REFINED ANALYSIS OF CO_2 EMISSIONS IN URBAN AIR MOBILITY NETWORKS

AIAA AVIATION Forum 2024, TF-03 Advanced Air Mobility Operations and Sustainability Considerations

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July 29, 3:30 PM PST, Summit Ballroom 232

PURDUE UNIVERSITY | School of Aeronautics and Astronautics

AIAA-2024-3727

Bottom Line Up Front (BLUF)

Challenge

- CO_2 emissions from Urban Air Mobility (UAM) operations could be a limiting factor for UAM operations at scale
- Require detailed modeling of CO_2 emissions to understand UAM implementation impacts on network wide emissions further than simple logistical justifications of electric aircraft

Importance

- There is growing interest for UAM implementation
- City planners and government entities are investigating the design of UAM networks on a metro-by-metro basis, and will benefit from a comprehensive environmental outlook

Summary of Work

- A refined computation method to calculate emissions for each trip in a travel network
- Considers the increasing usage of electric vehicles on the road
- Also considers ridesharing-enabled UAM operations

Key Takeaways

- Found that increasing electric vehicle usage will reduce overall CO_2 emissions in a network
- Enabling ridesharing in UAM network also provides a reduction in emissions
- **CO_2 emissions may not be a major operational limit to UAM operations with ridesharing**

Overview of Urban Air Mobility

- Urban air mobility (UAM) focuses on leveraging novel aviation capabilities for transportation within metropolitan areas
  - Often proposed with electric vertical takeoff and landing (eVTOL) aircraft
  - Focus on servicing large metropolitan areas
- Stakeholders in the success of UAM include urban planners and aircraft manufacturers
- UAM is a system of systems (SoS): UAM implementation involves interactions across the realms of technology, operations, policy, and economics

UAM has potential to facilitate fast, long-distance journeys within metro areas

AAM Operational Limits Study

Purdue AAM Operational Limits Group Efforts till Present

- Operational limits are factors that may inhibit large-scale UAM operations
- Previous work in this series has focused on quantifying limits regarding:
  - Weather
  - Emissions
  - Cargo Operations
  - Aerodrome Throughput
- Has also produced a computational framework capable of modeling a UAM travel network based on passenger demand

Evaluating Impact of Operational Limits by Estimating Potential UAM Trips in an Urban Area

Apoorv Maheshwari[*], Brandon E. Sells[*], Stephanie Harrington[*], Daniel A. DeLaurentis[†] and William A. Crossley[†]
Purdue University, West Lafayette, IN, 47907

Research Article

Modeling CO_2 Emissions from Trips using Urban Air Mobility and Emerging Automobile Technologies

Sai V. Mudumba, Hsun Chao, Apoorv Maheshwari, Daniel A. DeLaurentis, and William A. Crossley

Weather Impact Assessment for Urban Aerial Trips in Metropolitan Areas

Hsun Chao[*], Apoorv Maheshwari[*], Daniel A. DeLaurentis[†], and William A. Crossley[†]
School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN, 47907

A Comparative Study of Aerodrome-related Operational Limits for Passenger-Carrying Missions across Metropolitans

Brandon E. Sells[*], Keshav R. Iyengar[†], Byeonghun Kim[†], Nicholas Gunady[*], Ethan C. Wright[†], Seejay Patel[†], Daniel A. DeLaurentis[‡] and William A. Crossley[‡]
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A System-of-Systems Approach to Analyzing Future Advanced Air Mobility Cargo Operations

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Operational Limits in UAM

Viewing UAM as a SoS allows us to search for *operational limits*

- Previously identified operational limits to UAM include aerodrome throughput, weather, traffic, and economics
- Sustainability and environmental impact are potential operational limits
  - Emissions from all-electric UAM aircraft can be assumed to be directly related to the electric grid composition of a metro area.
  - When considering the full SoS of UAM and its environmental implications, there are a few key factors to be accounted for…

Ridesharing on UAM travel

- Potential to reduce per-passenger travel costs, incentivize UAM utilization, and reduce environmental impacts

Presence of battery-electric ground vehicles (EVs)

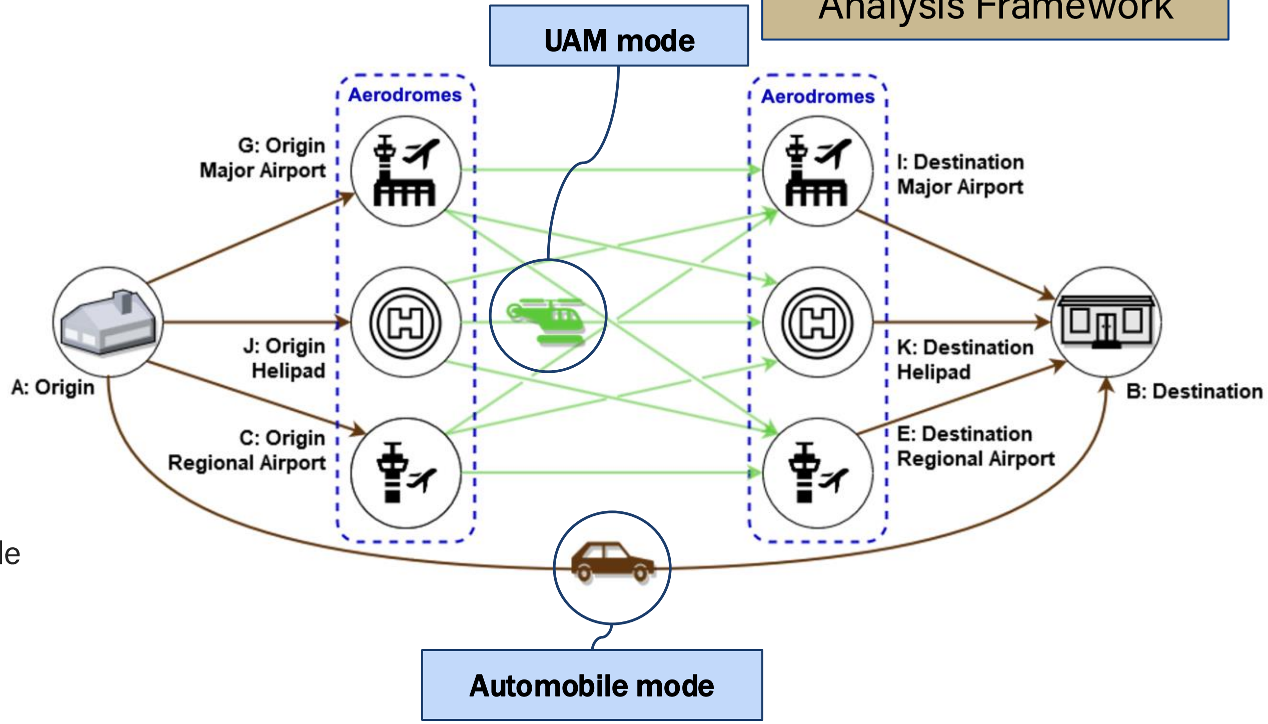
- Increase in EV utilization for car travel, replacing some internal combustion engine (ICE) vehicles

Assigning Travel Modes to Trips

Effective cost metric in the computational framework

- Analyzes for trip mode preferences for all commute trips in a metro area
  - Utilizes a traveler's value of time (VoT)
  - Compares effective costs between ground-only trips (car mode) and trips involving UAM segments (UAM mode)
- UAM-preferred trips
  - When effective cost$_{\text{UAM Mode}}$ < effective cost$_{\text{Car Mode}}$
  - Indicates potential demand for UAM services

Network Model of the Modular Computational Analysis Framework

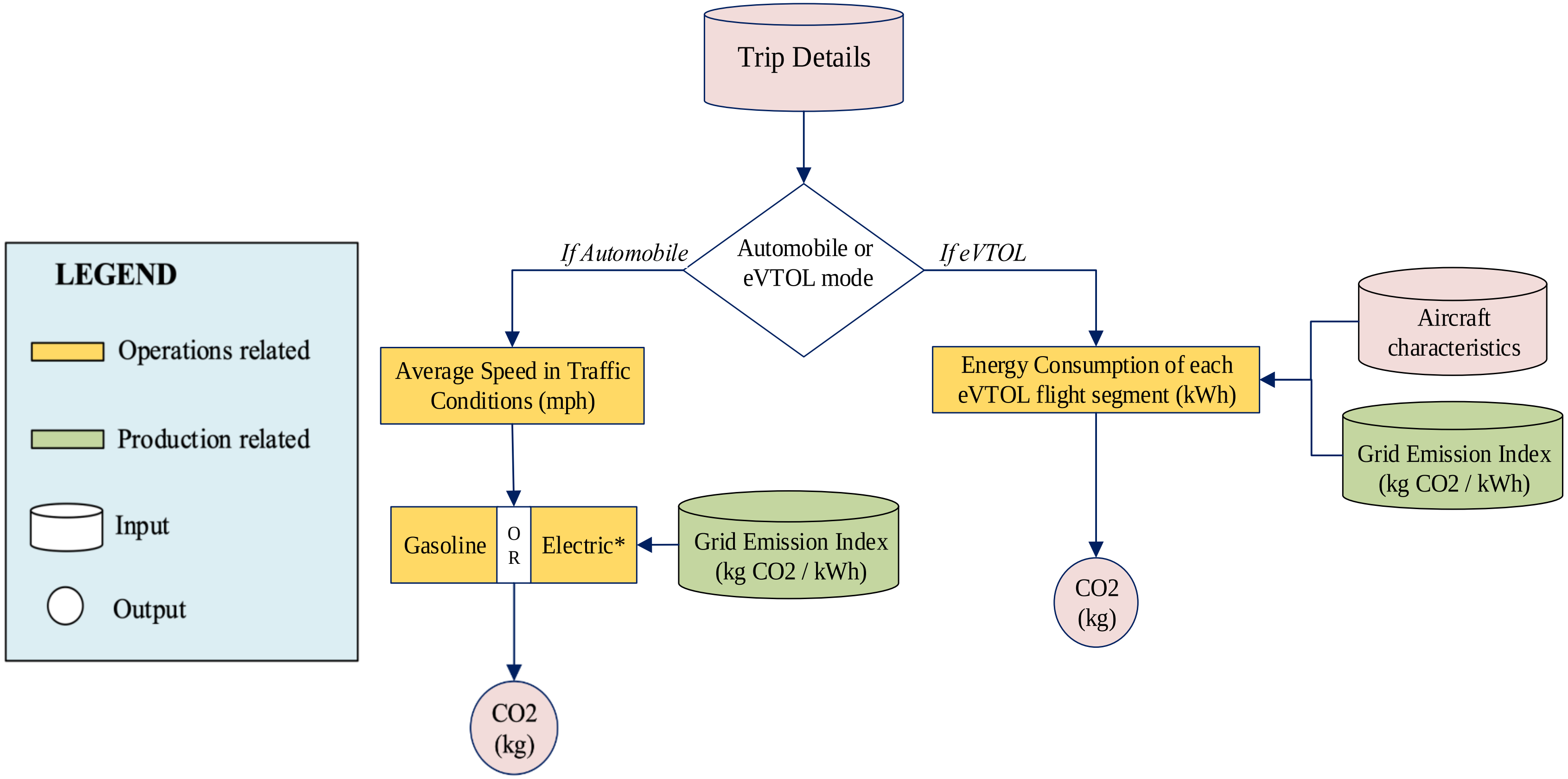


Past Work on UAM Emissions Modeling[1]

