Fast Forwarding to a World of On-Demand Air Transportation

Smart Urban Transportation Forum
IMA
University of Minnesota

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Uber Technologies
Rich problems

dynamic pricing
revenue management
uberPOOL
uberEATS

73+
Countries

450+
Cities

60M
Monthly riders

dynapco-temporal forecasting
driver positioning
stochastic routing
map matching
dispatch
latent demand modeling
anomaly detection
many more…
Uber Elevate
Noise
Speed
Efficiency
Emissions
Safety (thus cost)
Over a dozen VTOL companies developing prototypes to deploy within the next three years

Volocopter
Lilium
Zee.Aero
Ehang
Joby Aviation
A^3/Airbus
Very quiet compared with combustion engines, Many rotors -> lower tip speed

Inherently safer: Redundancy is tolerant of failures, partial autonomy

2X safer than driving

Emissions: Electric has zero operational emissions

10x more efficient: 3-4x improvement from tiltrotor, 3x improvement in fixed wing
<table>
<thead>
<tr>
<th></th>
<th>Multicopter</th>
<th>Autogyro</th>
<th>Helicopter</th>
<th>Co-Axial Helicopter</th>
<th>Compound Helicopter</th>
<th>Lift + Cruise</th>
<th>Vectored Thrust</th>
<th>Tilt Duct</th>
<th>Tilt Wing</th>
<th>Tilt Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>En-route cruise speed [mph]</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Lift/drag</td>
<td>1.5</td>
<td>3.5</td>
<td>4.25</td>
<td>5.5</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Disc-loading [lbs/ft²]</td>
<td>3.75</td>
<td>3.75</td>
<td>4.5</td>
<td>7</td>
<td>4.5</td>
<td>15</td>
<td>40</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOM</td>
<td>0.60</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.60</td>
<td>0.50</td>
<td>0.60</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Empty weight/gross weight</td>
<td>0.55</td>
<td>0.50</td>
<td>0.55</td>
<td>0.60</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>En-route energy [kwH/mile]</td>
<td>6.07</td>
<td>2.6</td>
<td>2.14</td>
<td>1.65</td>
<td>1.01</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
<td>0.76</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Flux Optimizer
Beyond the Vehicle...

Where to build infrastructure?

What are the network dynamics?

What does a good network need?
Flux Optimizer
Under the Hood

1. Estimate Demand
2. Generate Candidate Hubs
3. Hub Optimization
4. VTOL Route Optimization
Flux Optimizer
Under the Hood

1. Estimate Demand

2. Generate Candidate Hubs

3. Hub Optimization

4. VTOL Route Optimization

- k-means clustering on trip points
- centroids define candidate hubs
- also supports hubs defined by the user
Flux Optimizer

Under the Hood

1. Estimate Demand

2. Generate Candidate Hubs

3. Hub Optimization

4. VTOL Route Optimization

GOAL

maximize time savings of all riders

An itinerary \((o,d,i,j)\) is valid if the time saved \(s(o,d,i,j)\) exceeds some threshold \(s^*\):

\[
\begin{align*}
s(o, d, i, j) &= x(o, d) - \left[ \tau(o, i) + \tau(L) + \tau(i, j) + \tau(U) + \tau(j, d) \right] \\
&\geq s^* x(o, d)
\end{align*}
\]
Flux Optimizer
Under the Hood

1. Estimate Demand

2. Generate Candidate Hubs

3. Hub Optimization

4. VTOL Route Optimization

GIVEN
- all eligible VTOL itineraries
- set of candidate hubs $H$
- user inputs

Optimize subset of hubs $H^*$ to maximize coverage
1. Estimate Demand
2. Generate Candidate Hubs
3. Hub Optimization
4. VTOL Route Optimization

GIVEN
• optimal hub placements
• trips

DECIDE
• sequence of flight legs
• assign riders to VTOLs
• when/where/how much to recharge
• when/where to deadhead
• when to depart (savings vs. load)
Hub Optimization
DFW | Hub Optimization
DFW - Rolling Out Infrastructure

