

OPERATIONS LIMITS FOR PASSENGER-CARRYING URBAN AIR MOBILITY MISSIONS

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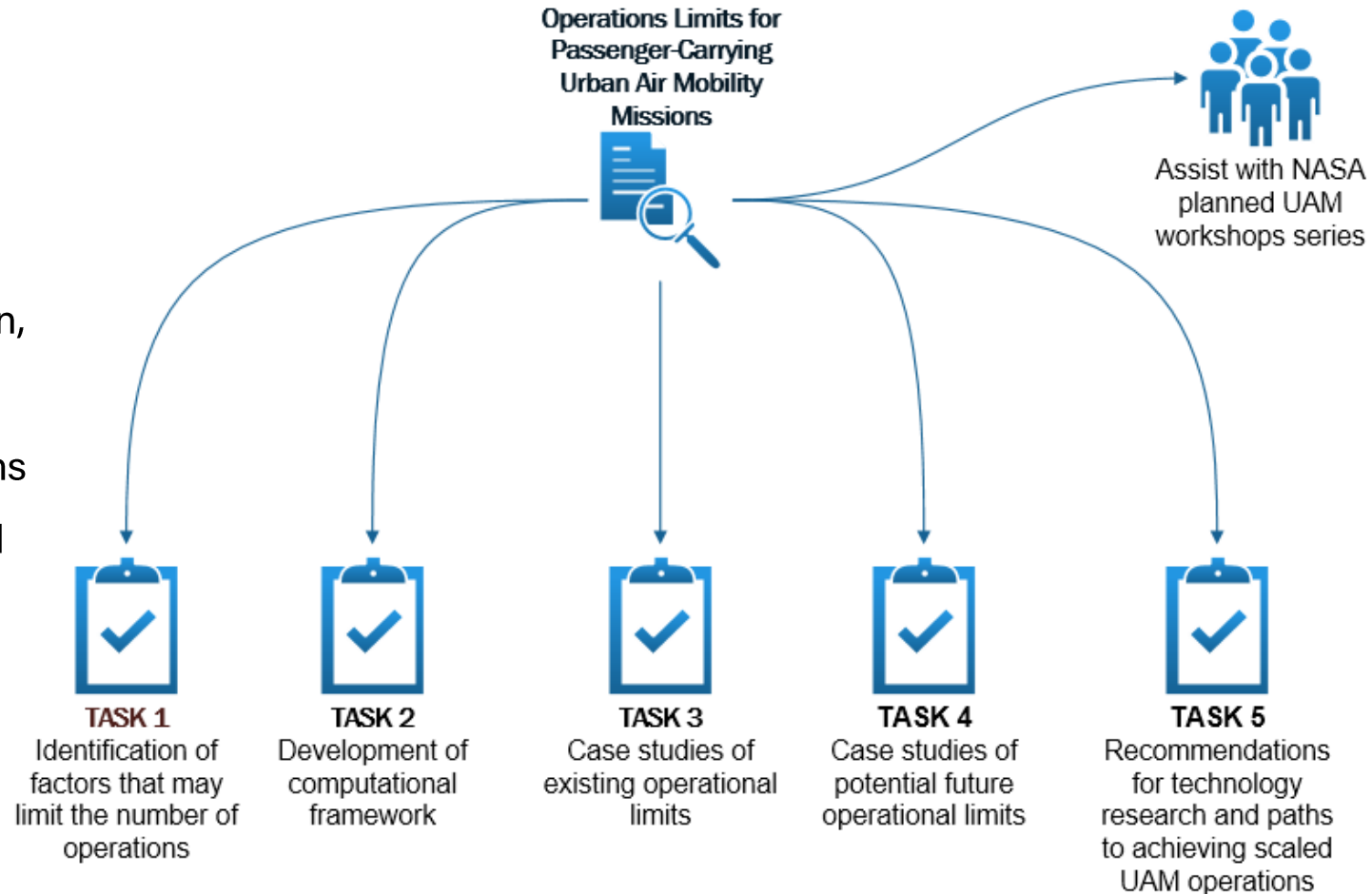
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Study Motivation and Overview

Motivation

- Convergence of new technologies and new business models leading to emergence of new aviation markets, e.g., passenger-carrying **Urban Air Mobility (UAM)**
- Important to assess the evolution of technology, infrastructure, societal acceptance, airspace integration, and many other factors to take us from the current state-of-the-art to the envisioned large-scale operations
- For near-term applications of passenger-carrying UAM and which issues will be the key “bottlenecks” limiting the scalability of early UAM operations (“Op Limits”)
- Create computer model, driven by appropriate data & scenarios, to analyze significance of key Op Limits

Overview*



Identify and Organize Potential Op Limits via “ROPE” Table

Challenge: There are many Op Limit factors, we want to organize them in a fashion that is comprehensible and that eases import to computational model.

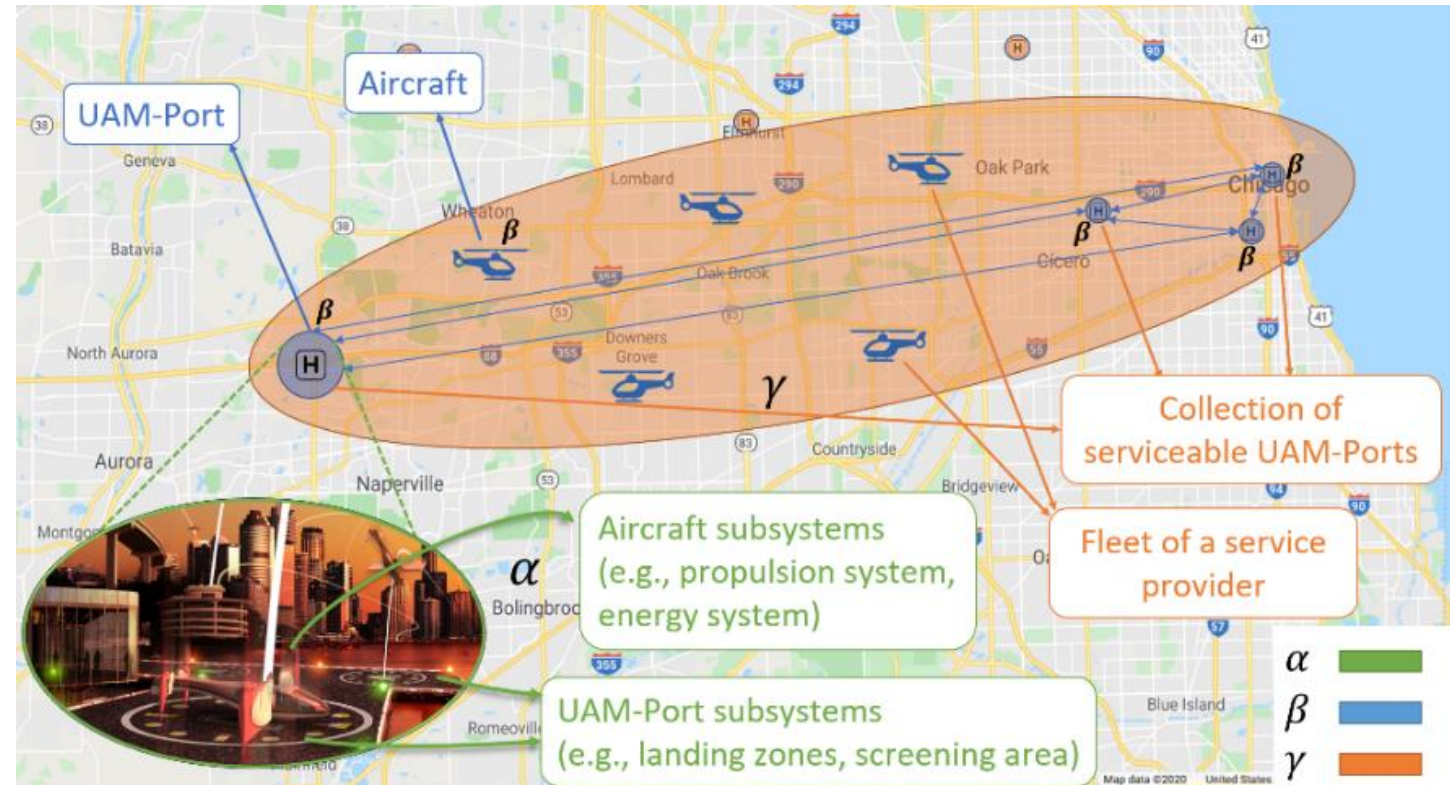
Approach: Build upon ROPE Table Methodology, a decomposition method, to examine any System-of-systems (SoS) problem

Product: Each identified Op Limit is classified based upon the category of the related system, identified as follows:

Categories	Descriptions
<u>R</u> esources	The entities (systems) that give physical manifestation to the system-of-systems
<u>O</u> perations	The application of intent to direct the activity of resources
<u>P</u> olicies	The external constraints that impact the operations and influence intent
<u>E</u> conomics	The behaviors and incentives of stakeholders that give intent to the SoS operation

Hierarchical Breakdown of ROPE Table Elements

- ROPE table enables view on key dimension of categorization: hierarchy level of an entity in SoS
- Identifying appropriate hierarchy level is essential to problem scoping, identification of interdependencies, and making reasonable assumptions for modeling