- Although eVTOL aircraft do not generate tailpipe emissions, battery charging generates emissions
- Thus, emissions caused by UAM operations depend on the energy source composition of the local electric grid

Grid Emission Index (EI_{GRID})

- Amount of CO_2 (kg/kWh) of electricity generated by the regional power grids



[1] Mudumba, S. V., Chao, H., Maheshwari, A., DeLaurentis, D. A., and Crossley, W. A., "Modeling CO2 Emissions From Trips Using Urban Air Mobility and Emerging Automobile Technologies," Transportation Research Record, Vol. 2675, No. 9, 2021, pp. 1224–1237. doi:10.1177/03611981211006439.

Projecting Electric Vehicle Usage

How can we model the number of EVs on the road that could be a part of the transportation network?

- EV utilization rate-proportion of EVs relative to all automobiles on the road that are a part of the travel network, with or without UAM applied
- EV market share-proportion of EV sales relative to sales of all cars
- Congressional Budget Office projects the EV market share up till 2050[1]

2022 EV Market Share	2050 Projected EV Market Share
7%	80%

- Assume that the EV utilization rate will continue to rise gradually in all metro areas due to a general projected increase in US EV market share
- **Simulation baseline set at 7% EV utilization, ranges to 100 percent in other scenarios**

Applying the EV utilization rate at random, there will now be segments of travel or full trips that will be conducted by EV instead of ICE vehicle

[1] U.S. Energy Information Administration (EIA), "Annual Energy Outlook 2023," https://www.eia.gov/outlooks/aeo/, 2023. Accessed: 2024-03-30.

Grid Emissions Index Use-Cases

How can we model the change in composition of the regional electric grid?

Chicago EI_{GRID} Values		
Name	Value ($kg\ CO_2/kWh$)	Source
EI_{GRID} Present	0.475	EPA 2022 Data for Chicago (RFCW)[2]
EI_{GRID} Projected	0.214	EIA Projection[1]
EI_{GRID} Idealized	0.011	IPCC Wind Power[3]

- Model the potential general variations in the grid using the emissions grid index
- US Energy Information Administration (EIA) projects a nearly 55% reduction in the EI_{GRID} value by 2050
- Sought an idealistic EI_{GRID} as reasonable lower bound

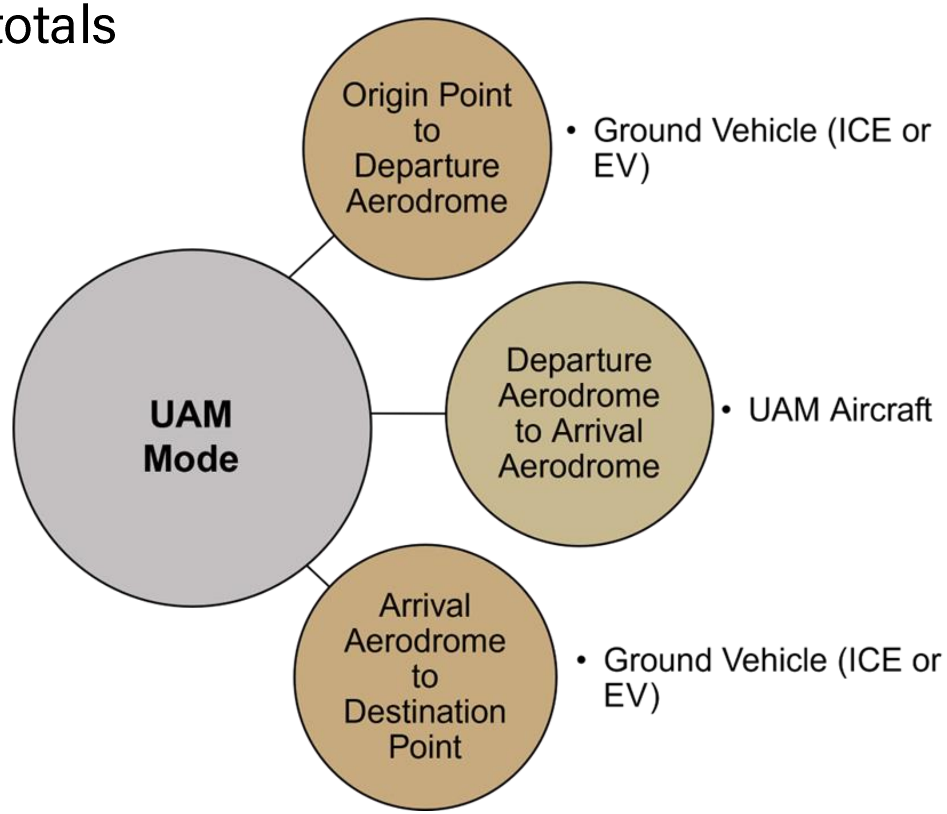
[1] U.S. Energy Information Administration (EIA), "Annual Energy Outlook 2023," https://www.eia.gov/outlooks/aeo/, 2023. Accessed: 2024-03-30.

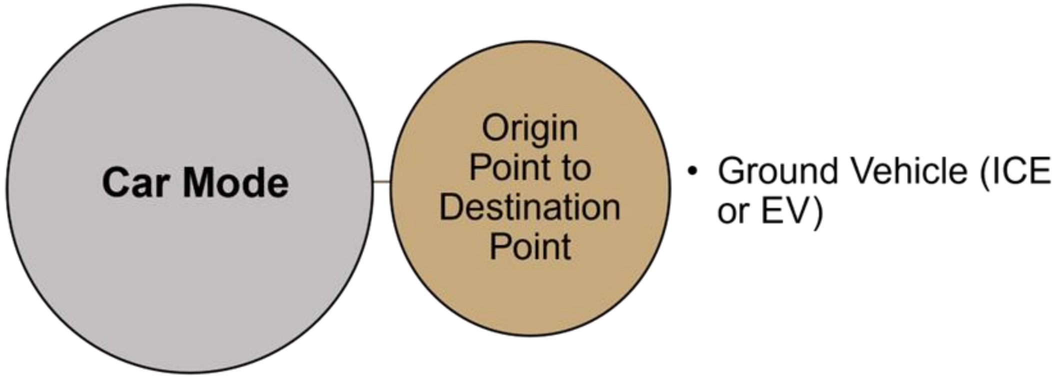
[2] Environmental Protection Agency, "Power Profiler | US EPA," https://www.epa.gov/egrid/power-profiler, 2023. Accessed: 2023-12-11.

[3] Intergovernmental Panel on Climate Change, "Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," https://www.ipcc.ch/ report/ar5/wg3/, 2014. Accessed: 2024-06-21.

Aggregated Travel Emissions Approach

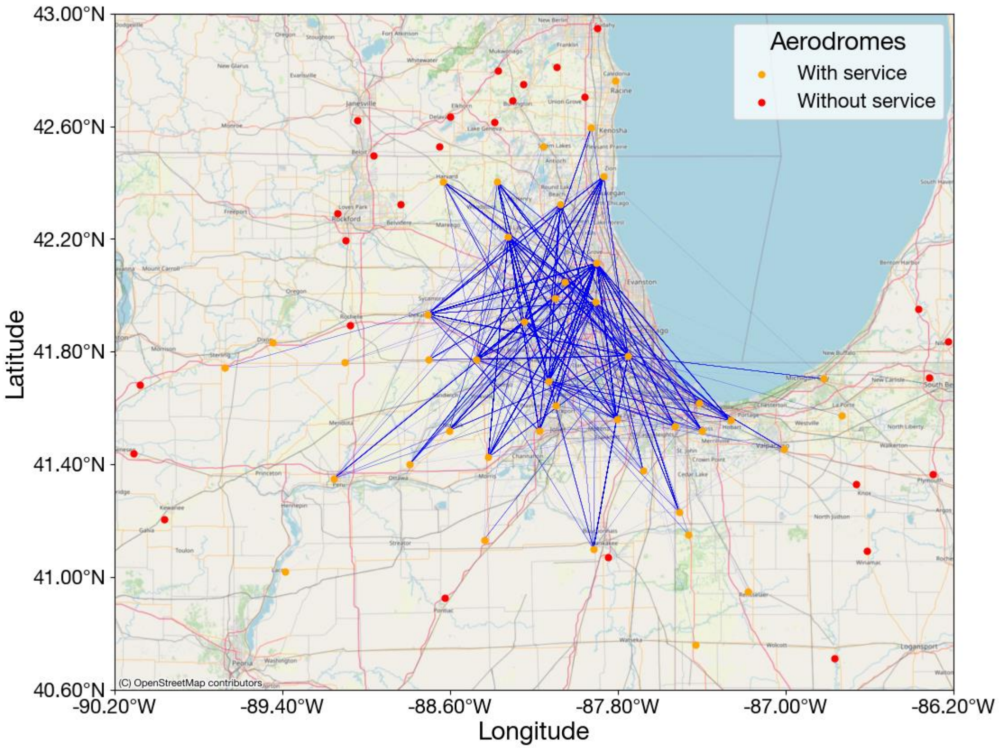
- Emissions calculation process derived from Mudumba et al. (2021)
  - Each vehicle has a different calculation process
  - All calculations are dependent on travel distance and grid emissions where applicable
- Summation of each travel segment over all the trips in the travel network to obtain the emissions totals





