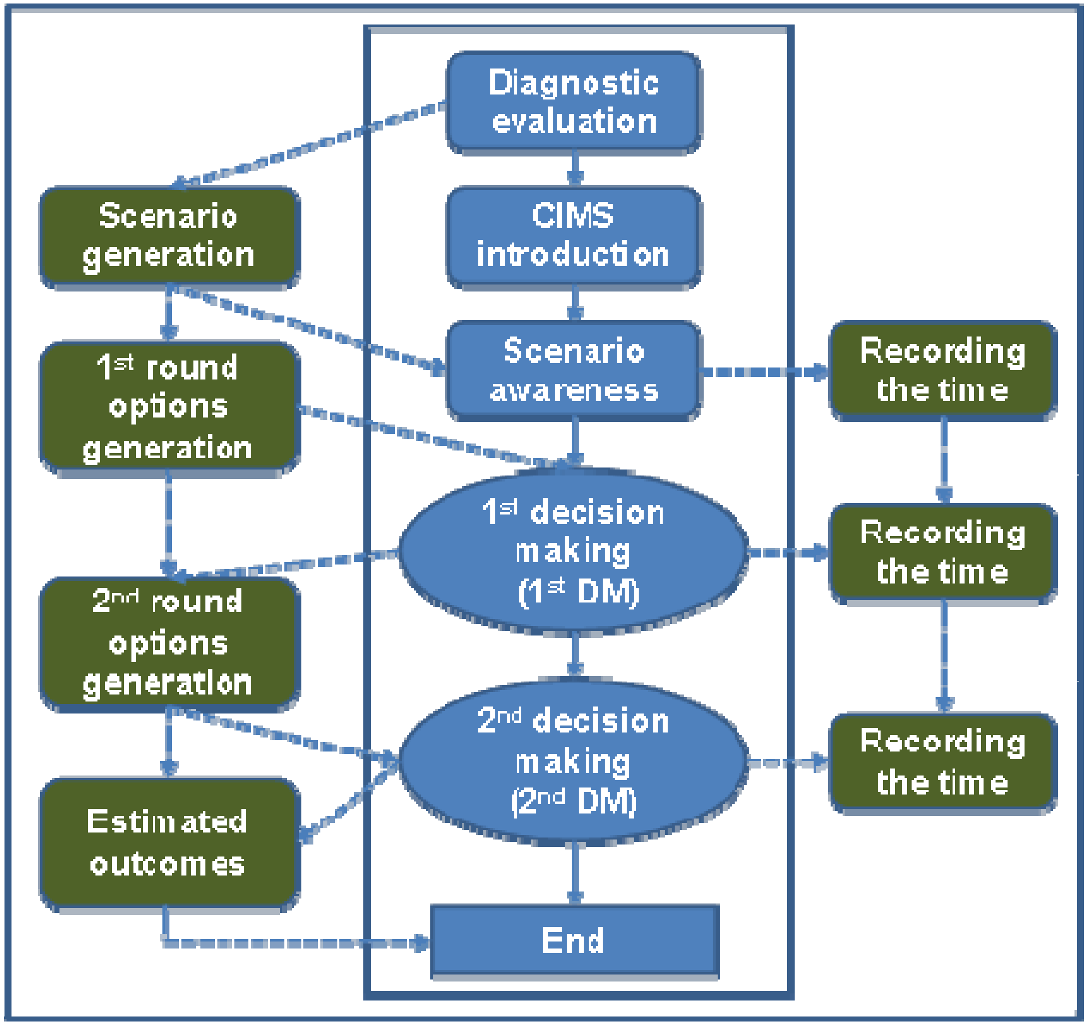
	Scenarios	Scenario 1	Scenario 2	Scenario 3
Substitution	Objective Function	370563	432608	466826
	Inbound Cancellation	7	11	11
	Substitution	6	10	11
	Outbound Cancellation	11	13	15
	Substitution	5	9	11
	Disrupted Passengers	264	264	227
Substitution+ Diversion	Objective Function	353343	397981	459850
	Inbound Cancellation	6	7	10
	Substitution	5	7	9
	Inbound Diversion	4	4	6
	Outbound Cancellation	10	12	14
	Substitution	4	7	10
	Outbound Diversion	4	4	4
	Disrupted Passengers	257	250	239