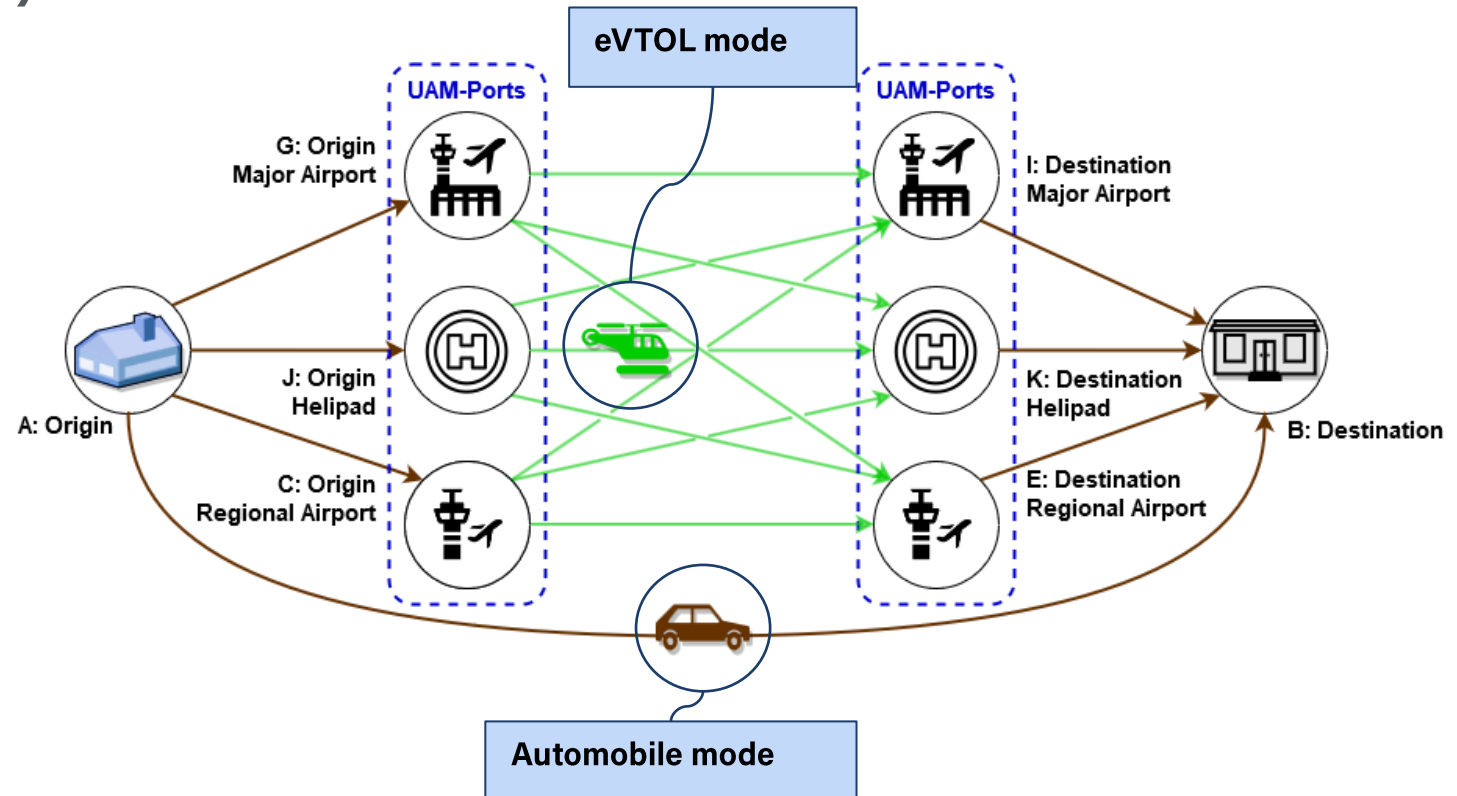


Background Map data © 2020 Google

Unit of Analyses- the Urban Trip

Transportation network model composes of electric vertical takeoff and landing (eVTOL) and automobile modes

- **Green edges** are trips made by eVTOL vehicles
- **Brown edges** are trips made by automobiles
- UAM trips consist of both automobile and eVTOL modes (e.g., branch: AJKB)
- Automobile trips are conventional, ground-based trips (e.g., branch: AB)



Note: UAM-Ports include only existing, publicly-owned infrastructures (i.e., major, regional airports, and heliports) in a metropolitan area

Effective Cost Metric Identifies UAM-preferred Trips

Effective Cost Metric Definition and UAM-preferred Trips Estimation

- Effective cost metric definition:

- $Cost_{eff,i} = Cost_{oper,i} + Cost_{time,i}$

- $Cost_{time,i} = time_{trip,i} * value_{time}$

$Cost_{eff,i}$: effective cost of mode i [$\frac{\$}{hr}$]

$Cost_{oper,i}$: operating cost of mode i [$\frac{\$}{hr}$]

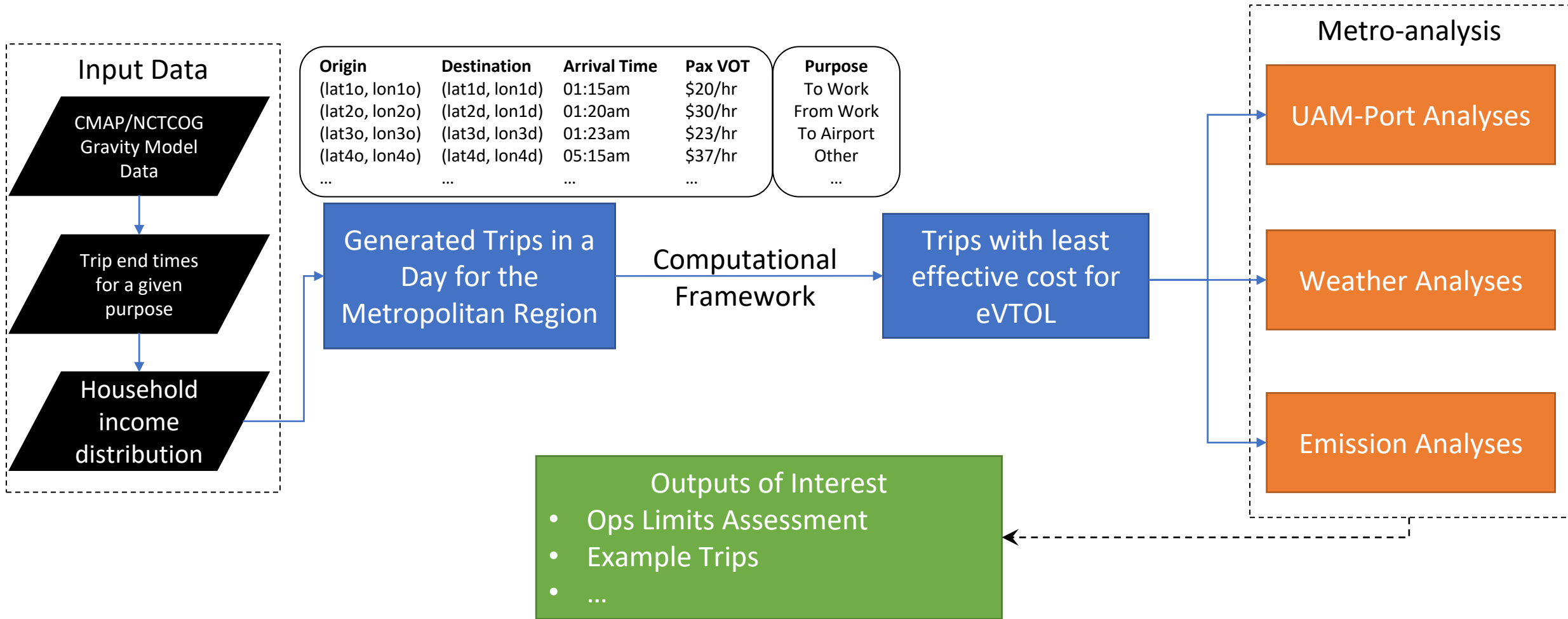
$Cost_{time,i}$: time cost of mode i [$\frac{\$}{hr}$]

$time_{trip,i}$: trip time of mode i [hr]

$value_{time}$: individual's value of time [$\frac{\$}{hr}$]

- Effective cost metric is used to determine the mode of travel with the least effective cost
- A trip is called UAM-preferred when the UAM trip has a lower effective cost than the equivalent automobile trip