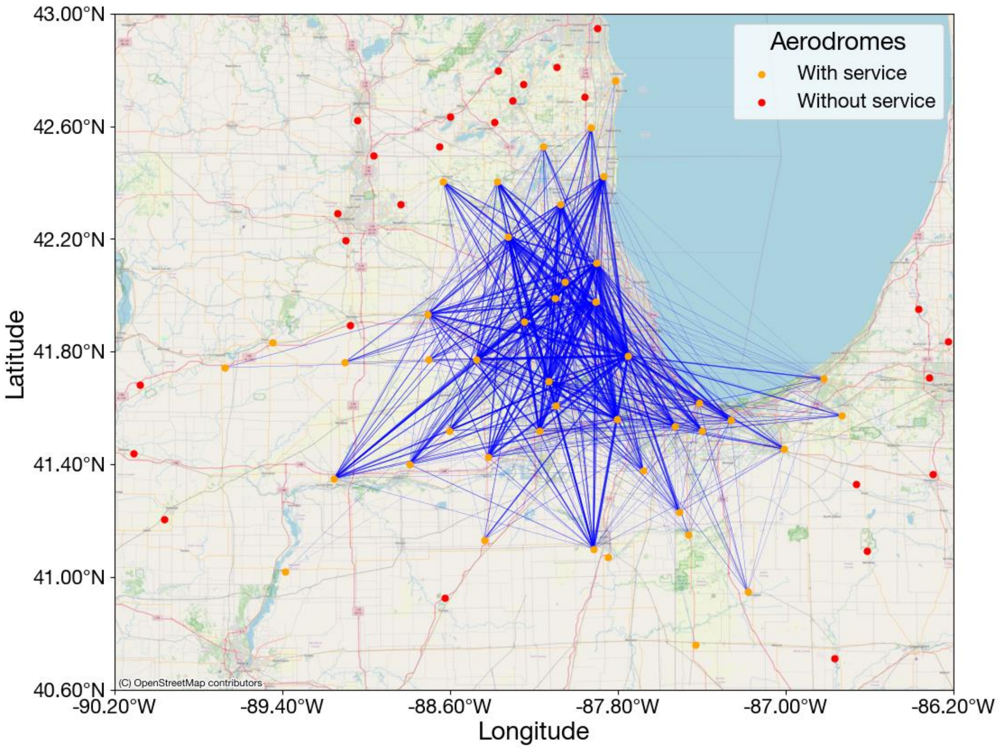
Chicago Case Study Overview[1]:

Chicago full 70-aerodrome network for UAM Services: Over 8.6 million daily trips



Without UAM ridesharing

2,900+ UAM-preferred trips

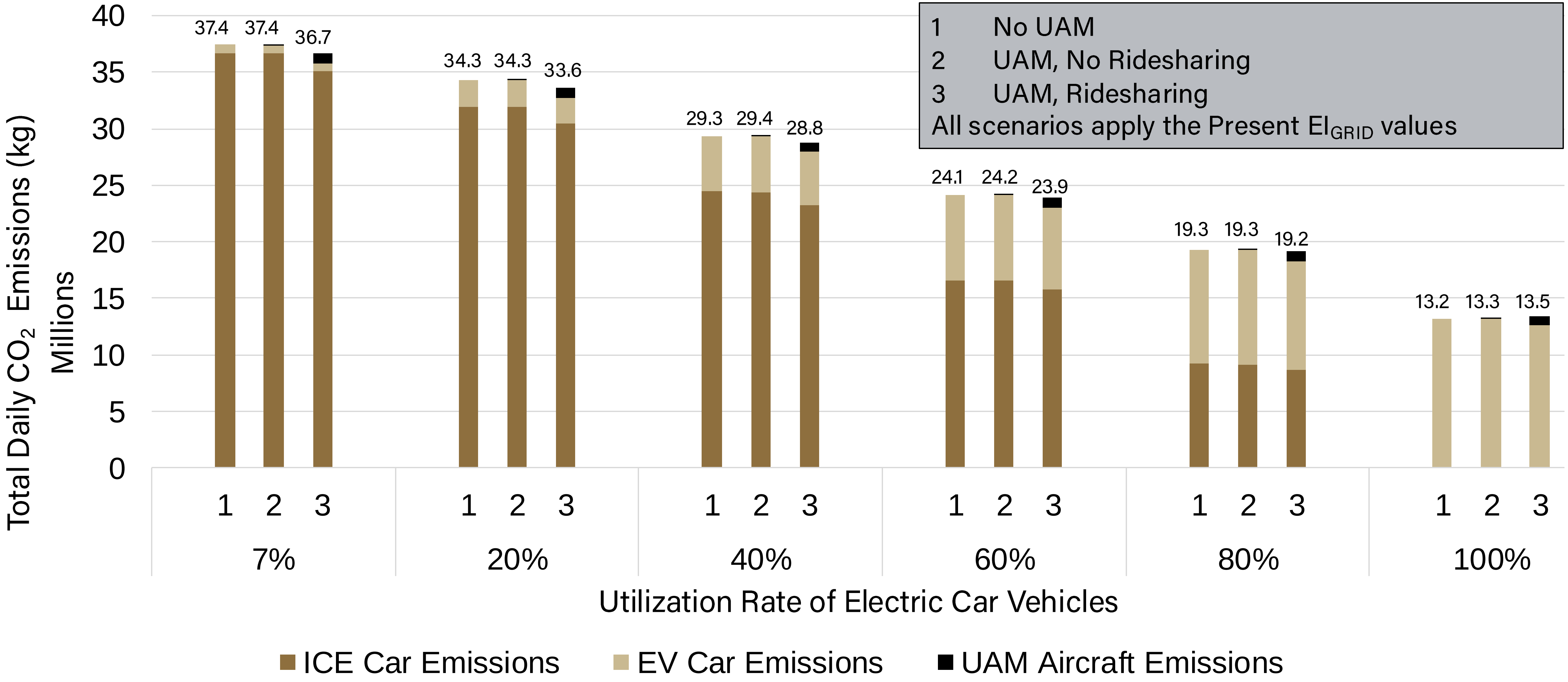


With UAM ridesharing

154,000+ UAM-preferred trips

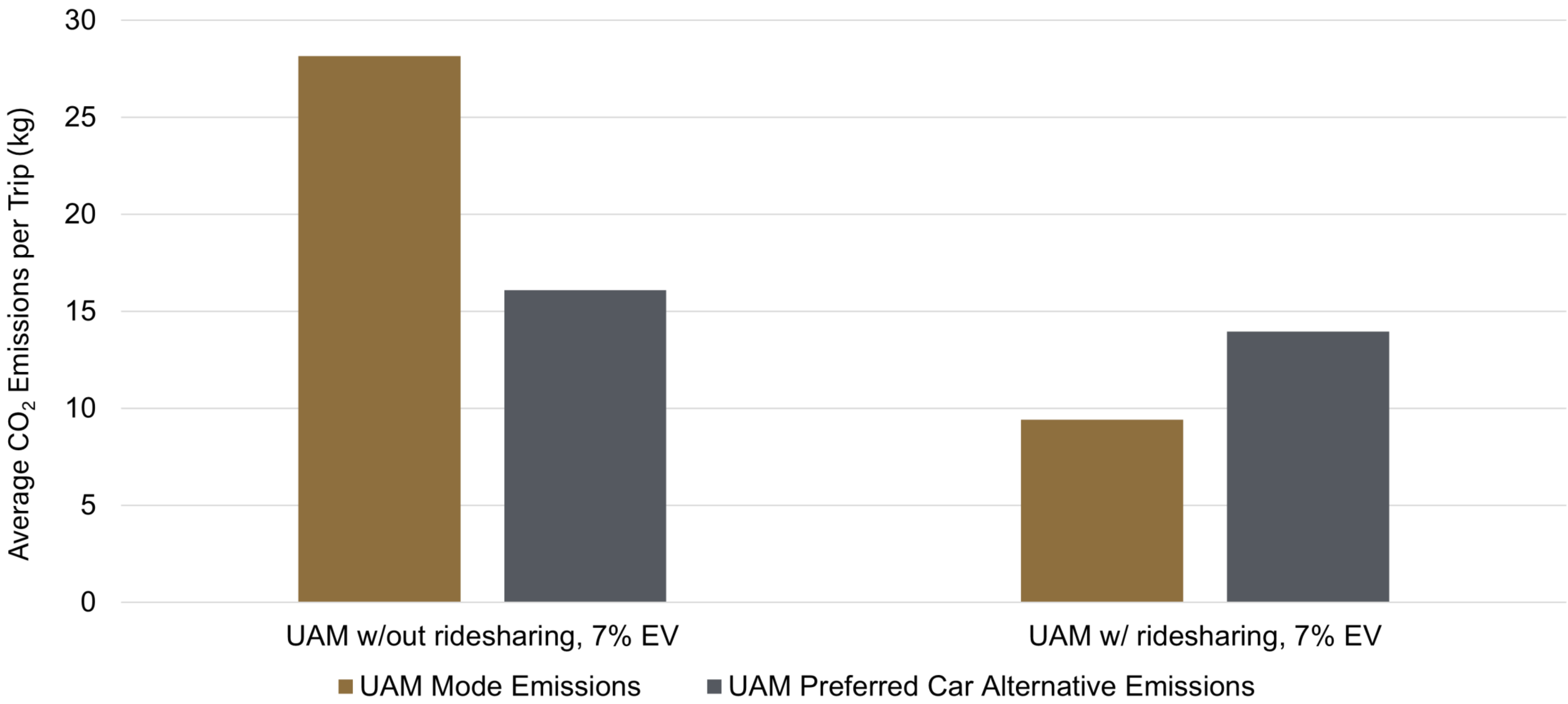
[1] Edsel, A., Biswas, S. D., Kilbourne, M., Gadre, R., Vashi, S., Mall, K., Crossley, W. A., DeLaurentis, D. A., Patterson, M. D., and Sells, B. E., "EXPLORING RIDESHARING IN PASSENGER URBAN AIR MOBILITY: A COMPARATIVE ANALYSIS," ICAS 2024, 2024. Manuscript accepted.