Scenario 1 - Capacity continuously reduced to half for 5 hours
Scenario 2 - Airport closed for 3 hours and back to normal
Scenario 3 - Airport closed for 5 hours and back to normal

Implementation Challenges

- Resistance from passengers
- Information sharing in enhanced Collaborative Decision Making
- Alternative transportation mode
- ……

Study of Passenger Behavior under Stress and Uncertainty – Simulator Framework



Identify Appropriate Cognitive Load for Decision Making

- Design the presentation of reassignment options and determine how many options to be presented to passengers.
- The current approaches of measuring cognitive load falls into four categories that are the combination of two dimensions, objectivity (subjective or objective) and casual relation (direct or indirect).
- The dual-task method is a promising approach for direct measurement in working memory research, cognitive load research, and multimedia learning.

HYPOTHESIS IN PASSENGER BEHAVIOR RESEARCH

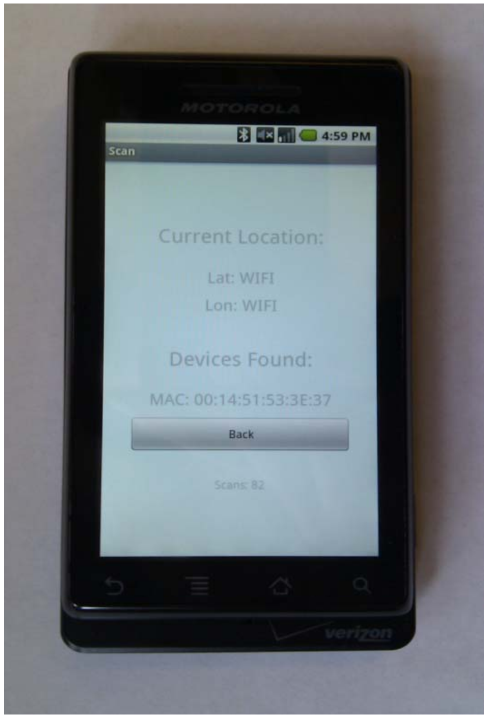
Experimental Group	Experimental Group	Hypothesis
Travelers w/disruption experience: 1st round simulation recalling disruption experience.	Travelers w/o disruption experience.	Stress affect decision making.
1st DM without knowing options in 2nd DM.	1st DM knowing options in 2nd DM.	Information reversely affects 1st DM in sequential decision making.
1st time exposed to the concept.	2nd time exposed to the concept.	Knowledge affect decision making.