Computational Framework Analyzes Op Limits

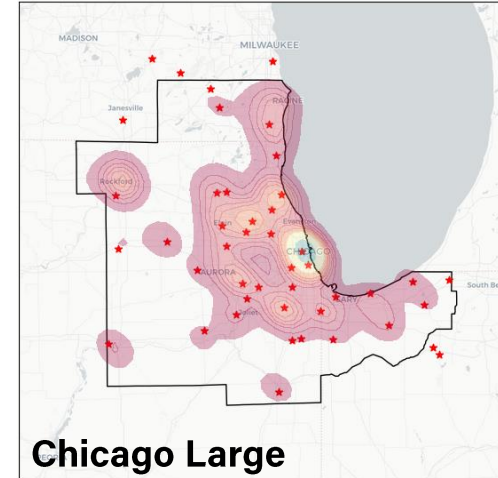
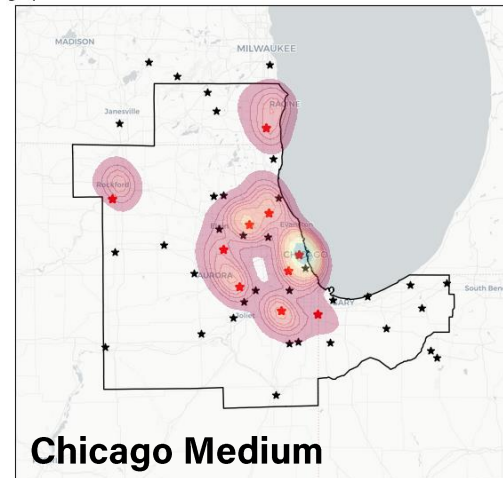
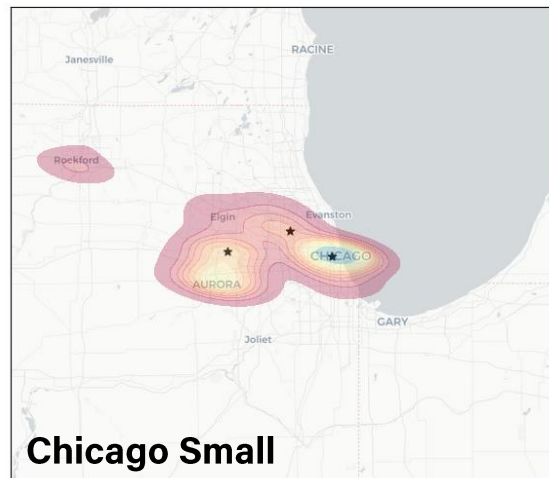


UAM Preferred Trips For Different Network Sizes (Launch)

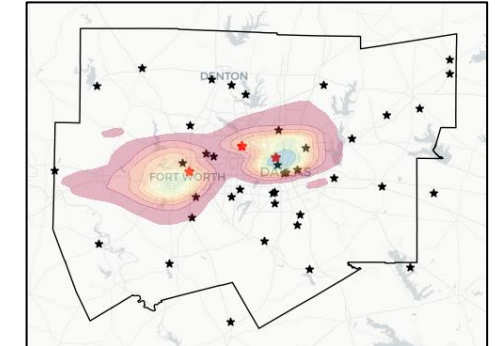
Chicago Commute Trips: 6,221,968

Dallas Commute Trips: 5,306,336

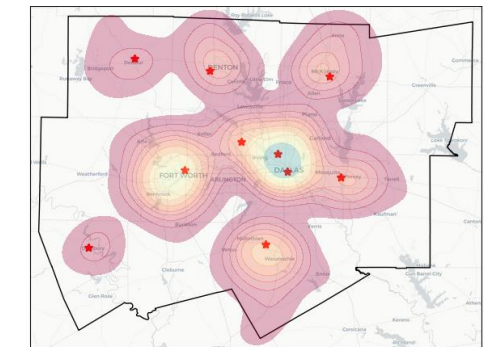
	Small (3 Vertiports)	Medium (10 Vertiports)	Large (All existing infra)
Chicago	397	3504	6305
Dallas	853	2330	6928



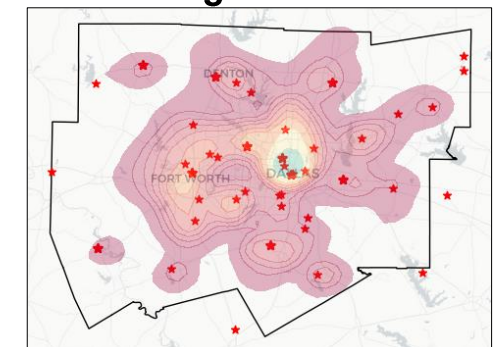
Dallas Small



Dallas Medium



Dallas Large



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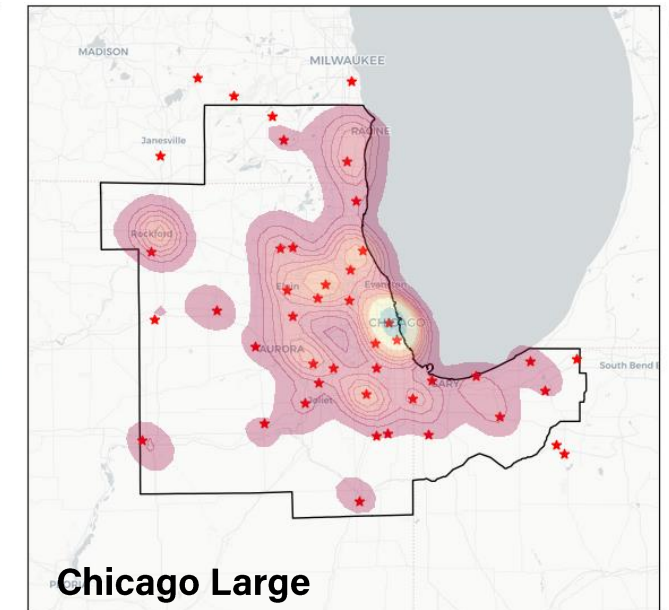
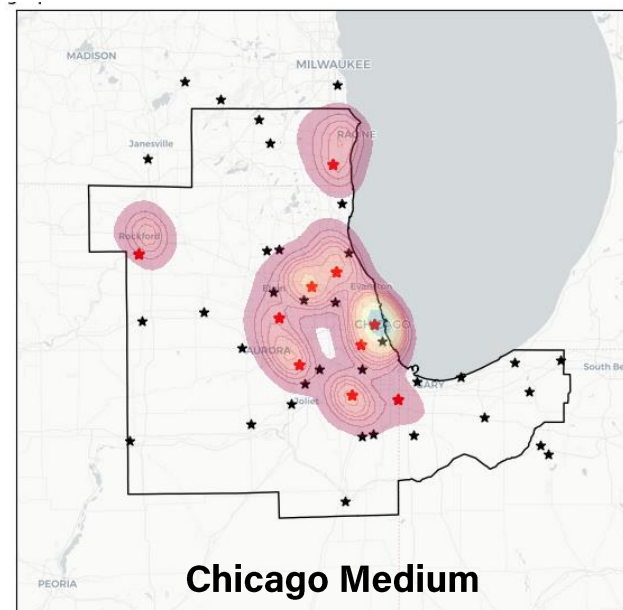
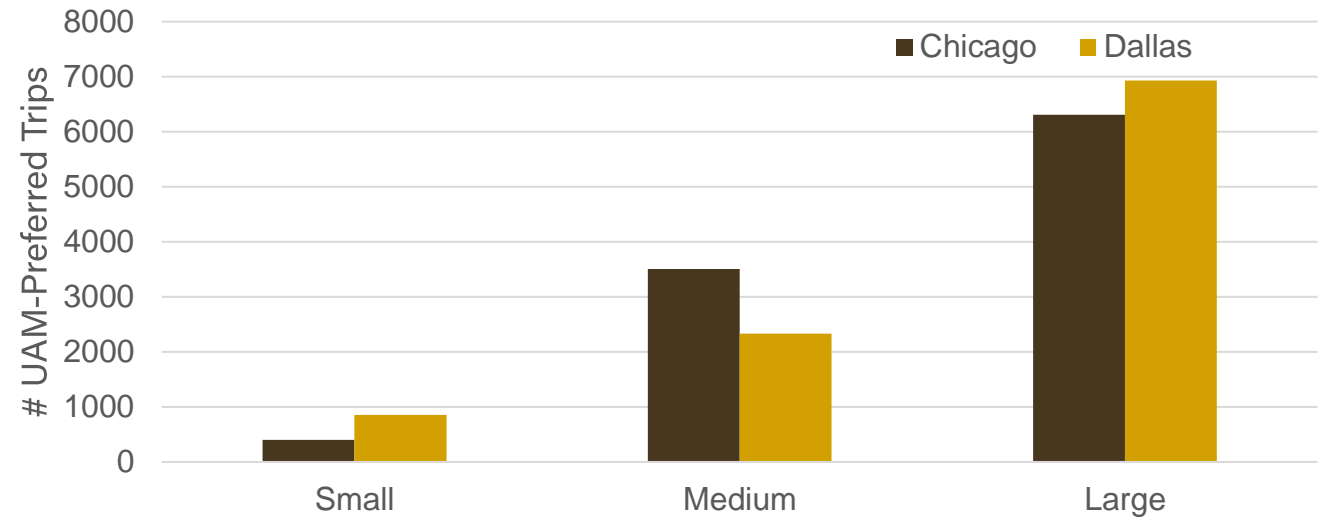


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Note: Launch Scenario UAM Operation
Cost \$605/hr + 1pax

