Passenger-Oriented Total Mobility Using Digital Engineering (PAX Mobility)

Opportunity Concept Report (OCR)

August 2024

Husni Idris, David Wagner, Malina Slizik, Abigail Glenn-Chase

[Sections originally generated by Chat GPT-4o are marked with an asterisk (*).]

Prelude

NASA aeronautics has an opportunity to unlock a new era of passenger-oriented mobility by developing end-to-end models using passenger-level data that seamlessly integrates aviation into a safe and sustainable transportation ecosystem.

The problem 2
The opportunity concept 3
The research question 3
The wicked problem space* 4
Stakeholder co-design outcome: aviation barriers identified 4
Why NASA? Why now? 6
Potential solution vectors 7
Road to demonstration 15
Potential CAS execution efforts and partners 17
Potential impacts 20
Stakeholders 21
Potential transition paths 21
Conclusion* 22
References 23
Appendix: Capability details 25

The problem

From the regular daily commute to the iconic family vacation, modern travel can be fraught with difficulties. Freeways become parking lots. Connections disconnect. Your luggage tours the world while you scavenge for a toothbrush in the middle of the night. It's almost enough to work fully remotely, self-quarantine, vacation in the realm of virtual reality, and abandon your freedom of movement to apps and their professional gauntlet runners.

How often do we find ourselves stranded both in normal day-to-day travel, and especially during disruptions due to weather or significant events, unable to make it to our destination on time? How often do we find ourselves missing a medical appointment or an important work meeting or a vacation because of limitations in mobility and access? How often does it seem that there are not enough mobility options? How do these limitations and frustrations affect underserved versus affluent communities? How will rural communities respond to increasingly dangerous disaster scenarios like wildland fire?

The main problem addressed in this work is how complicated, time-consuming, frustrating, uncomfortable, and expensive it can be to efficiently navigate door to door using local, regional, and national transportation systems. Itineraries will become more complicated as advanced air mobility is integrated into an increasingly autonomous and multi-modal transportation system. It is NASA's mission to ensure that the advent of advanced air mobility does not exacerbate complexity, inefficiency, and inequity, but rather alleviates them, improving accessibility to services. It is time to relieve traveler pain points and increase freedom of movement in a total door-to-door mobility ecosystem for the benefit of humanity.

Traveler pain points

Some of the many travel difficulties that travelers regularly encounter are listed below.

- Cost
- Inconvenience
- Travel and wait times
- Lack of accessibility
- Lack of seamless connectivity
- Inequities
- Discomfort
- Complex trip planning
- Confusing per-mode costs and payment
- Difficulty comparing routing alternatives
- And many others…

These problems persist despite technological advances. What is needed is a paradigm shift that transforms the problem and illuminates new solutions.

The opportunity concept

A transformational paradigm shift towards passenger-oriented total mobility (PAX mobility) will ease traveler pain points through aviation integration.

PAX mobility addresses the passenger experience directly to overcome barriers and relieve pain points such as cost, inconvenience, travel and dwell times, lack of accessibility, inequities, discomfort, and other aspects important to travelers.

PAX mobility

To achieve this paradigm shift, several key barriers were identified through co-design conversations with key stakeholders from transportation governance, academia, and industry. NASA has the opportunity to reduce these barriers through innovative research and integrated passenger-oriented solutions.

PAX mobility is an opportunity for NASA aeronautics to unlock a new era of passenger-oriented mobility by developing end-to-end models using passenger-level data that enable aviation to seamlessly integrate into a safe and sustainable transportation ecosystem.

Opportunity concept

This opportunity leads directly to a corresponding research question.

The research question

By seizing this opportunity, NASA aeronautics can begin to transform passenger transportation by answering the following research question.

Through the use of end-to-end models using passenger level data, how much would integrating aviation into a seamless transportation system improve accessibility and relieve traveler pain points?

Research question

This broad research question becomes more specific while planning for the demonstration of a PAX mobility minimum viable product (MVP). With this MVP, NASA aeronautics takes the first step to transform passenger travel and better integrate advanced air mobility (AAM) operations into the transportation ecosystem. Stakeholder co-design sessions informed the selection of potential solution vectors, detailed later in this document, that combine to address this wicked problem.

The wicked problem space*

Navigating the wicked problem space of contemporary transportation systems is akin to untangling a Gordian knot of complexity. At its heart lies a landscape where multiple, interdependent modalities—each with its own operational nuances—vie for efficiency, ridership, and integration. These systems, diverse in their functions and jurisdictions, often find themselves ensnared in a web of incompatible protocols and competing interests, making the journey from point A to B an exercise in patience and endurance for the traveler.

The architecture of today's transportation network has evolved in an ad hoc manner, leading to a primarily infrastructure-centric model. Data, often vehicle-centric, informs development and implementation strategies, whereas passenger experience, and its corresponding data, has historically been a secondary consideration. This creates a manifold problem, further exacerbated as we usher in an era of AAM, which promises to weave yet another thread into the already intricate fabric of our transportation systems.

The challenge, therefore, involves not simply the integration of new modes of mobility but the harmonization of the entire ecosystem – airplanes with automobiles, trains with trams, and everything in between. It is about cultivating a system that resonates with the rhythms of those it serves, adapting to changes while safeguarding the seamless flow of both people and information.