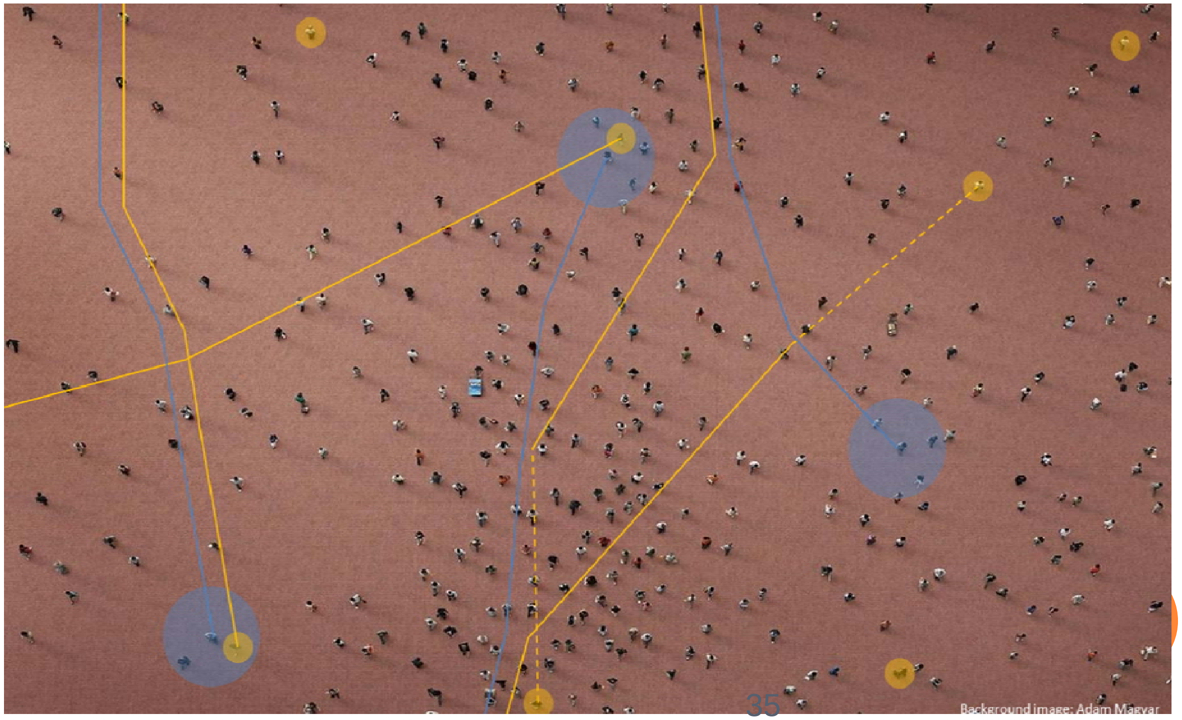
Information Exchanges in Real-Time Intermodalism

- Airport monitoring the movement of passengers and give estimated information for passengers going through various key points (***TPA Case***).
- Within the passenger-centric architecture, an individual airline passenger database is needed to be shared with airport operators so they can obtain a precise estimate of passenger transit through critical spots of the terminal building, such as security checkpoints. These estimations, in turn, provide information to airlines on passenger progress towards take-off.
- The instrumentation needed for other modes of transportation includes real-time information about road traffic and the capacity of the railway system, public transit system, and hired vehicle companies.
- Some information is common— for instance, real-time travel time broadcast from ***Florida District 7 Traffic Management Center*** —but other information may not be easily accessible and will require negotiation among stakeholders to determining a sharing agreement and protocol.