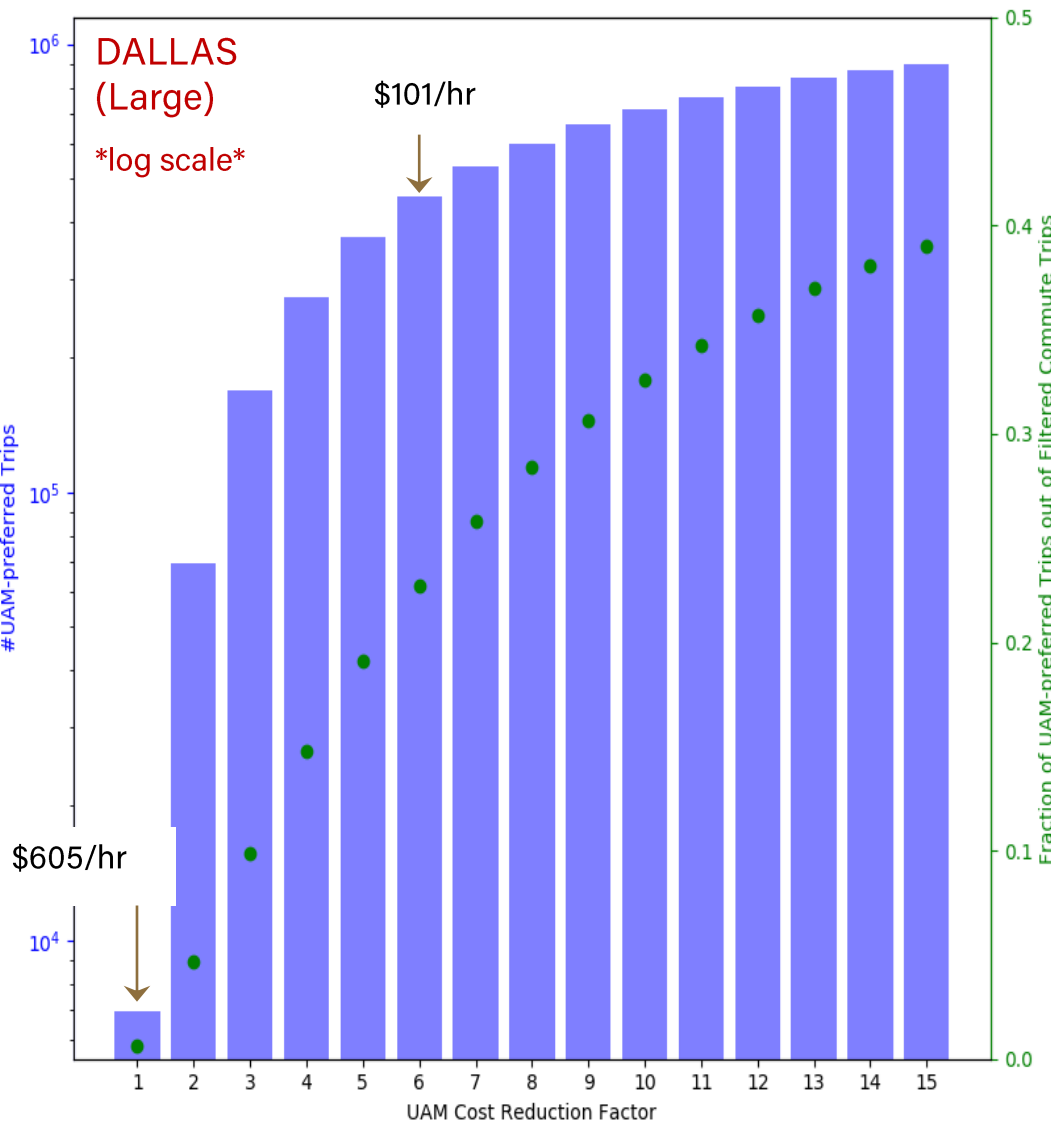
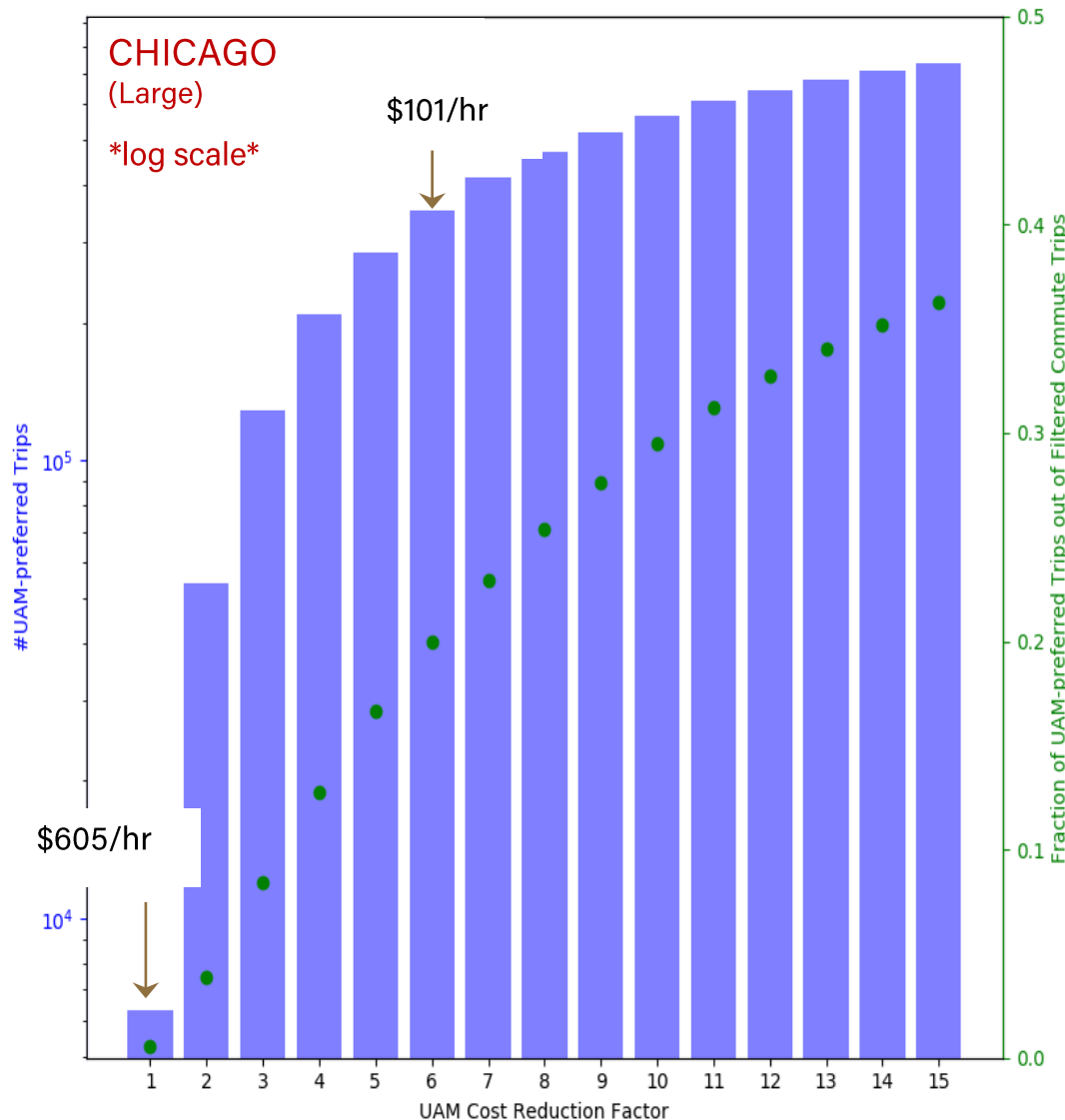
Key Observations from # UAM Preferred Trips

- #Trips increase with the number of vertiports; seems to follow a non-linear relationship
- Vertiport siting plays a significant role
 - Most trips concentrated around the vertiport locations
 - A few vertiports had quite high concentration of trips, even with high-cost launch scenario
 - Implications for congestion management



Sensitivity Studies w/ Trip Cost and Related Factors

Impact of UAM Cost Reduction on # of UAM-preferred Trips



Uber Elevate Scenarios
 Launch: \$605/hr + 1pax
 Near: \$583/hr + 3pax
 Long: \$186/hr + 4pax