EV Utilization Rate Impact



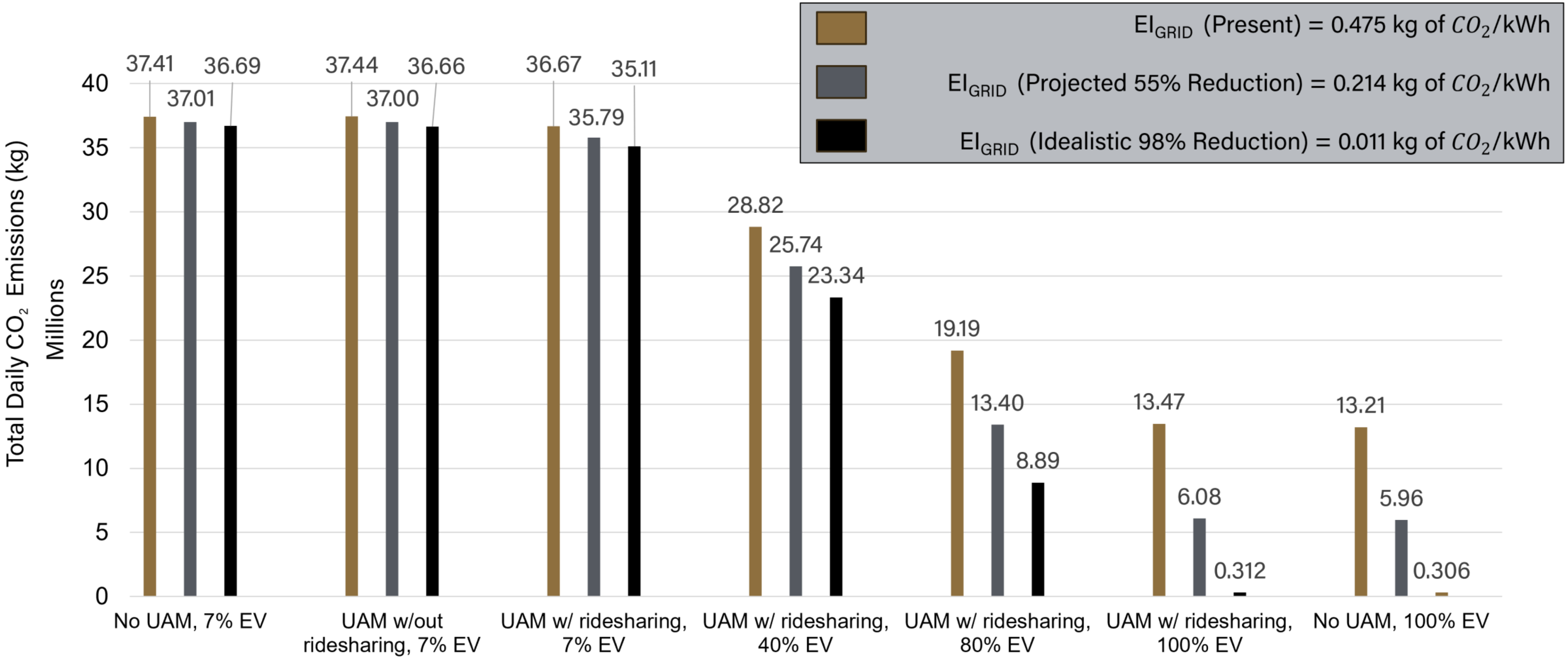
A clear emissions reduction trend emerges with increasing EV utilization. In most cases, the implementation of ridesharing-enabled UAM results in small decreases in total daily emissions.

Ridesharing Impact on Emissions



Enabling ridesharing in UAM operations results in lower average per-passenger emissions from UAM mode trips compared to that from equivalent car mode trips.

Scenario Comparisons



At a 100% EV utilization rate, introducing ridesharing-enabled UAM operations in the Chicago travel network results in at most a 2% increase in total daily emissions across all EI_{GRID} values

Conclusions

- Introducing UAM operations could result in a *net reduction in emissions* in Chicago
- Ridesharing in UAM is beneficial for emissions on a per passenger basis
- EV integration will greatly improve the emissions outlook compared to changes in EI_{GRID} or ridesharing
- Varying EI_{GRID} does not have major implications on environmental performance
- Will become more significant when more vehicles in the network are reliant on the grid- more UAM aircraft trips and EVs

CO_2 emissions may not be a major operational limit to UAM operations when ridesharing is enabled in UAM

Future Work

- Assessing emissions across more metro areas
- Assign more specific parameters to each metro
  - EV utilization rates
  - Grid emissions index projections

Thank You!

We welcome any comments or questions!

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This research is supported by the National Aeronautics and Space Administration (NASA) through the Logistics Management Institute under contract number DATSS 80HQTR18A0013-80HQTR23F0116 (TO#70).

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BACK-UP

Agenda

- Overview
- Motivation and Background
- Methodology
- Assumptions
- Results
- Conclusions
- Summary & Future Work

Considering Emissions as a UAM Operational Limit

UAM applied to a transportation network can be more than just eVTOLs

- Ridesharing on UAM travel
  - Potential to reduce per-passenger travel costs, promote more UAM utilization, and reduce emissions
- Battery-electric ground vehicles (EVs) present in the travel network
  - Increase in interest for utilizing EVs for travel, and will replace some internal combustion engine (ICE) vehicles

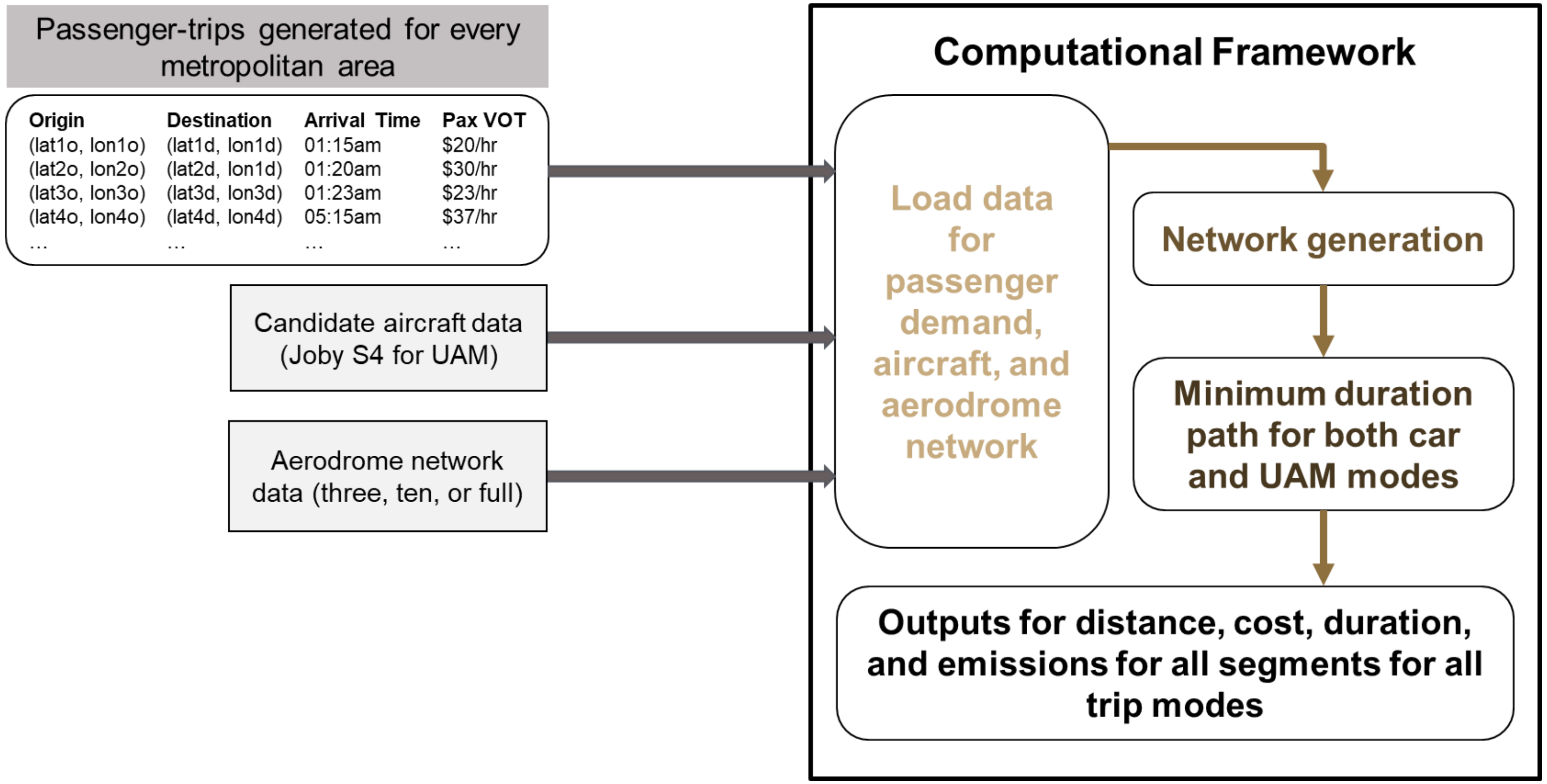
Research Questions

1. **How do the increased incorporation of EVs and reductions in the metro electricity grid carbon intensity impact emissions within a multimodal transportation setting that includes a passenger UAM network?**
2. **How can we assess total emissions in the presence of ridesharing for the UAM mode and compare these emissions to the potential reductions from the adoption of EVs?**