Mobile Sensors: Opportunistic Encounters

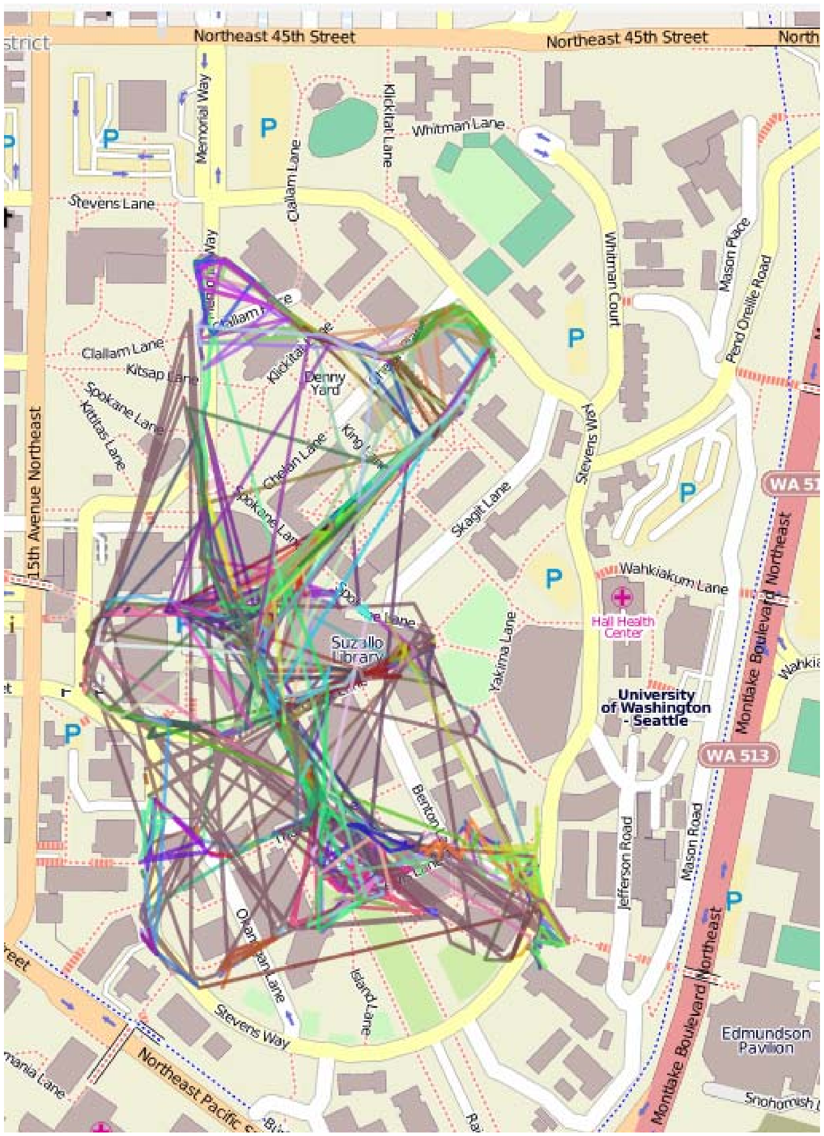
- Smartphone App (Mobile Monitor)
  - Scans the Bluetooth spectrum
  - Writes down GPS coordinates and MACs seen @ timestamp