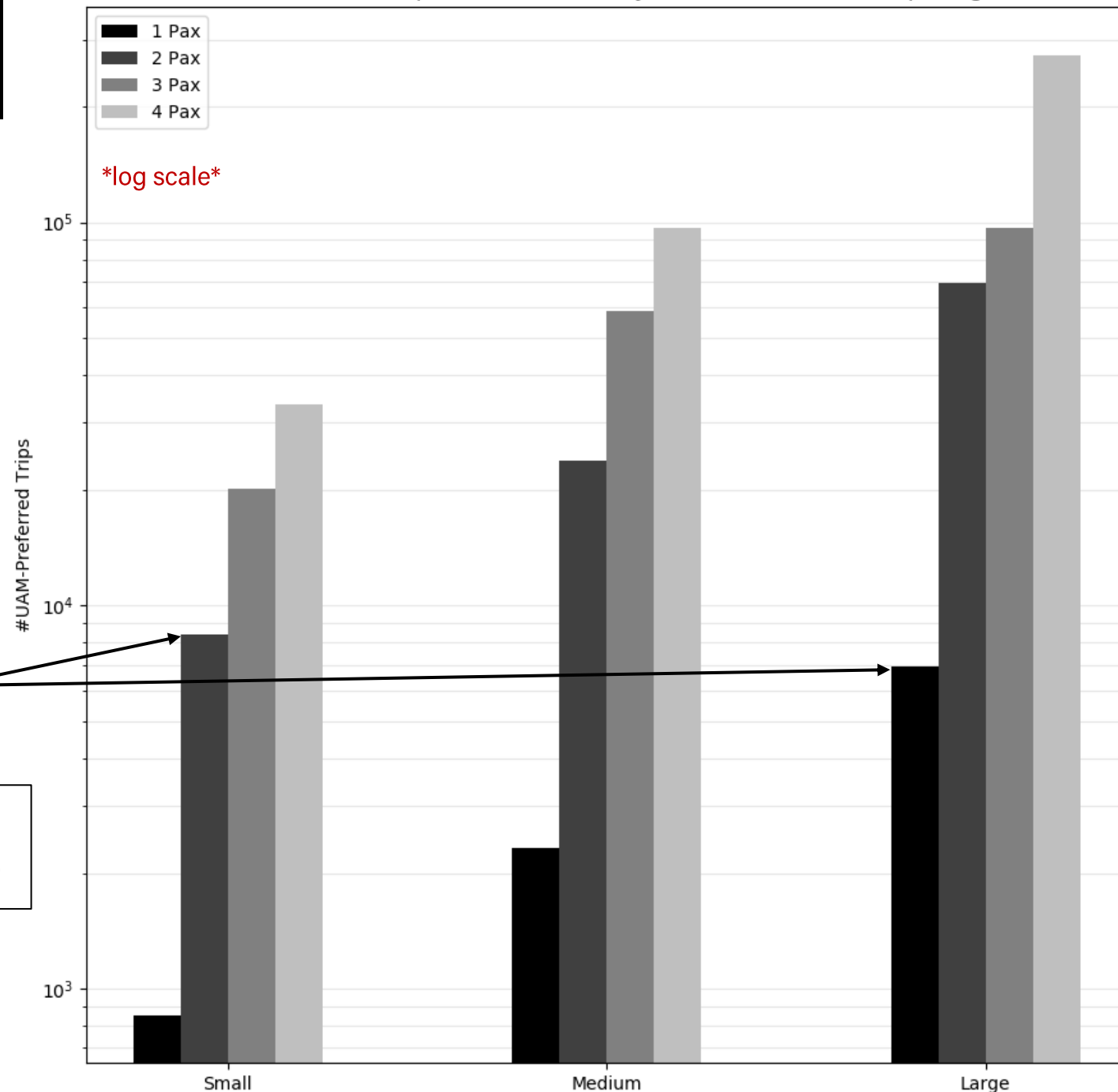
Filtered Trips
 Trips with different UAM-ports closest to the origin and destination

Impact of Ridesharing (DALLAS)

- Assuming the direct impact to the operating cost due to ride-sharing, #UAM-preferred trips are calculated
- For example, operating cost for
 - 1 pax → \$605/hr
 - 2 pax → \$303/hr (=605/2)
- Surprisingly, increasing the #pax per flight to 2 produces a larger impact as compared to operating at all available infrastructure locations with ridesharing not enabled!

Enabling ride sharing will be key to lowering UAM operating cost to make it a real market

#UAM-Preferred Trips for Launch Cost by Network size and #Pax per flight



WEATHER ANALYSIS

Overview and Results Snapshot

Quantifying Weather Impact

Weather data source:

- National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD)
- NOAA ISD contains worldwide hourly ground weather data

UAM weather impact scoring:

- Based on UAM Market Study Report* impact score table
 - 33 unique weather conditions
 - Score from 1 (good) to 10 (bad)
- Impact Score (IS) is used to assess the level of UAM operational impact by weather phenomena

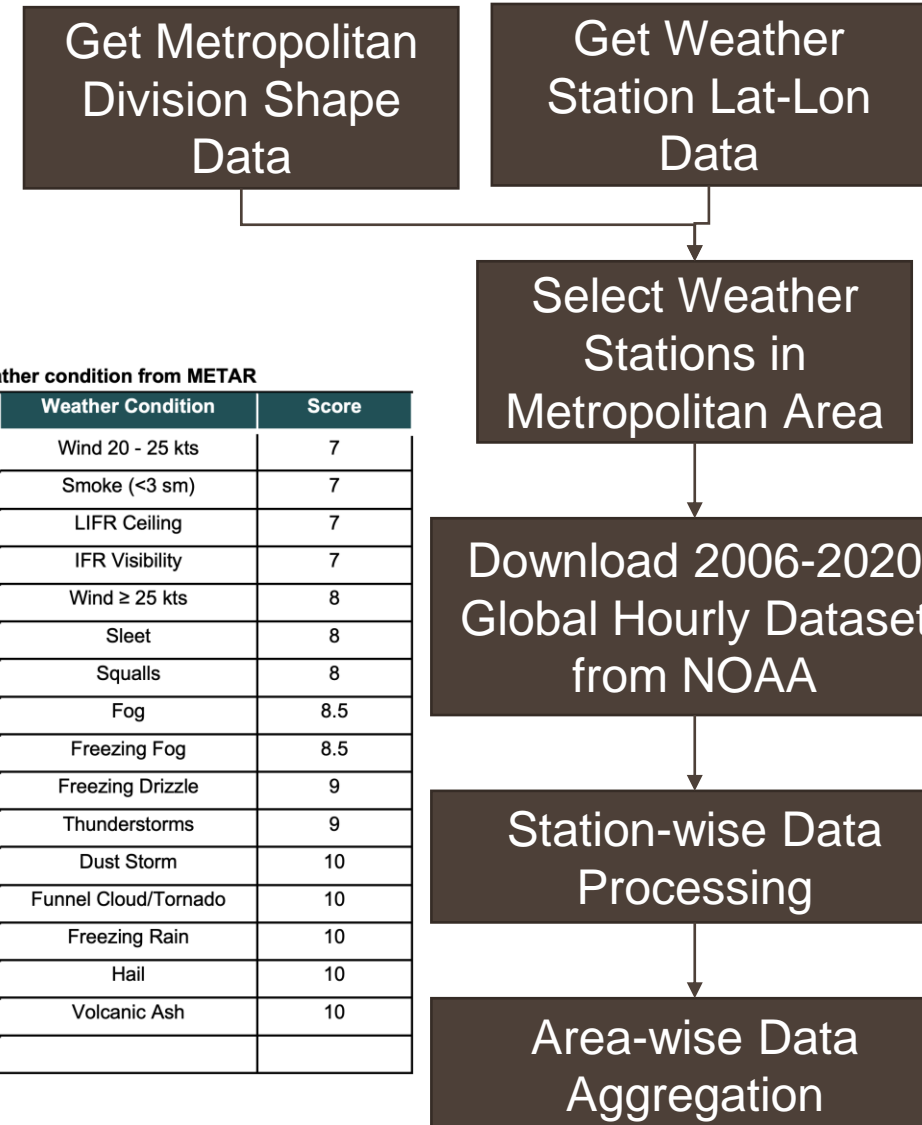


Table 10: Impact Scores for each weather condition from METAR

Weather Condition	Score	Weather Condition	Score
Drizzle	1	Wind 20 - 25 kts	7
Rain	1	Smoke (<3 sm)	7
MVFR Ceiling	1	LIFR Ceiling	7
Haze	1	IFR Visibility	7
Ice Crystals	1	Wind ≥ 25 kts	8
Sand Whirls	1	Sleet	8
Sand	2	Squalls	8
Snow Grains	2	Fog	8.5
Temp ≤ 32°F	3	Freezing Fog	8.5
Temp ≥ 100°F	3	Freezing Drizzle	9
IFR Ceiling	4	Thunderstorms	9
Dust	5	Dust Storm	10
Snow	5	Funnel Cloud/Tornado	10
Sandstorm	5	Freezing Rain	10
Wind 15 - 20 kts	5	Hail	10
Mist (vis ≥ 5/8 sm)	6	Volcanic Ash	10
Snow Pellets	6		

Booz Allen Hamilton. (2018). *Final Report Urban Air Mobility (UAM) Market Study*. Retrieved from <https://ntrs.nasa.gov/api/citations/20190001472/downloads/20190001472.pdf>

Weather Condition Ranking - Results

Wind 15-20 knots is the most frequently occurring weather condition in both cities

