REAL-TIME INTERMODALISM FOR AIRLINE SCHEDULE PERTURBATION RECOVERY AND AIRPORT CONGESTION MITIGATION UNDER COLLABORATIVE DECISION MAKING

Yu Zhang
University of South Florida

META-CDM Workshop
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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)
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
GEOGRAPHIC DISTRIBUTION OF US AIRPORTS

- Large Hub airports with ~15% short-haul flights within a 160-mi radius
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

<table>
<thead>
<tr>
<th>Range of Seating</th>
<th>San Francisco</th>
<th>Los Angeles</th>
<th>New York</th>
<th>Chicago</th>
<th>Miami</th>
<th>Texas</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Type</td>
<td>100</td>
<td>188</td>
<td>260</td>
<td>153</td>
<td>88</td>
<td>114</td>
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<tr>
<td>Deluxe Motorcoach</td>
<td>36-68</td>
<td>63</td>
<td>113</td>
<td>189</td>
<td>83</td>
<td>59</td>
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<tr>
<td>Executive Coach</td>
<td>18-30</td>
<td>1</td>
<td>5</td>
<td>11</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Limo Bus</td>
<td>18-30</td>
<td>10</td>
<td>9</td>
<td>34</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

## Charter Company’s Response to Urgent Service Request

<table>
<thead>
<tr>
<th></th>
<th>San Francisco</th>
<th>Los Angeles</th>
<th>New York</th>
<th>Chicago</th>
<th>Miami</th>
<th>Texas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SFO</td>
<td>LAX</td>
<td>JFK</td>
<td>ORD</td>
<td>MIA</td>
<td>DFW</td>
</tr>
<tr>
<td>Not available</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>1-1.5 hours</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>3-4 hours</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

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

Average is 124 minutes
**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

\( x_{f_t}^a \): =1 if aircraft \( i \) should be flown and landed during time \( t \) period, 0 otherwise.

\( x_{s_t}^a \): =1 if aircraft \( i \) should be substituted with buses and arrive at the hub airport during time \( t \) period, 0 otherwise.

\( y_{f_t}^f \): =1 if aircraft \( j \) should take off during time \( t \) period, 0 otherwise.

\( y_{s_t}^f \): =1 if aircraft \( j \) should be substituted with buses and depart from the hub airport during time \( t \) period, 0 otherwise.

\( P_f \): The number of passengers on a departure aircraft \( f \)

Where:

\[ a \in A \] 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

Passenger decision variables

Flight decision variables
**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

\[
\begin{align*}
\text{Min} & \quad \left( \sum_a AD_a \cdot AHPax_a + \sum_f DD_f \cdot P_f \right) \cdot \text{Cost}_p + IO_s \cdot \text{Cost}_P' \\
& + \left( \sum_a AD_a + \sum_f DD_f \right) \cdot \text{Cost}_F + BO + DP \cdot \text{Cost}_D
\end{align*}
\]

Where:
- \( \text{Cost}_p \)  Passenger time value of delaying
- \( \text{Cost}_P' \)  Passenger time value of waiting at terminal
- \( \text{Cost}_F \)  Flight delay cost of a discrete time unit
- \( \text{Cost}_D \)  Penalty cost of one disrupted passenger
OBJECTIVE FUNCTION COMPONENTS (1)

Passenger Waiting Time at Airport Terminal

\[ IO_s = \sum_s \sum_{\tau} (IPax_s^{\tau} - OPax_s^{\tau}) \]

Where:

The cumulated in-flow at time \( \tau \)

\[ IPax_s^{\tau} = IPax_s^o + \sum_{i=1}^{\tau} \sum_a \sum_f \left( x_{fa}^{i} + x_{sa}^{i} \right) \cdot Pax_{af} \cdot Spoke_{fs} \]

The cumulated out-flow at time \( \tau \)

\[ OPax_s^{\tau} = OPax_s^o + \sum_{i=1}^{\tau} \sum_f \left( y_{fa}^{i} + y_{sa}^{i} \right) \cdot \left( P_f - DHPax_f \right) \cdot Spoke_{fs} \]

\[ Pax_{af} \quad \text{The connecting passengers take arrival aircraft i and departure aircraft j} \]

\[ Spoke_{fs} \quad \text{The indicator of departure flight j and destination s, =1 if j goes to s, 0 otherwise} \]
OBJECTIVE FUNCTION COMPONENTS (2)

Flight Arrival Delay

\[ AD_a = \sum_i (t - AT_a) \cdot (xf_a^i + xs_a^i) + \left( 1 - \sum_i (xf_a^i + xs_a^i) \right) \cdot ACanT_a \]

Flight Departure Delay

\[ DD_f = \sum_i (t - DT_f) \cdot (yf_f^i + ys_f^i) + \left( 1 - \sum_i (yf_f^i + ys_f^i) \right) \cdot DCanT_f \]

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

\[
BO = \left( \sum_a APax_a \cdot ABT_a \cdot \sum_t xs'_a + \sum_f P_f \cdot DBT_f \cdot \sum_t ys'_f \right) \cdot CostBP
+ \left( \sum_a \sum_t xs'_a + \sum_f \sum_t ys'_f \right) \cdot CostB
\]

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

\[
DP = \sum_a \left( 1 - \sum_t \left( x_f^t + xs'_a \right) \right) \cdot APax_a + \sum_s \left( IPax_s^T - OPax_s^T \right)
\]
CONSTRANTS (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: \( \sum_{i} (xf_a^i + xs_a^i) \leq 1 \quad \forall a \in A \)

4. Departure constraint: \( \sum_{i} (yf_f^i + ys_f^i) \leq 1 \quad \forall f \in \Phi \)

5. Aircraft conservation:

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

   \[ TypeO_k + IAircraft_k^T \geq OAircraft_k^T + TypeT_k \quad \forall k \in K \]