1, 2
Rider Coverage = 15.2%

+ 3, 4, 5
Rider Coverage = 42.2%

+ 6, 7, 8, 9, 10
Rider Coverage = 47.3%
Dubai Hub Optimization

% Trip Coverage

2 Hubs: 23%
5 Hubs: 52%
10 Hubs: 69%
50 Hubs: 86%
VTOL Route Optimization
Multicommodity Network Flow Model

\[\begin{align*}
\min & \sum_{v \in V} \sum_{(i,j) \in A} e_{ij}^v x_{ij}^v + \sum_{p \in P} \sum_{(i,j) \in A} f_{ij}^p y_{ij}^p \\
\text{s.t.} & \sum_{j \in O(i)} x_{ij}^v - \sum_{j \in I(k)} x_{ji}^v = d_i^k \quad \forall k \in N, \forall v \in V \\
& \sum_{p \in P} y_{ij}^p \leq \sum_{v \in V} C_{ij}^v x_{ij}^v \quad \forall (i,j) \in A \cap F \\
& \sum_{(i,j) \in A} x_{ij}^v + \sum_{v \in V} \sum_{(i,j) \in A \cap G: s(i) = s(j)} x_{ij}^v \leq \kappa_{s(t)} \quad \forall t \in N \\
& b_{t-1}^v = \sum_{j \in O(i)} e_{ij} x_{ij}^v = b_i^v \quad \forall i \in N, \forall v \in V \\
x \in \mathcal{X}
\end{align*}\]
VTOL Routing Model

Better modeling approach:

identify path \( P \) that is a minimum cover

\[
\sum_{p \in P} \left( \sum_{(i,j) \in O(i)} e_{ij} x_{ij}^p - \sum_{(i,j) \in D(i)} e_{ij} x_{ij}^p \right) > \theta b
\]

\[
\sum_{p \in P \setminus \{(i,j)\}} \left( \sum_{(i,j) \in O(i)} e_{ij} x_{ij}^p \right) \leq \theta b \quad \forall k \in P
\]

then lift following arcs \((i', j')\) following the final arc in \( P \)

\[
\sum_{(i,j) \in P} x_{i'j}^y + \alpha_{i'j'} x_{i'j'}^y \leq |P| - 1
\]
## DALLAS, TX

### Assumptions
- **# of Hub**: 5
- **Airspace Sep.**: ≥ 2 mi
- **eVTOL Range**: 20-120 mi
- **Ascend**: 75 sec
- **Decend**: 45 sec

### Input

<table>
<thead>
<tr>
<th>eVTOL Count [% Capacity]</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Count</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Minimum Ground Time [min]</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>en-route Speed [mph]</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>170</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Recharge Minutes [20-90%]</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trip Volume [1.0 = reference]</td>
<td>0.3</td>
<td>0.7</td>
<td>1.0</td>
<td>1.3</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Min Savings Threshold [%]</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>Min VTOL Range [m]</td>
<td>10</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Output
DALLAS, TX