- Implies technology solution should be integrated onboard the vehicle

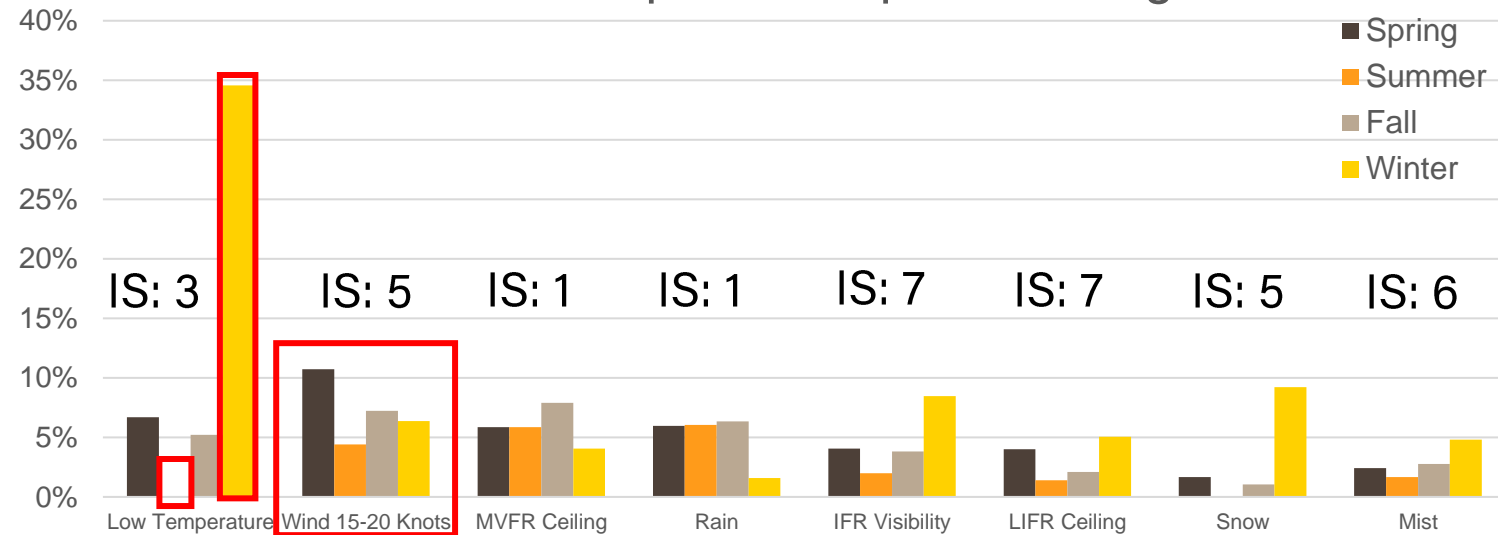
Low temperatures in Winter is important for Chicago

- Higher number of trips impacted in winter; 0 impacted in summer
- Modular technology solution might be suitable for this weather condition

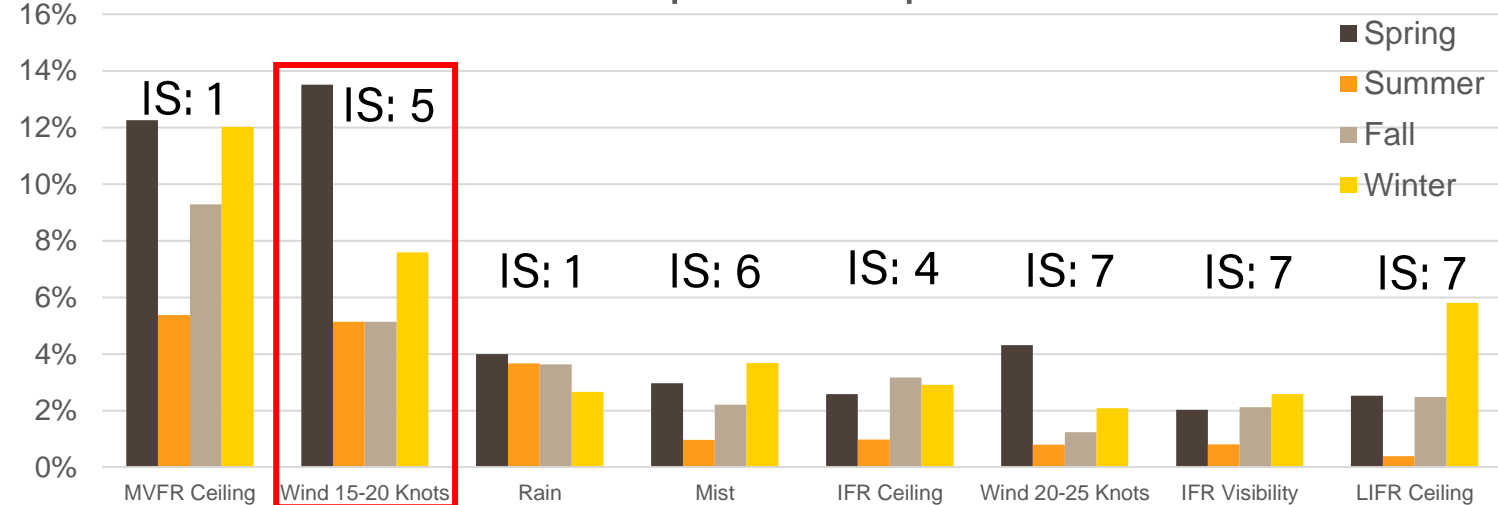


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Fraction of Impacted Trips in Chicago