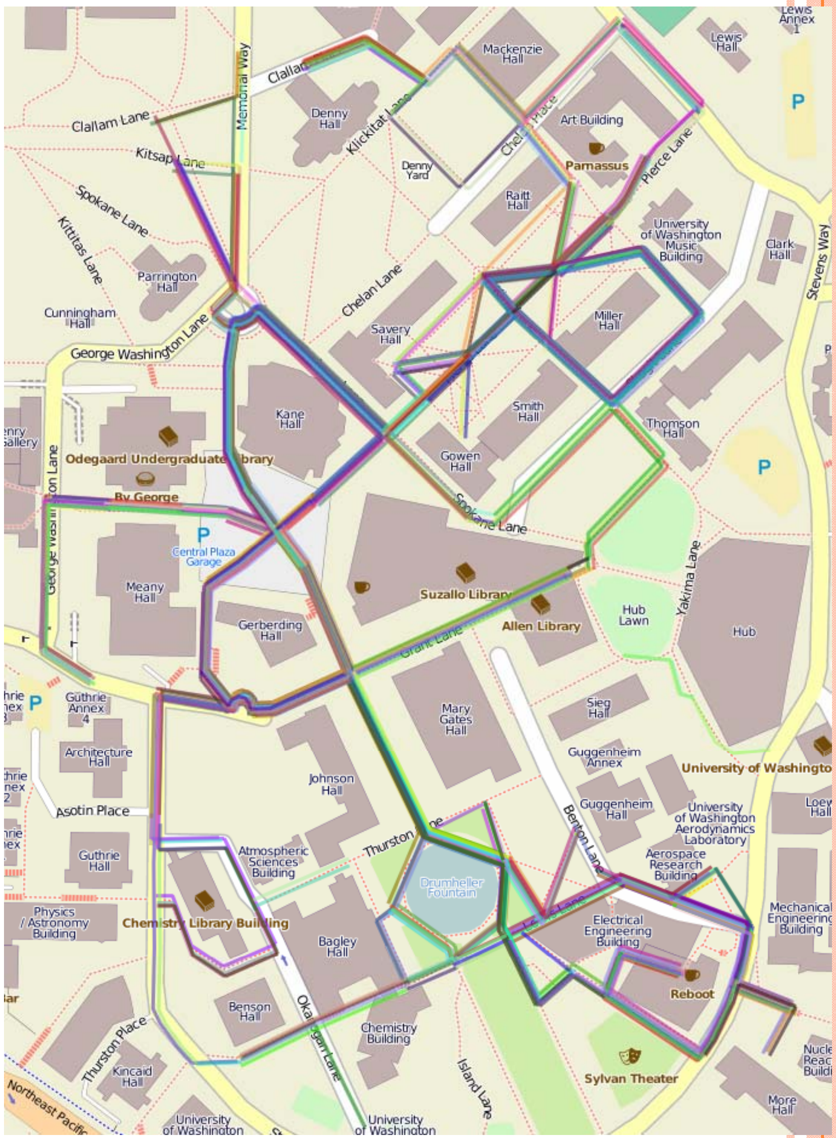




*phones used in testing courtesy of Dr. Borning

Routing Trajectories on Network





INFORMATION EXCHANGES IN REAL-TIME INTERMODALISM

- Airport monitoring the movement of passengers and give estimated information for passengers going through various key points (***TPA Case***).
- Within the passenger-centric architecture, an individual airline passenger database is needed to be shared with airport operators so they can obtain a precise estimate of passenger transit through critical spots of the terminal building, such as security checkpoints. These estimations, in turn, provide information to airlines on passenger progress towards take-off.
- Real-time information of ground transportation modes are needed. Some of the information exists already— for instance, real-time travel time broadcast from ***Florida District 7 Traffic Management Center*** —but other information, the capacity of the railway system, public transit system, and hired vehicle companies, may not be easily accessible and will require negotiation among stakeholders to determining a sharing agreement and protocol.

Airline Perturbation Recovery with Responsive Passenger Reassignment

- An iterative process to solve the airline recovery problem with both ***distributed decision makers (passengers) and a centralized decision maker (airline)***.
- While booking air tickets, passengers are asked if they would like to **participate** in the program and if they are willing to reveal their locations before certain hours of their boarding time (e.g. 3 hours; airlines can trace their location with apps on passenger smart phones).
- During disruptive events, knowing the **location** of passengers and the **availability** of alternative transportation modes, as well as airport operation conditions and aircraft movements, airlines can offer passengers specific options of reassignment, either to later flights, to another airport in the same region, or to alternative transportation (it is possible to be indicated as virtual flights in airline system).
- Passengers select the options, and their **responses** are sent back to the airline. Airlines then can adjust their operational decisions accordingly. When inflight Wi-Fi becomes commonplace, this model can easily cover both passengers on and off flights.

Best Equipped Best Serve? Best Cooperated Best Serve?

Emerging Technologies in The Future -- Autonomous Vehicles for Intermodal Connectivity

- Autonomous vehicle ownership and scheduling
  - Airlines
    - Flexibility
    - Passenger loyalty
  - Airports
    - Resource utilization
    - Funding support
    - Facility development: loading and unloading area, baggage screening
  - Third Party
    - No inventory cost
    - Risk sharing

SUMMARY

- Real-time intermodalism provides a substitution of cancellation in airlines' recovery
  - Reduce number of disrupted passengers
  - Reduce delay propagation to later flights and other parts of the network
- Flight diversion reduces flight cancellation and works better under more severe capacity shortfall circumstances
- Real-time intermodalism would improve the ability of emergency reaction of air transportation system
- The design and implementation of proposed ideas need the wisdom of different entities with enhanced collaborative decision making platform.

Thank you !