Where:

\[ IAircraft_k^\tau = \sum_{t=1}^{\tau} \sum_{a} xf_a^i \cdot TypeA_{ak} \]

\[ OAircraft_k^\tau = \sum_{t=1}^{\tau} \sum_{f} yf_f^i \cdot TypeD_{fk} \]
CONSTRAINTS (2)

6. Airport capacity constraints:
\[
\sum_{6(n-1)<t\leq 6n} \sum_a x_{f_a}^t \leq AHCap_n
\]
\[
\sum_{6(n-1)<t\leq 6n} \sum_a y_{f_a}^t \leq DHCap_n \quad \forall n \in N
\]

7. Arrival time constraint:
\[
\sum_{t} t \cdot x_{f_a}^t \geq AT_a \cdot \sum_{t} x_{f_a}^t \quad \forall a \in A
\]
\[
\sum_{t} t \cdot x_{s_a}^t \geq (AT_a + (BAT_a - AAT_a)) \cdot \sum_{t} x_{s_a}^t
\]
\[
\sum_{t} t \cdot (y_{f_f}^t + y_{s_f}^t) \geq DT_f \cdot \sum_{t} (y_{f_f}^t + y_{s_f}^t) \quad \forall f \in \Phi
\]

8. Departure time constraint:

9. Decision variable constraints:
\[
\begin{align*}
xF_a^t, xS_a^t, yF_f^t, yS_f^t & \text{ binary } & \forall a, f, t \\
P_f & \text{ Integer } & \forall f \in \Phi
\end{align*}
\]
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

<table>
<thead>
<tr>
<th></th>
<th>w/o Substitution</th>
<th>Approximation</th>
<th>w Substitution</th>
<th>Lower bound</th>
</tr>
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<tbody>
<tr>
<td><strong>Total Cost ($)</strong></td>
<td>411046</td>
<td>221575</td>
<td>220188</td>
<td>216250</td>
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<tr>
<td><strong>Total Arrivals and Departures</strong></td>
<td>80</td>
<td>80</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td><strong>Inbound Cancellation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substitution</td>
<td>12</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Outbound Cancellation</strong></td>
<td>2</td>
<td>14</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Substitution</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Longest Delay (hrs)</strong></td>
<td>5.5</td>
<td>1.5</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td><strong>Total Passengers</strong></td>
<td>7360</td>
<td>7360</td>
<td>7360</td>
<td></td>
</tr>
<tr>
<td><strong>Disrupted Passengers</strong></td>
<td>90</td>
<td>14</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td><strong>Computation Time (secs)</strong></td>
<td>~10^3</td>
<td>10^1-10^2</td>
<td>~10^3</td>
<td>10^1-10^2</td>
</tr>
</tbody>
</table>
## Sensitivity Analysis – Passenger Delay Cost

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Passenger Delay Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CostP</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>220188</td>
</tr>
<tr>
<td>Total Arrivals and Departures</td>
<td>80</td>
</tr>
<tr>
<td>Inbound Cancellation</td>
<td>14</td>
</tr>
<tr>
<td>Substitution</td>
<td>10</td>
</tr>
<tr>
<td>Outbound Cancellation</td>
<td>16</td>
</tr>
<tr>
<td>Substitution</td>
<td>10</td>
</tr>
<tr>
<td>Total Passengers</td>
<td>7360</td>
</tr>
<tr>
<td>Disrupted Passengers</td>
<td>16</td>
</tr>
</tbody>
</table>
## Sensitivity Analysis – Load Factor

<table>
<thead>
<tr>
<th>Load Factor (Aircraft Capacity)</th>
<th>0.82</th>
<th>0.88</th>
<th>0.93</th>
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</thead>
<tbody>
<tr>
<td><strong>Objective Function</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost ($), Total Arrivals and Departures</td>
<td>212141</td>
<td>220188</td>
<td>228084</td>
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<tr>
<td>Inbound Cancellation</td>
<td>12</td>
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<td>12</td>
</tr>
<tr>
<td>Substitution</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
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<td>14</td>
</tr>
<tr>
<td>Substitution</td>
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<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total Passengers</td>
<td>7360</td>
<td>7360</td>
<td>7360</td>
</tr>
<tr>
<td>Disrupted Passengers</td>
<td>0</td>
<td>16</td>
<td>43</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective Function</strong></td>
<td>370563</td>
<td>432608</td>
<td>466826</td>
</tr>
<tr>
<td>Inbound Cancellation</td>
<td>7</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Substitution</td>
<td>6</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Outbound Cancellation</td>
<td>11</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Substitution</td>
<td>5</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Disrupted Passengers</td>
<td>264</td>
<td>264</td>
<td>227</td>
</tr>
<tr>
<td><strong>Scenario 1</strong> - Capacity continuously reduced to half for 5 hours</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Scenario 2</strong> - Airport closed for 3 hours and back to normal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Scenario 3</strong> - Airport closed for 5 hours and back to normal</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Experimental Group</th>
<th>Experimental Group</th>
<th>Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travelers w/disruption experience: 1st round simulation recalling disruption experience.</td>
<td>Travelers w/o disruption experience.</td>
<td>Stress affect decision making.</td>
</tr>
<tr>
<td>1\textsuperscript{st} DM without knowing options in 2\textsuperscript{nd} DM.</td>
<td>1\textsuperscript{st} DM knowing options in 2\textsuperscript{nd} DM.</td>
<td>Information reversely affects 1\textsuperscript{st} DM in sequential decision making.</td>
</tr>
<tr>
<td>1st time exposed to the concept.</td>
<td>2nd time exposed to the concept.</td>
<td>Knowledge affect decision making.</td>
</tr>
</tbody>
</table>
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.
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!