Fraction of Impacted Trips in Dallas

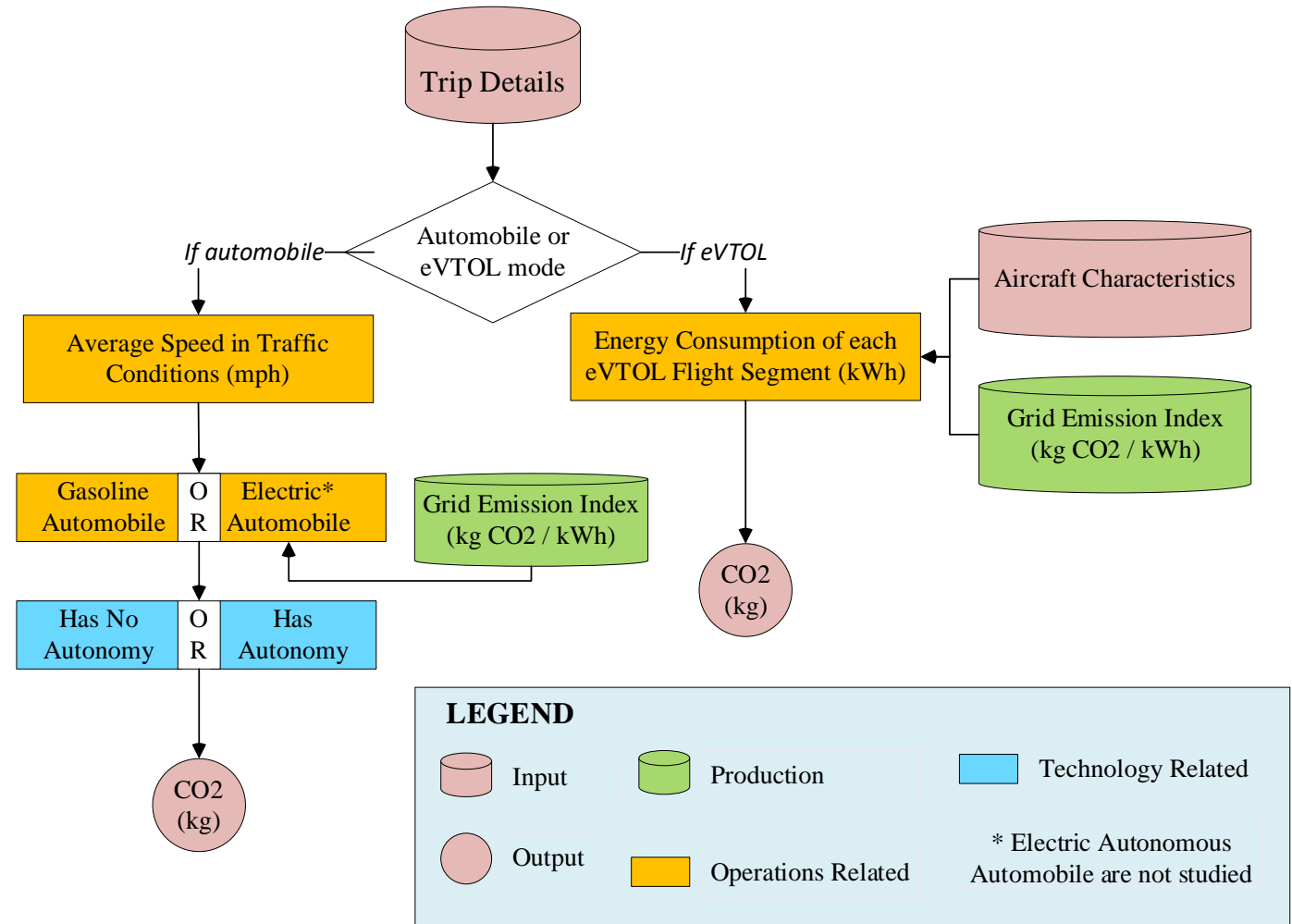


EMISSIONS ANALYSIS

Overview and Results Snapshot

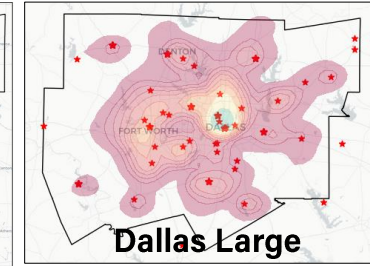
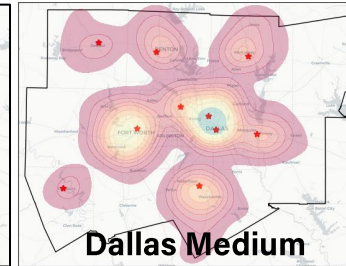
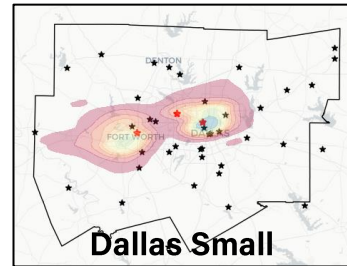
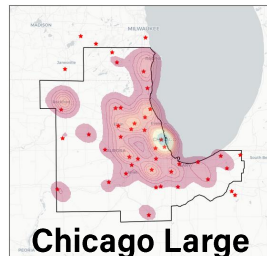
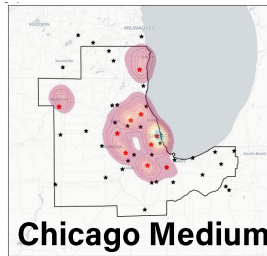
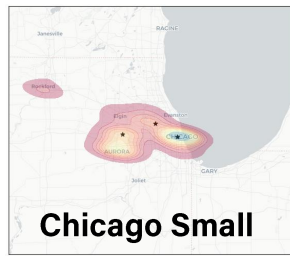
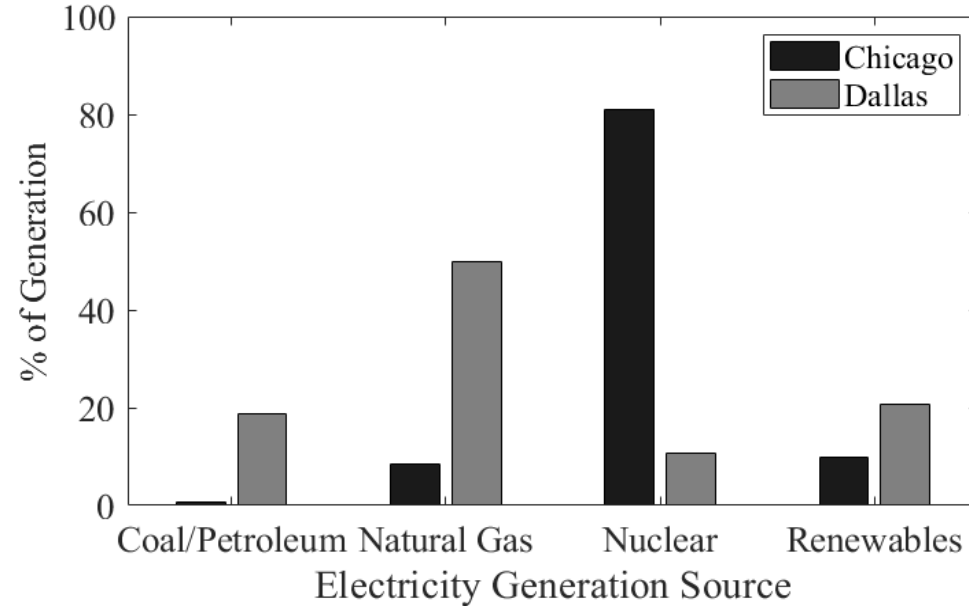
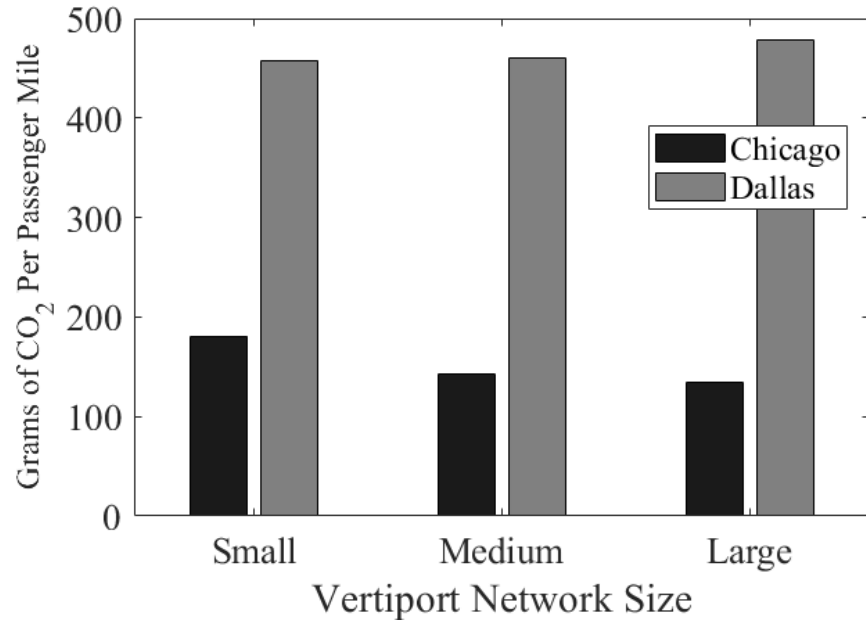
CO2 Emissions Framework for Urban Trips

- A framework for estimating CO2 emissions for any UAM trip and similar automobile-based trips considering current and emerging technologies
- **Use Cases:**
 - eVTOL + Gasoline Cars without autonomy
 - eVTOL + Gasoline Cars with autonomy
 - eVTOL + Electric Autos without autonomy



Estimates of CO₂ Emissions in Dallas and Chicago

- Electricity grid makeup drives emissions from UAM operations with eVTOL + Gasoline Cars without autonomy



Overview of New Study Effort (Commenced Oct. 2021)

Further exploration of operations limits for Advanced Air Mobility (AAM) missions

- Identify further factors that may limit the number of AAM (e.g., Emergency medical, sUAS package delivery, etc.) operations and potential interdependencies with already identified UAM limits
- Perform case studies on additional Metro areas considering existing and potential future operational limits
- Compare and contrast results across the various Metro areas/case studies
- Recommend technology research most promising for paths to achieving scaled AAM operations

BACKUP SLIDES

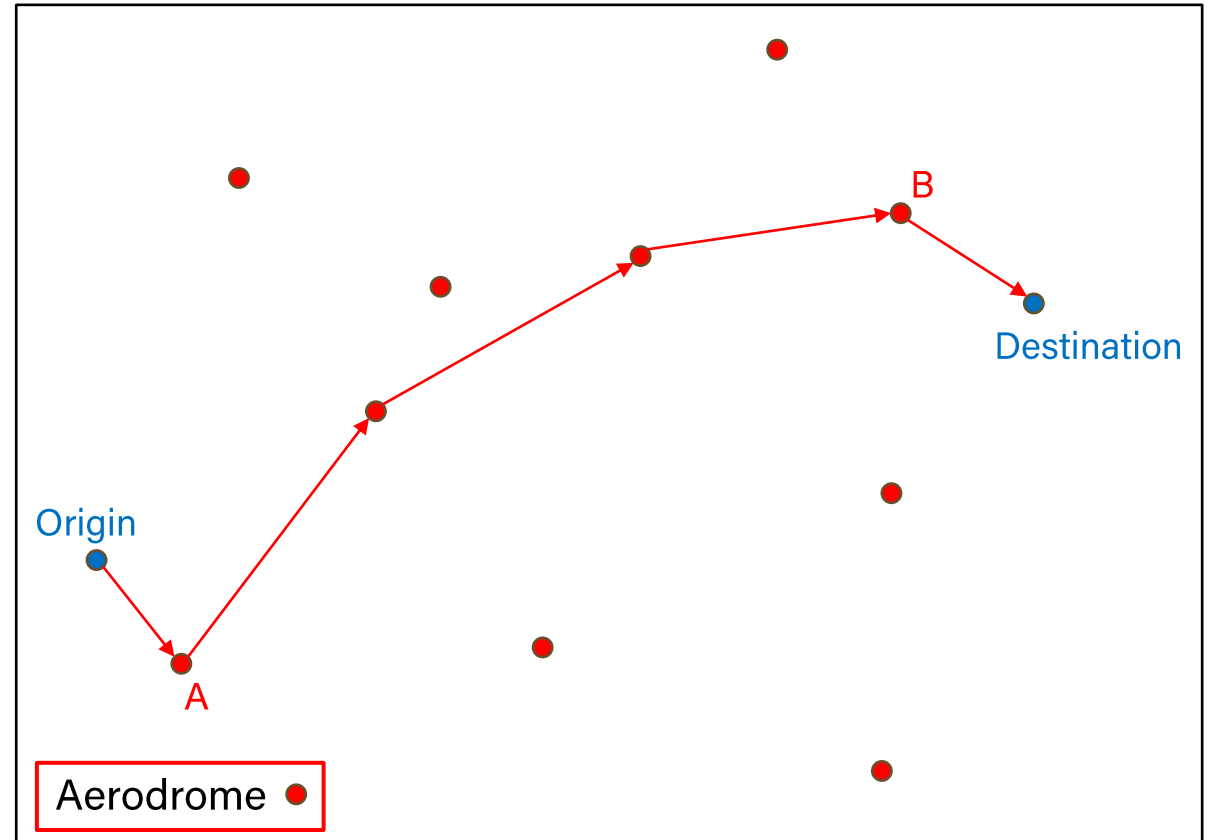
COMPUTATIONAL FRAMEWORK

Detailed Slides

COMPUTATIONAL FRAMEWORK

3 Distinct Problems:

- Distance Between Points
 - Foundation for all other problems
 - Lots of Formulations: Haversine, Ellipsoidal Distance, Google Maps API, etc.
- Nearest Aerodrome Determination
 - Find Aerodromes A and B efficiently at scale
- Flight Routing
 - How to fly from Aerodrome A to Aerodrome B minimizing travel time