UAM Allocation Utilizing Travel Demand

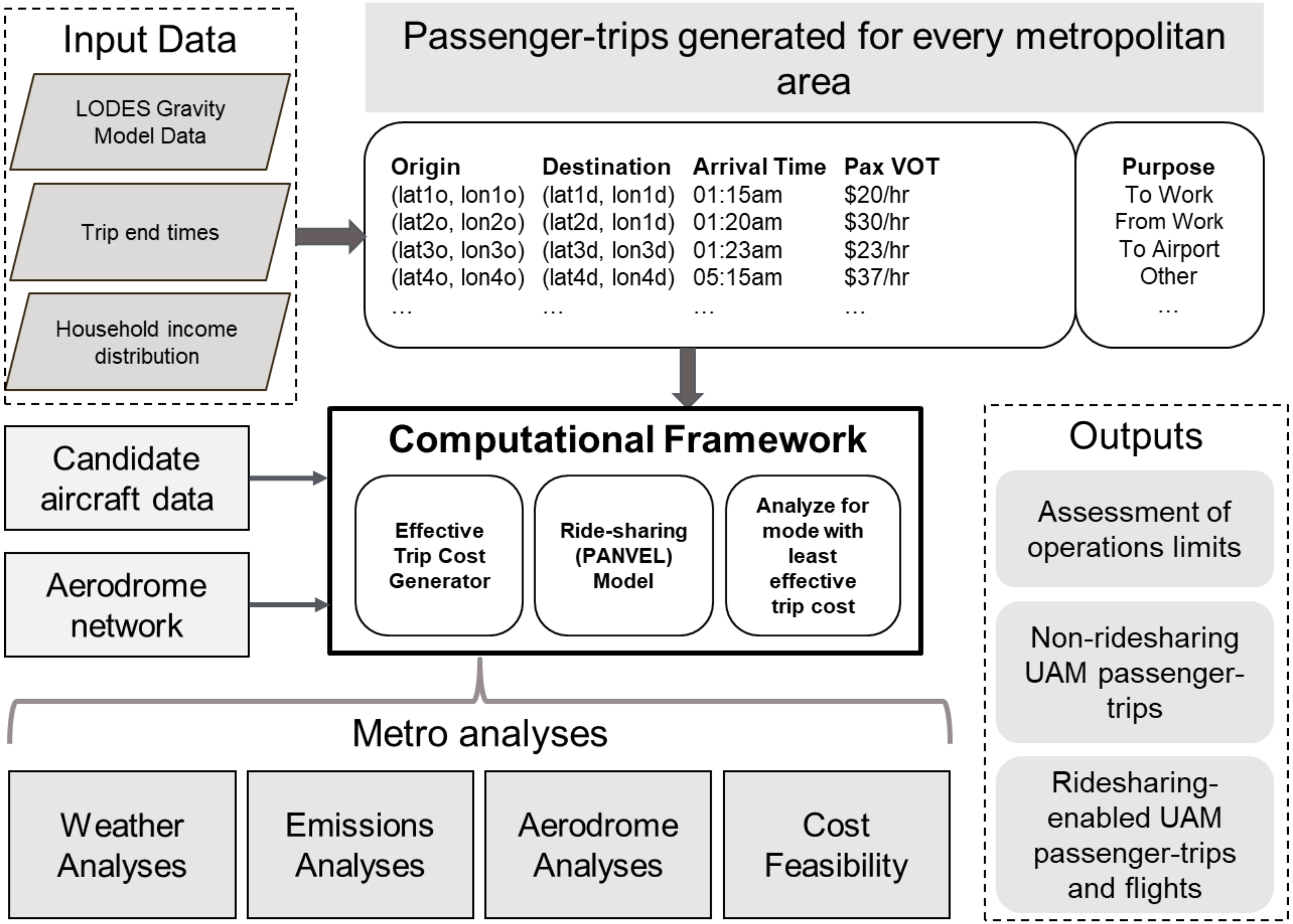
Understanding the composition of a metro area’s travel network

- Computational framework manipulates original trip dataset to apply UAM
- Computational Framework
  - Inputs of original trip dataset, passenger travel demand, and eVTOL characteristics to model a UAM network
  - Different network sizes based on number of aerodromes selected



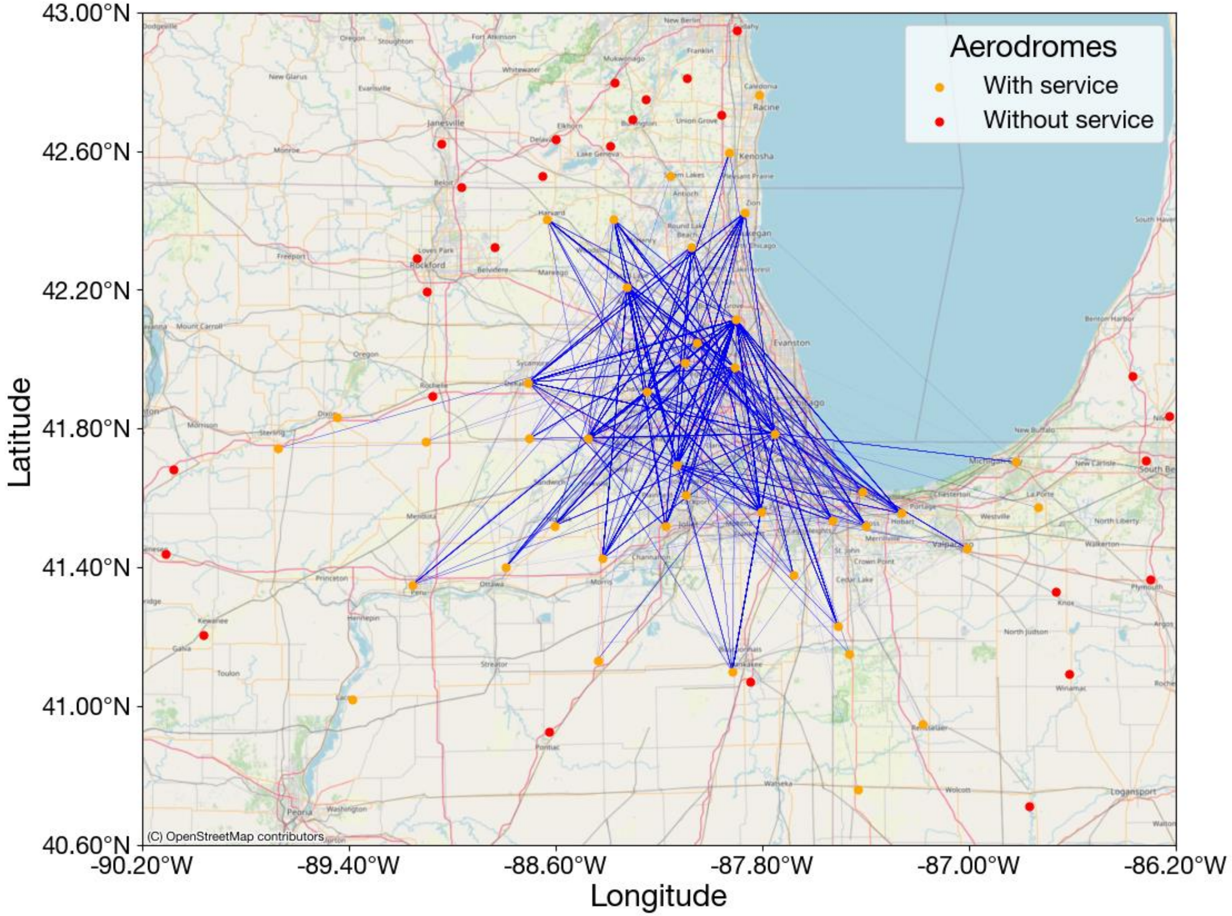
Simplified Flow of Computational Framework

Computational Framework

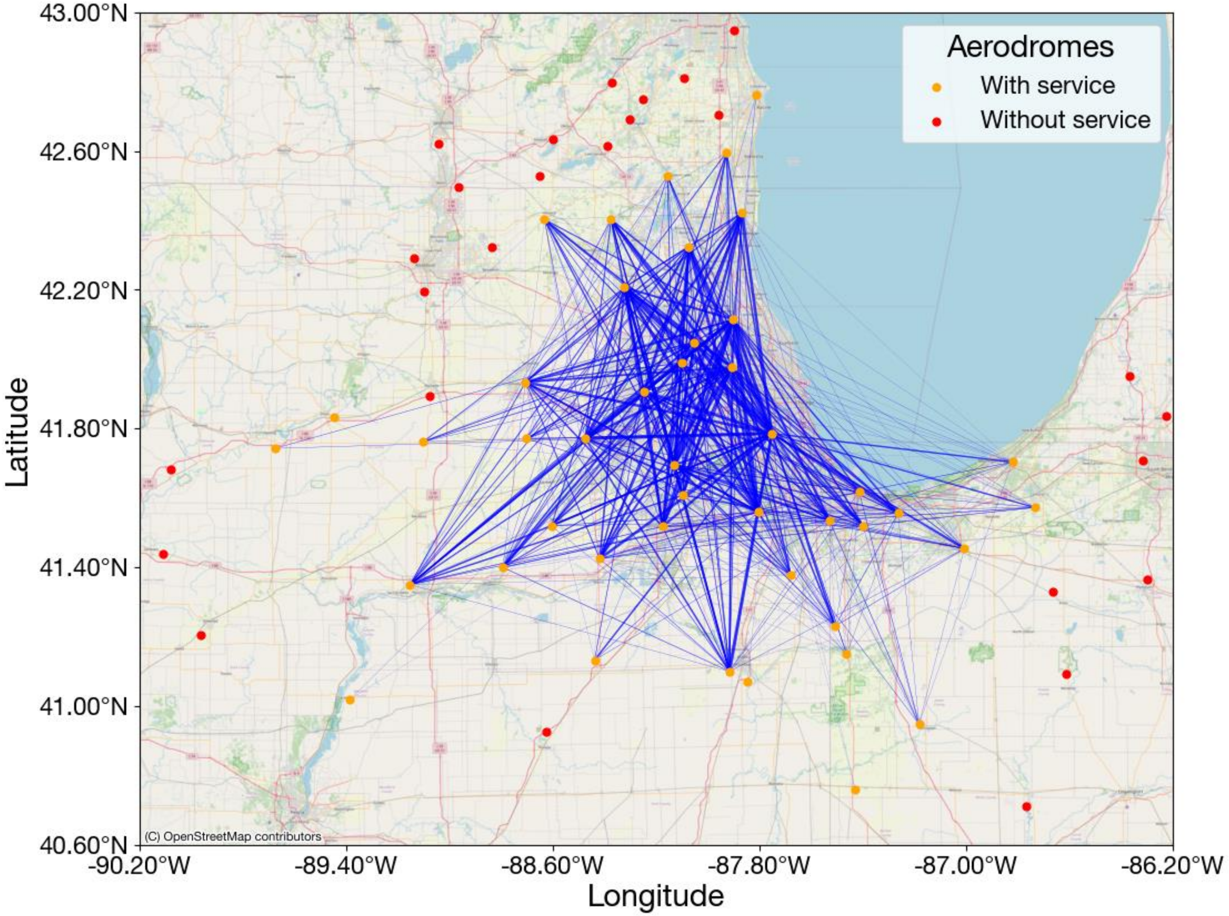


Ridesharing Impact on Notional Chicago UAM Network

Comparative Analysis of Ridesharing, Future Publication: Edsel et al. (2024)