# OF HUB
5

AIRSPACE SEP.
≥ 2 mi

eVTOL RANGE
20-120 mi

ASCEND
75 sec

DECEND
45 sec

**eVTOL COUNT [% CAPACITY]**

| 20 | 25 | 30 | 35 | 40 | 100 |

**SEAT COUNT**

| 1 | 2 | 3 | 4 | 5 | 6 |

**MINIMUM GROUND TIME [min]**

| 2 | 3 | 4 | 5 | 6 |

**EN-ROUTE SPEED [mph]**

| 50 | 100 | 150 | 170 | 200 |

**RECHARGE MINUTES [20-90%]**

| 15 | 20 | 25 | 30 |

**TRIP VOLUME [1.0 = reference]**

| 0.3 | 0.7 | 1.0 | 1.3 | 1.7 |

**MIN SAVINGS THRESHOLD [%]**

| 30 | 35 | 40 | 45 | 50 | 55 |

**MIN VTOL RANGE [m]**

| 10 | 20 |
Demand may be met using ~ 40% of vehicle capacity

Load factor ~ 1.55 per flight
DALLAS, TX

# OF HUB
5

AIRSPACE SEP.
≥ 2 mi

eVTOL RANGE
20-120 mi

ASCEND
75 sec

DECEND
45 sec

ASSUMPTIONS

eVTOL COUNT (% CAPACITY)
20 25 30 35 40 - 100

SEAT COUNT
1 2 3 4 5 6

MINIMUM GROUND TIME (min)
2 3 4 5 6

EN-ROUTE SPEED (mph)
50 100 150 170 200

RECHARGE MINUTES [20-90%]
15 20 25 30

TRIP VOLUME [1.0 = reference]
0.3 0.7 1.0 1.3 1.7

MIN SAVINGS THRESHOLD [%]
30 35 40 45 50 55

MIN VTOL RANGE (m)
10 20
most sharing of VTOLs is attained with 3 seats

routes with highest load factors

Frisco ↔ DFW
Downtown Dallas
DALLAS, TX

ASSUMPTIONS

# OF HUB
5

AIRSPACE SEP.
≥ 2 mi

eVTOL RANGE
20-120 mi

ASCEND
75 sec

DECEND
45 sec

INPUT

eVTOL COUNT [% CAPACITY]

20 25 30 35 40 - 100

SEAT COUNT

1 2 3 4 5 6

MINIMUM GROUND TIME [min]

2 3 4 5 6

EN-ROUTE SPEED [mph]

50 100 150 170 200

RECHARGE MINUTES [20-90%]

15 20 25 30

TRIP VOLUME [1.0 = reference]

0.3 0.7 1.0 1.3 1.7

MIN SAVINGS THRESHOLD [%]

30 35 40 45 50 55

MIN VTOL RANGE [m]

10 20
**MIN VTOL RANGE [m]**
- 10
- 20

**eVTOL COUNT [% CAPACITY]**
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

**EN-ROUTE SPEED [mph]**
- 170

**MINIMUM GROUND TIME [min]**
- 5

**TRIP VOLUME [1.0 = reference]**
- 1.0

**RECHARGE MINUTES [20-90%]**
- 15

**SEAT COUNT**
- 3

**ASSUMPTIONS**

- Las Colinas
  - 5 min MGT

- North Denton
  - 3 min MGT
<table>
<thead>
<tr>
<th><strong>ASSUMPTIONS</strong></th>
<th><strong>INPUT</strong></th>
<th><strong>OUTPUT</strong></th>
</tr>
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<tbody>
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<td><strong>DALLAS, TX</strong></td>
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<tr>
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<td>1 2 3 4 5 6</td>
<td></td>
</tr>
<tr>
<td>MINIMUM GROUND TIME [min]</td>
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</tr>
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<td></td>
</tr>
<tr>
<td>MIN SAVINGS THRESHOLD [%]</td>
<td>30 35 40 45 50 55</td>
<td></td>
</tr>
<tr>
<td>MIN VTOL RANGE [m]</td>
<td>10 20</td>
<td></td>
</tr>
</tbody>
</table>
DALLAS, TX

170 mph cruise

200 mph cruise

- MIN VTOL RANGE [m]: 20
- eVTOL COUNT [% CAPACITY]: 170
- MINIMUM GROUND TIME [min]: 5
- TRIP VOLUME [1.0 = reference]: 1.0
- RECHARGE MINUTES [20-90%]: 15
- SEAT COUNT: 200
- ASCEND: 75 sec
- DECEND: 45 sec
- eVTOL RANGE: 20-120 mi
- AIRSPACE SEP.: 2 mi
- 170 mph cruise
- 200 mph cruise
EVTOL COUNT [% CAPACITY]

20 25 30 35 40 100

SEAT COUNT

1 2 3 4 5 6

MINIMUM GROUND TIME [min]

2 3 4 5 6

TRIP VOLUME [1.0 = reference]

0.3 0.7 1.0 1.3 1.7

MIN SAVINGS THRESHOLD [%]

30 35 40 45 50 55

MIN VTOL RANGE [m]