COMPUTATIONAL FRAMEWORK ARCHITECTURE

Primary output of the computational framework is an effective cost measure designed to effectively capture two elements of a trip: operating cost and travel time

$$Cost_{eff,i} = Cost_{oper,i} + Cost_{time,i}$$

$$Cost_{time,i} = time_{trip,i} * value_{time}$$

where,

$Cost_{eff,i}$: Effective cost for the mode i

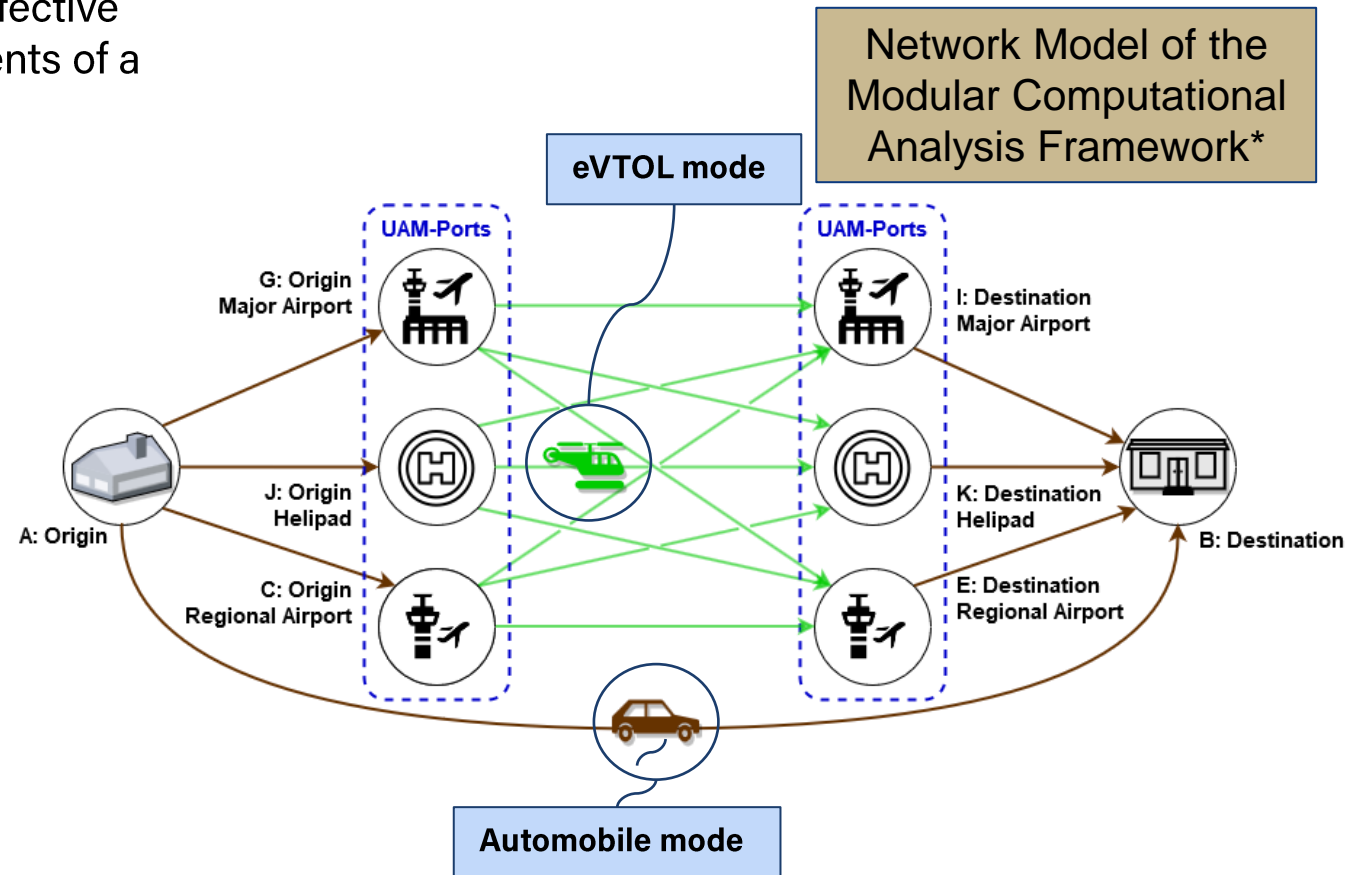
$Cost_{oper,i}$: Operating cost of mode i

$Cost_{time,i}$: Cost due to the travel time on mode i

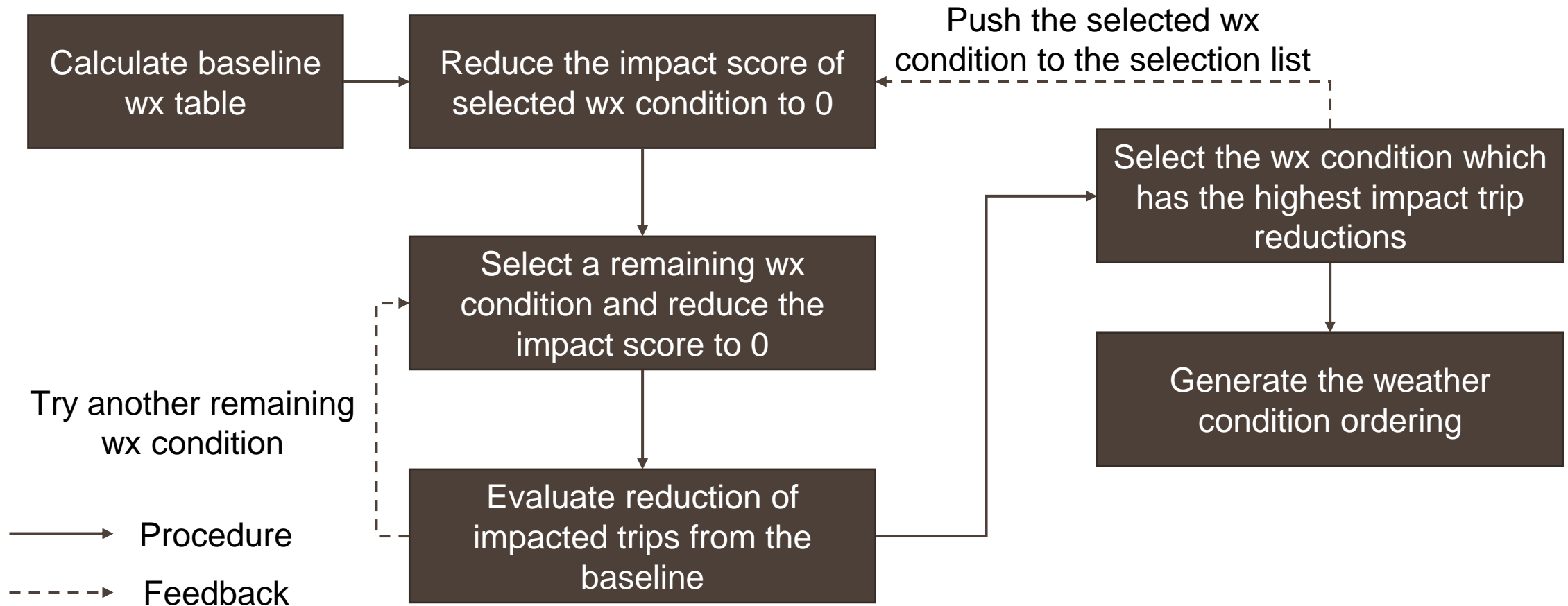
$time_{trip,i}$: Total door-to-door trip time for mode i

$value_{time}$: Value of time of the passenger

Our framework assumes that the traveler always picks the mode with the least effective cost



GREEDY ALGORITHM FOR WEATHER CONDITION RANKING



EMISSIONS RESULTS - OP LIMITS 1

Percentage of UAM Preferred trips and % Decrease in CO₂ emissions compared to driving conventional cars

- Bar graphs show % decrease in CO₂ emissions of UAM trips + gasoline auto and UAM trips + electric auto compared to conventional gas autos for Chicago and Dallas, respectively
- X-axis shows the network size of vertiports, for both Chicago and Dallas metros.
- UAM-preferred trips percentage (%) is shown in red lines for small, medium, and large networks. These are % of UAM-preferred trips from the total commute trips in Chicago and Dallas regions. The total number of commute trips for Chicago and Dallas are 6,221,698 and 5,306,336 respectively.

Grid CO₂ Emissions Rate for Chicago:

[2020, 2030, 2040] = [0.0470, 0.1000, 0.1274] kg CO₂/kWh of electricity generated

Grid CO₂ Emissions Rate for Dallas:

[2020, 2030, 2040] = [0.4090, 0.3334, 0.3073] kg CO₂/kWh of electricity generated