Without UAM ridesharing

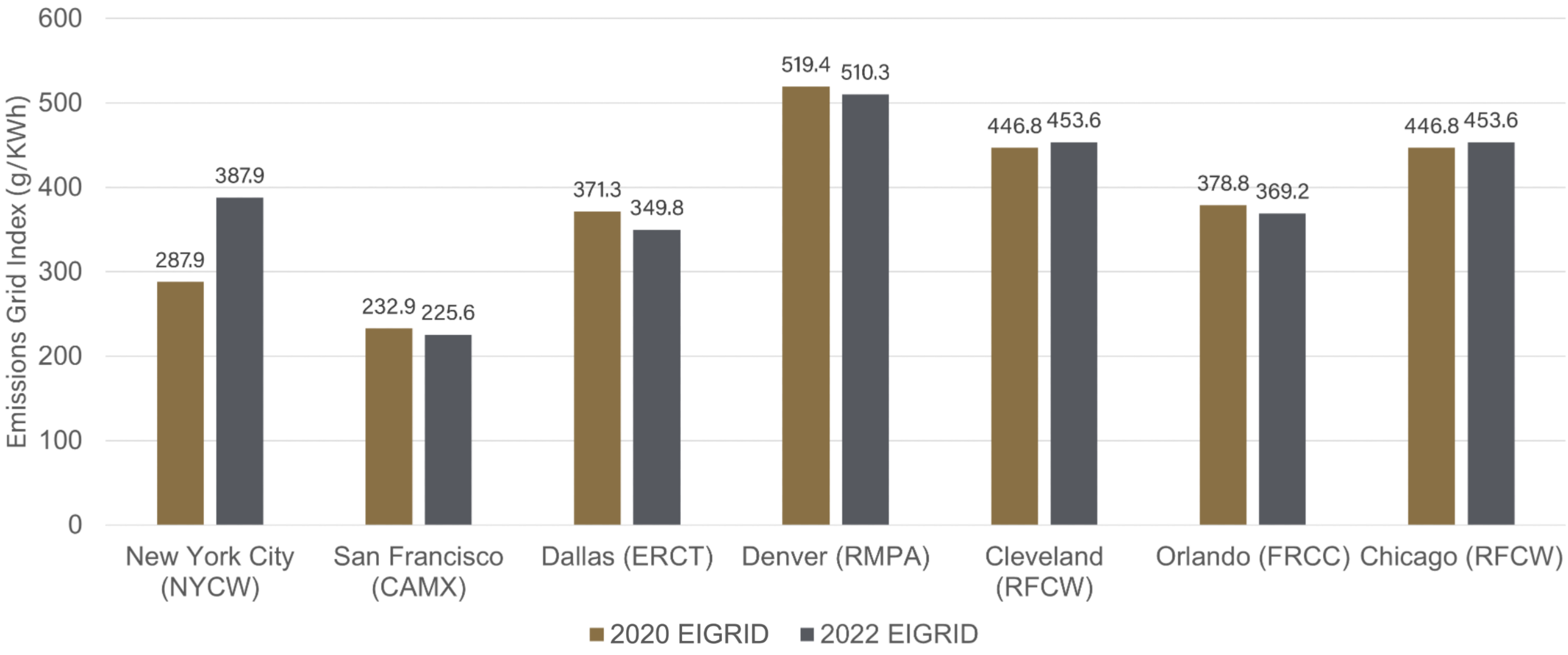


With UAM ridesharing

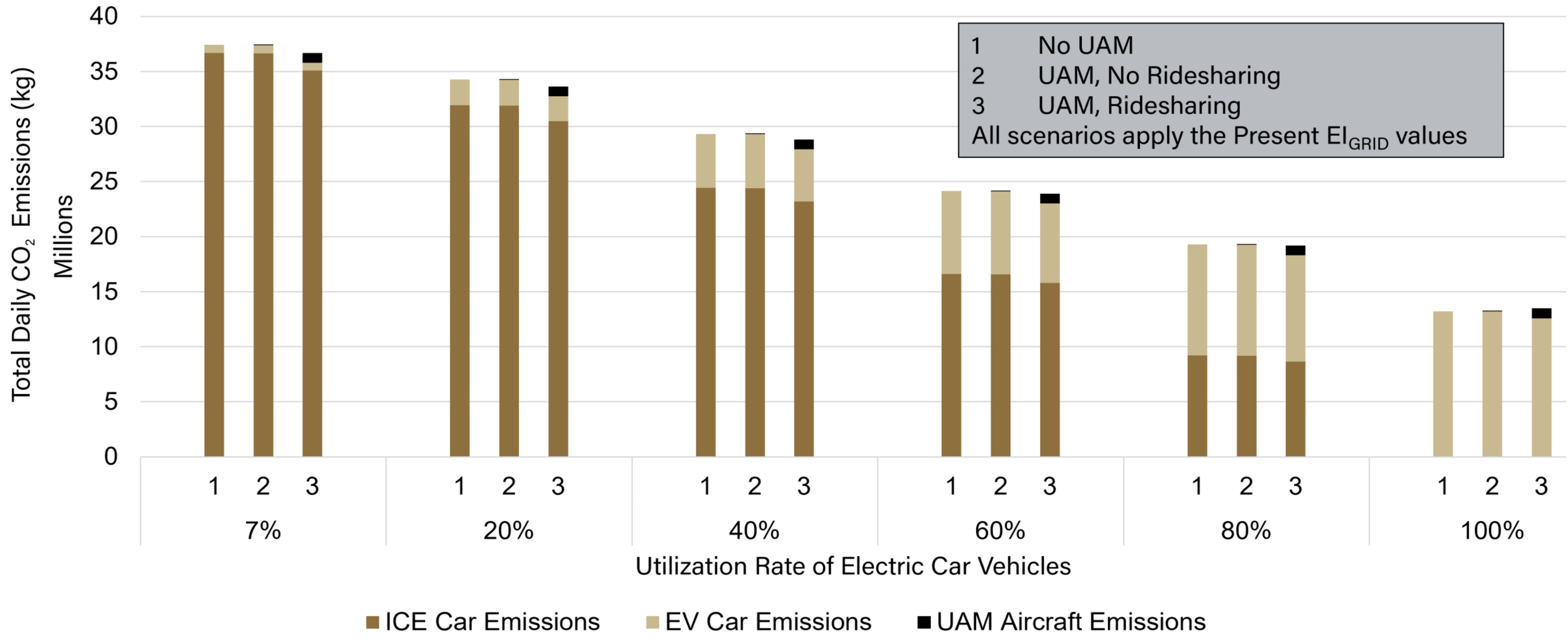
Chicago full 70-aerodrome network, Edsel et al. (2024)

The Grid Emissions Index

The grid emission index is the amount of CO_2 in kilograms that is emitted per kWh of electricity generated by the regional power grids