10 20
Charging only at mega vertiports

DALLAS, TX

ASSUMPTIONS

# OF HUB
5

AIRSPACE
≥ 2 mi

eVTOL RANGE
20-120 mi

ASCEND
75 sec

DECEND
45 sec

OUTPUT

Riders Served
- 4.0%

Time Saved
+ 0.0%

Battery Charge at Landing
-17%

eVTOL Utilization
- 2.3%

Deadheads Per eVTOL
+ 0.5%

Load Factor
+ 1.5%

Input

Output

Output
ASSUMPTIONS

DALLAS, TX

# OF HUB
5

AIRSPACE SEP.
≥ 2 mi

eVTOL RANGE
20-120 mi

ASCEND
75 sec

DECEND
45 sec

INPUT

eVTOL COUNT [% CAPACITY]
20 25 30 35 40 100

SEAT COUNT
1 2 3 4 5 6

MINIMUM GROUND TIME [min]
2 3 4 5 6

EN-ROUTE SPEED [mph]
50 100 150 170 200

RECHARGE MINUTES [20-90%]
15 20 25 30

TRIP VOLUME [1.0 = reference]
0.3 0.7 1.0 1.3 1.7

MIN SAVINGS THRESHOLD [%]
30 35 40 45 50 55

MIN VTOL RANGE [m]
10 20

OUTPUT

Lod Factor, DFW

Average Rider Savings, DFW

Average VTOL Utilization, DFW
**DALLAS, TX**

**ASSUMPTIONS**

- # OF HUB: 5
- AIRSPACE SEP.: ≥ 2 mi
- eVTOL RANGE: 20-120 mi
- ASCEND: 75 sec
- DECEND: 45 sec

**INPUT**

- eVTOL COUNT [% CAPACITY]
  - 20 25 30 35 40 - 100

- SEAT COUNT
  - 1 2 3 4 5 6

- MINIMUM GROUND TIME [min]
  - 2 3 4 5 6

- MINIMUM GROUND TIME [min]
  - 2 3 4 5 6

- TRIP VOLUME [1.0 = reference]
  - 0.3 0.7 1.0 1.3 1.7

- RECHARGE MINUTES [20-90%]
  - 15 20 25 30

- eVTOL RANGE
  - 20-120 mi

- EN-ROUTE SPEED [mph]
  - 50 100 150 170 200

- ASPECT RATIO: 1.0

**OUTPUT**

- MIN SAVINGS THRESHOLD [%]
  - 30 35 40 45 50 55

- MIN VTOL RANGE [m]
  - 10 20
DUBAI, UAE

# OF HUB
5

AIRSPACE SEP.
≥ 2 mi

eVTOL RANGE
10-120 mi

ASCEND
75 sec

DECEND
45 sec

INPUT

eVTOL COUNT [% CAPACITY]
20 25 30 35 40 - 100

SEAT COUNT
1 2 3 4 5 6

MINIMUM GROUND TIME [min]
2 3 4 5 6

EN-ROUTE SPEED [mph]
50 100 150 170 200

RECHARGE MINUTES [20-90%]
15 20 25 30

TRIP VOLUME [1.0 = reference]
0.3 0.7 1.0 1.3 1.7

MIN SAVINGS THRESHOLD [%]
30 35 40 45 50 55

MIN VTOL RANGE [m]
10 20

OUTPUT
# VTOLs

Rider Capacity

Minimum Ground Time

Cruise Speed

Trip Volume (Rider Savings)

Min Rider Savings
What if pick-up times were longer?
Simulate ETAs +10%, +25%, +50%
Ongoing & Future Work

Incorporating stochasticity
  vehicle design (speed, battery consumption)
  VTOL travel times
  latent demand

Air Traffic Management
  Flight planning for noise abatement
  Unmanned Aircraft Systems Traffic Management (UTM)

Irregular Operations

Marketplace Optimization: Pricing, Dispatch, Pooling
Thanks!

Questions?

more about Uber Elevate: www.uber.com/info/elevate/

Uber Elevate summit videos: www.uber.com/info/elevate/summit/

Questions, comments: petersen@uber.com