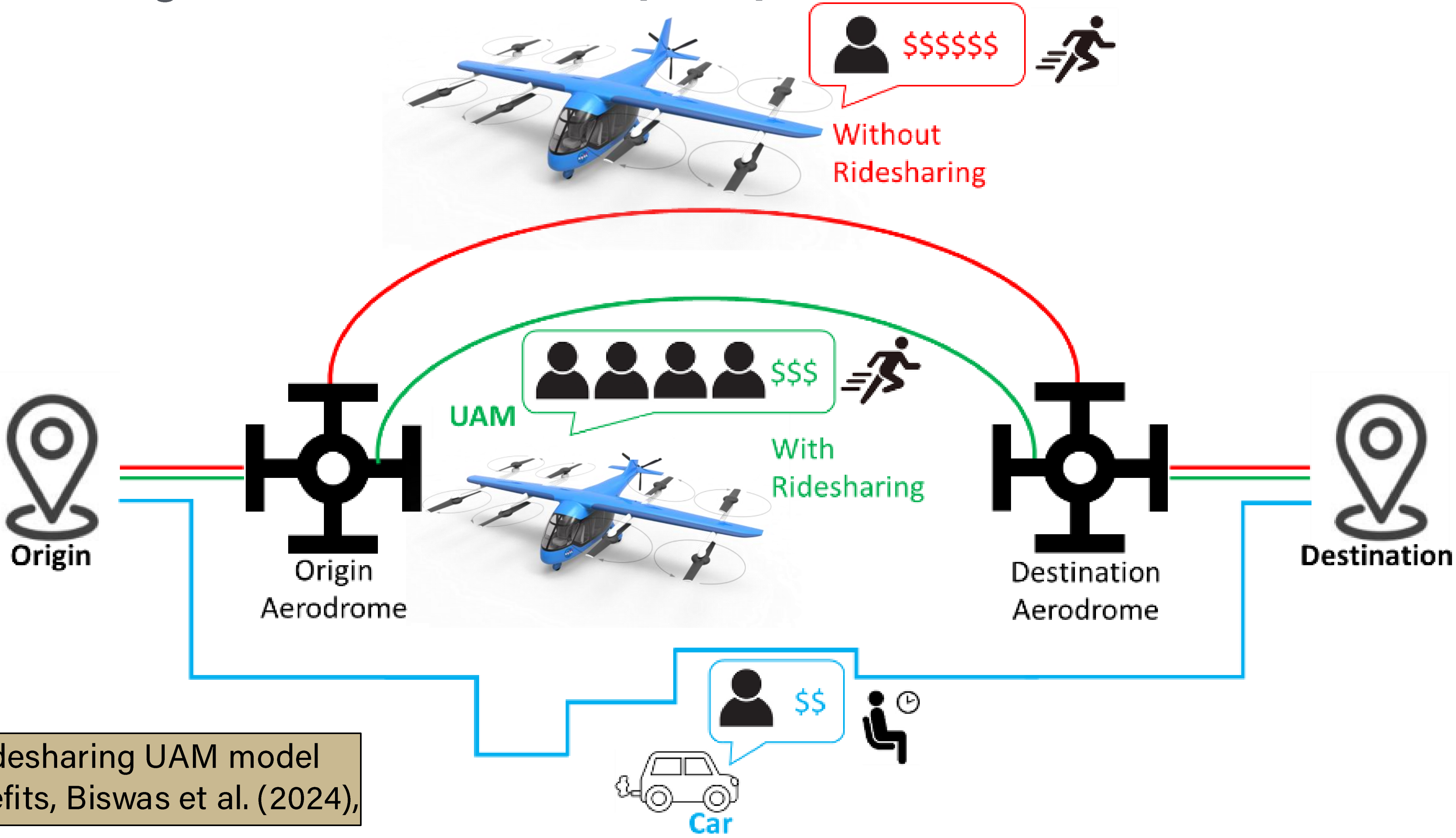
EV Utilization Rate Impact



A clear emissions reduction trend emerges with increasing EV utilization. In most cases, the implementation of ridesharing-enabled UAM results in small decreases in total daily emissions.

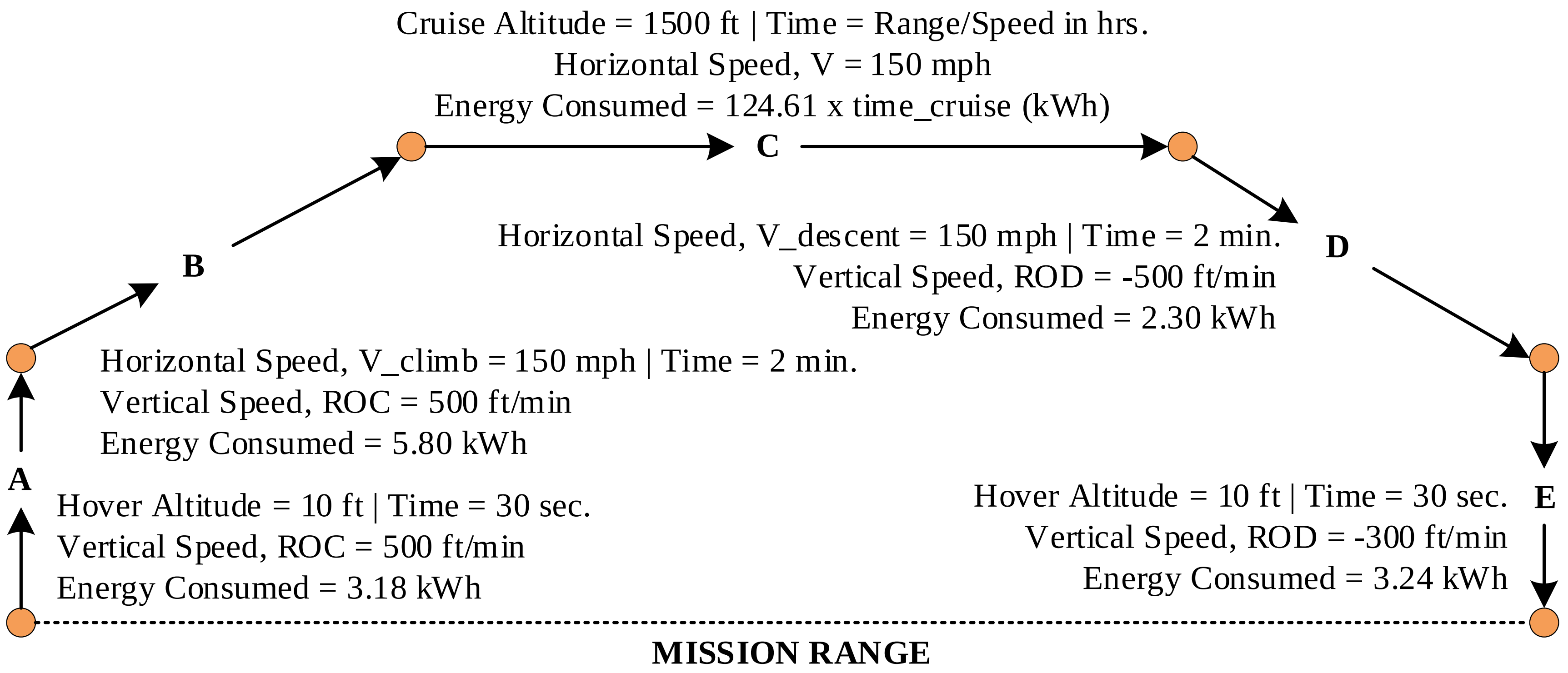
Ridesharing Models for UAM Networks

Passenger Aggregation Network with Very Efficient Listing (PANVEL) Ridesharing Model, Biswas et al. (2024)



Simplified ridesharing UAM model indicating benefits, Biswas et al. (2024),

UAM Aircraft Characteristics



Mudumba et al. (2021)

Passenger Capacity	Direct Operating Cost ($)	Nonstop Range (nmi)
4	605	50

Calculated Aggregated Emissions Per Metro Area

We perform a summation of each of these segments over all the trips in the travel network to obtain the emissions totals for each type of travel segment

1. Ground segment, Car mode, ICE Vehicle
2. Ground segment, Car mode, EV Vehicle
3. Flight segment, UAM mode, eVTOL Aircraft
4. Ground segments to/from aerodromes, UAM mode, ICE Vehicle
5. Ground segments to/from aerodromes, UAM mode, EV Vehicle

Calculating Emissions by Mode of Travel

$$E_{\text{mode,car}} = \sum_{i=1}^{N_{\text{EV,car}}} E_{\text{trip,EV},i} + \sum_{j=1}^{N_{\text{ICE,car}}} E_{\text{trip,ICE},j}$$

$$E_{\text{mode,UAM}} = \sum_{i=1}^{N_{\text{UAM}}} E_{\text{trip,UAM},i} + \sum_{j=1}^{N_{\text{EV,UAM}}} E_{\text{ADtrip,EV},j} + \sum_{k=1}^{N_{\text{ICE,UAM}}} E_{\text{ADtrip,ICE},k}$$

Calculating Emissions by Vehicle Type

$$E_{\text{type,EV}} = \sum_{i=1}^{N_{\text{EV,car}}} E_{\text{trip,EV},i} + \sum_{j=1}^{N_{\text{EV,UAM}}} E_{\text{ADtrip,EV},j}$$

$$E_{\text{type,ICE}} = \sum_{i=1}^{N_{\text{ICE,car}}} E_{\text{trip,ICE},i} + \sum_{j=1}^{N_{\text{ICE,UAM}}} E_{\text{ADtrip,ICE},j}$$

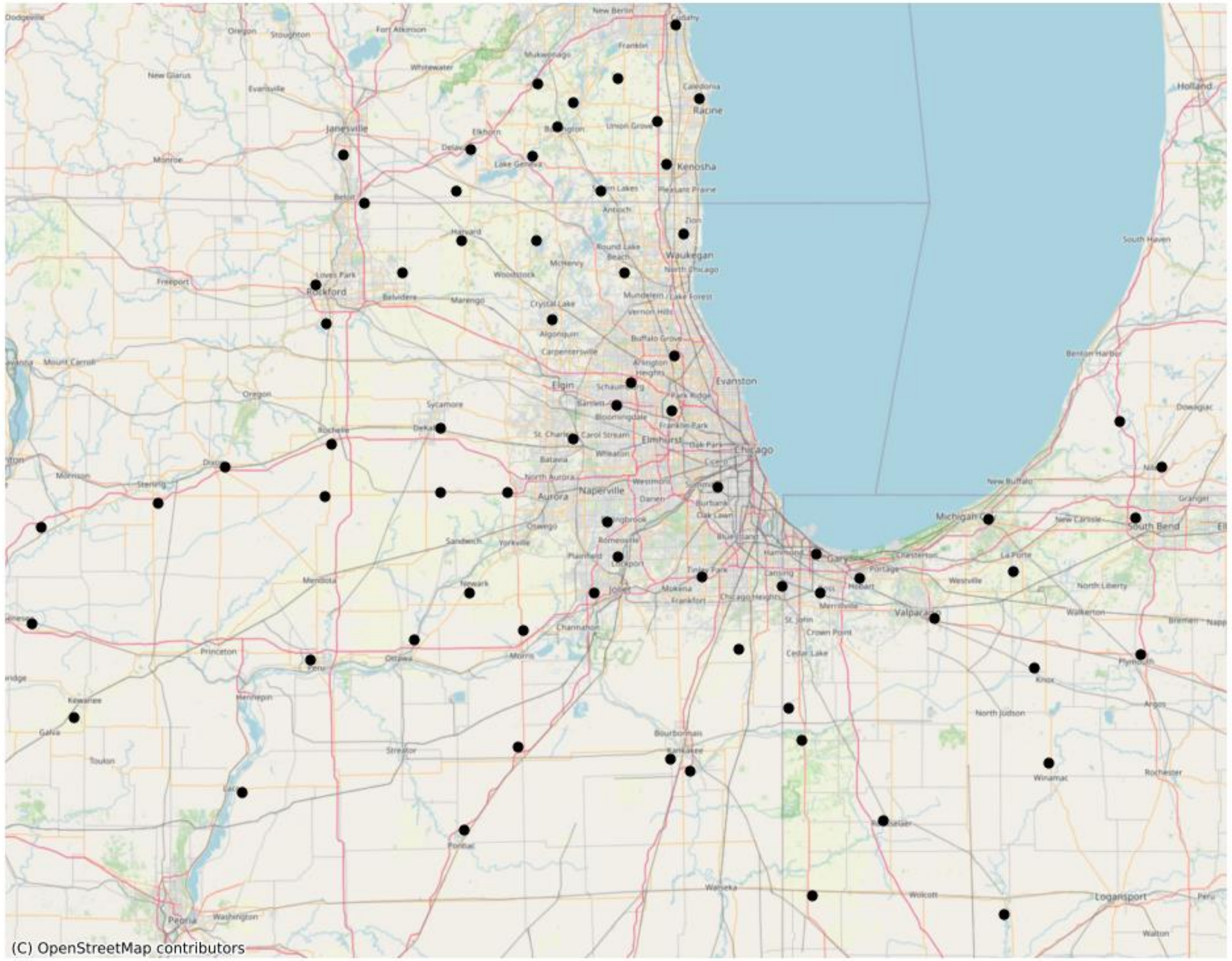
$$E_{\text{type,UAM}} = \sum_{i=1}^{N_{\text{UAM}}} E_{\text{trip,UAM},i}$$

Chicago Case Study Overview

Chicago full 70-aerodrome network for UAM services

Investigate effects of:

- modifying EV utilization rates
- applying ridesharing to UAM network
- modifying grid emissions index values on net transportation emissions
- Case Study Results
  - 8,627,698 daily trips in the Chicago metro area
  - 2,907 daily trips UAM-preferred
  - 154,093 daily trips UAM-preferred



Background map data © OpenStreetMap contributors
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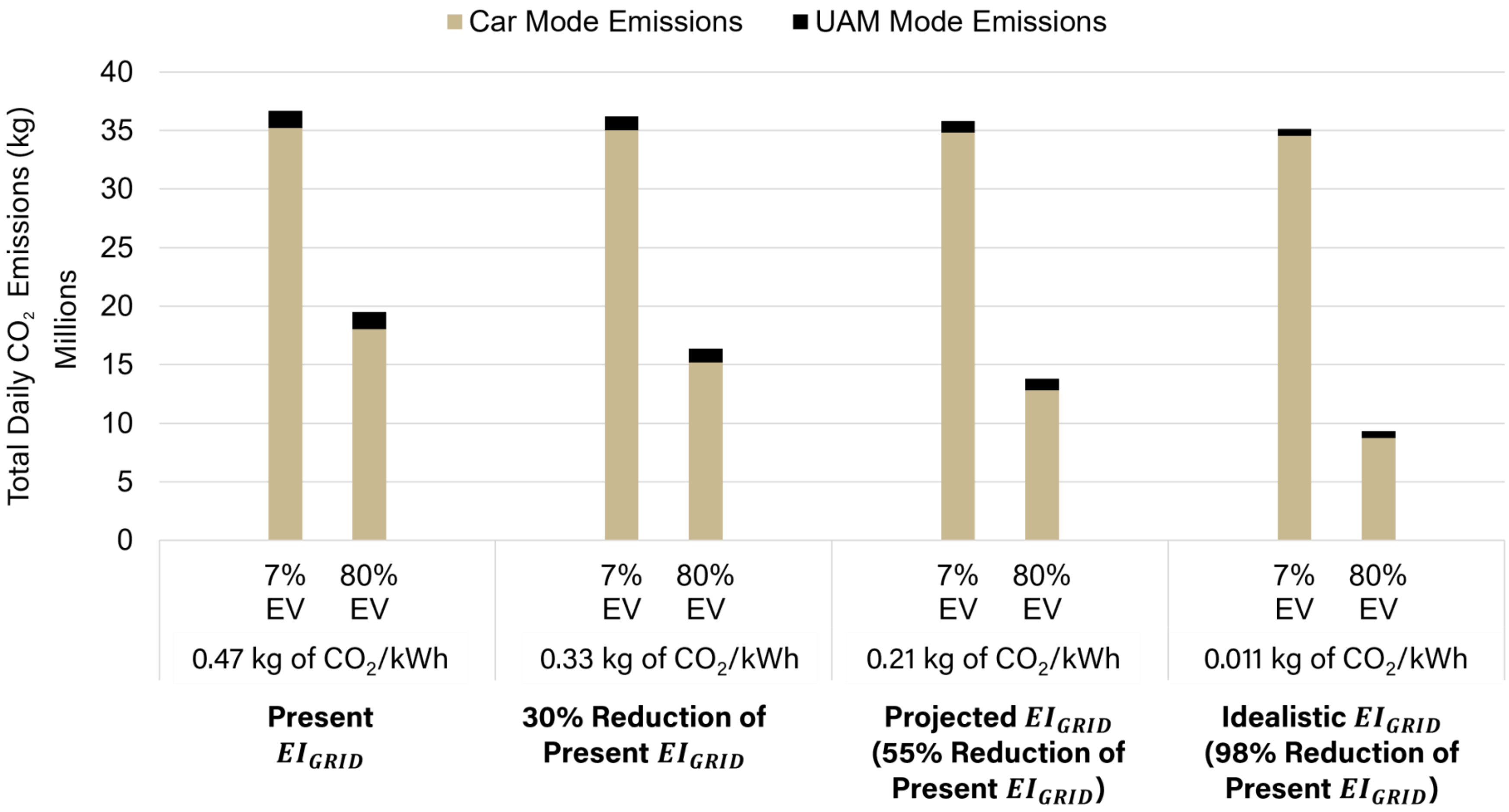
Scenario Descriptions

Scenario	UAM Applied?	Ridesharing Applied?	EV Utilization Rate (%)
1 (Baseline)	NO	NO	7
2	YES	NO	7
3	YES	YES	7
4	YES	YES	40
5	YES	YES	80
6	YES	YES	100
7	NO	NO	100

Impacts of Grid Emissions Index



Although there is a small decrease in total daily emissions across all scenarios with decreasing EI_{GRID} values, increasing EV utilization rates result in much larger total daily emissions decreases.

Scenario Results: By Vehicle Type

Scenario	EI_Grid Applied	ICE Vehicle Emissions (kg)	EV Vehicle Emissions (kg)	UAM Vehicle Emissions (kg)
Scenario 1: No UAM, 7% EV	Present	36,676,520	730,614	-
	Projection	36,676,520	329,871	-
	Idealistic	36,676,520	16,922	-
Scenario 2: UAM w/out ridesharing, 7% EV	Present	36,640,921	730,370	70,935
	Projection	36,640,921	329,760	32,027
	Idealistic	36,640,921	16,916	1,643
Scenario 3: UAM w/ ridesharing, 7% EV	Present	35,072,160	710,697	887,724
	Projection	35,072,160	320,878	400,805
	Idealistic	35,072,160	16,461	20,561
Scenario 4: UAM w/ ridesharing, 40% EV	Present	23,206,960	4,728,398	887,724
	Projection	23,206,960	2,134,860	400,805
	Idealistic	23,206,960	109,516	20,561
Scenario 5: UAM w/ ridesharing, 80% EV	Present	8,641,596	9,660,408	887,724
	Projection	8,641,596	4,361,651	400,805
	Idealistic	8,641,596	223,748	20,561
Scenario 6: UAM w/ ridesharing, 100% EV	Present	-	12,586,558	887,724
	Projection	-	5,682,800	400,805
	Idealistic	-	291,522	20,561
Scenario 7: No UAM, 100% EV	Present	-	13,206,667	-
	Projection	-	5,962,778	-
	Idealistic	-	305,884	-

Scenario Results: Total Emissions

Scenario	EI_Grid Applied	Total Emissions	Percent Difference from Scenario 1
Scenario 1: No UAM, 7% EV	Present	37,407,134	0.0%
	Projection	37,006,390	0.0%
	Idealistic	36,693,442	0.0%
Scenario 2: UAM w/out ridesharing, 7% EV	Present	37,442,227	0.1%
	Projection	37,002,709	-0.010%
	Idealistic	36,659,481	-0.1%
Scenario 3: UAM w/ ridesharing, 7% EV	Present	36,670,580	-2.0%
	Projection	35,793,843	-3.3%
	Idealistic	35,109,181	-4.3%
Scenario 4: UAM w/ ridesharing, 40% EV	Present	28,823,082	-22.9%
	Projection	25,742,626	-30.4%
	Idealistic	23,337,037	-36.4%
Scenario 5: UAM w/ ridesharing, 80% EV	Present	19,189,728	-48.7%
	Projection	13,404,052	-63.8%
	Idealistic	8,885,905	-75.8%
Scenario 6: UAM w/ ridesharing, 100% EV	Present	13,474,282	-64.0%
	Projection	6,083,605	-83.6%
	Idealistic	312,082	-99.1%
Scenario 7: No UAM, 100% EV	Present	13,206,667	-64.7%
	Projection	5,962,778	-83.9%
	Idealistic	305,884	-99.2%

Future Work

- Assessing emissions across more metro areas
  - Cleveland, OH
  - Dallas, TX
  - Denver, CO
  - New York City, NY
  - Orlando, FL
  - San Francisco, CA
- Assign more specific parameters to each metro
  - EV utilization rates
  - Grid emissions index projections
- Updates to ridesharing model may require recalculation of emissions

UAM ridesharing case study: Chicago

Large network (8,627,698 total trips, 70 aerodromes)

- With ridesharing: 154,093 passengers on 38,996 flights (1.79% of all trips)
  - Non-ridesharing: 2907 passengers on 2907 flights
- 730 flight routes carrying UAM-preferring passengers between 43 aerodromes
- 27 aerodromes do not have service