The wickedness of this problem space is multi-dimensional: from tackling the labyrinth of overlapping jurisdictions to aligning disparate infrastructure and operational paradigms; from fostering public-private collaboration to breaking through barriers of privacy and proprietary restrictions. It necessitates not just technical solutions but a reimagining of our conceptual frameworks, the fostering of innovation hubs where siloed processes give way to interoperable systems and where the transit experience becomes a symphony of coordinated movement, rather than a cacophony of disjointed legs of a journey.

As daunting as it may seem, addressing this wicked problem space is essential. It is the key to unlocking an era where the entire transportation ecosystem is designed and built for human mobility. It is about ensuring that, as we navigate both our daily commutes and the occasional voyage, the systems that facilitate our movement are as fluid and adaptable as the lives they seek to serve. Untangling the travel ecosystem requires the diverse perspectives of many transportation stakeholders and subject matter experts (SMEs).

Stakeholder co-design outcome: aviation barriers identified

Conversations with over 25 transportation stakeholders and subject matter experts helped identify barriers to mobility and accessibility from a passenger perspective. The stakeholders included the Bay Area Metropolitan Transportation Commission (MTC), Contra Costa County and San Francisco County transportation planning teams, the Port Authority of New York and New Jersey, and authorities in Washington State, Alaska, and Texas. Several academic SMEs also contributed their thoughts, including researchers from the University of California, Berkley, Massachusetts Institute of Technology, University of Texas at Austin, University of Michigan at Ann Arbor, and the medical department of the University of California San Francisco.

The PAX mobility team discussed several journeys with stakeholders to identify pain points. These included, for example, remote patients traveling to a major medical center, super commuters across county boundaries, and students traveling to remote campuses. Based on these discussions, the local, regional, and national transportation networks face several systemic issues that are barriers to rapid and widespread adoption of AAM. The following are some highlights.

- As different modes of transportations evolved over time and communities were built, transportation gaps appeared, separating communities, and increasing travel time. For example, communities were built around rail systems; when highways were built these communities had to travel longer to the highway while the rail system became underused. As AAM is introduced, transportation gaps should be reduced rather than increased, improving accessibility, and reducing travel time.

- **Underserved communities,** including Native populations, are often limited to road transportation with disadvantages in terms of road infrastructure, land use, and high rate of highway accidents.

- New trends such as **remote work and remote health care**, enabled by the digital transformation, have allowed people to move away from costly urban centers, resulting in longer trips that are often limited to ground transportation options that are prohibitive from cost, convenience, and even health perspectives (such as a remote patient with a home clinic having to rush to the hospital for urgent care).

- These trends are also causing **unbalanced use** of the different modes of transportation. For example, because of the increase in remote work and home deliveries, the **transit systems are underutilized and underfunded** while the highways are at unprecedent levels of congestion.

- **Small airports are often underutilized** and neglected resulting in the lack of their readiness to respond to disasters for example. These airports can be revitalized with regional air mobility options and used to connect to other transit networks. They can be outfitted, for example, with **multi-modal charging nodes**, increasing revenue by capitalizing on the expected dominance of electric charging across the different mobility modes (aircraft, buses, ferries, etc.).

- Passenger transfer between different means of transportation is often hindered by the inability to use the same ticket over multiple modes, or even multiple operators of the same mode. Issues of **operator interoperability** and **public-private interoperability** exacerbate this issue. The seamless transition of passengers is also hindered by the **lack of passenger data sharing**, which is limited by **privacy and proprietary restrictions**.

- **Focused growth of communities** is often considered by urban planners to balance environmental impacts with travel and accessibility needs. There is a strong need for metrics and models to enable proper tradeoff **assessments of total impacts,** including time, cost, green house effects, equity, and others. Aviation is missing from other multi-modal models.

- The communication between the aviation community and the communities of the other modes is lacking due to a history of **siloed culture and disconnected operations**. Successful integration of AAM will hinge on better communication and more robust collaboration.

Several SMEs also identified ongoing transportation planning efforts that include the introduction of AAM and have needs that align with one or more of the NASA Aeronautics Research Mission Directorate (ARMD) strategic thrusts.

- **Strategic Thrust 1**: Safe, Efficient Growth in Global Operations
- **Strategic Thrust 4**: Safe, Quiet, and Affordable Vertical Lift Air Vehicles
- **Strategic Thrust 5**: In-Time System-Wide Safety Assurance
- **Strategic Thrust 6**: Assured Autonomy for Aviation Transformation

Alignment of ARMD strategic thrusts with stakeholder needs to support ongoing transportation planning indicates the benefit of prompt NASA participation.

Why NASA? Why now?

NASA has an opportunity to play a key role in addressing the wicked problem of PAX mobility and alleviating the associated barriers described above for the following reasons.

- Individual stakeholders are not likely to invest in the fundamental and overarching research necessary for the paradigm shift proposed by PAX mobility.
- NASA has expertise in several areas necessary for this research effort, including air transportation analysis, modeling and management capabilities, data science and AI/ML methods, simulation and digital twins, autonomy, and high-performance computing capabilities.
- Transportation stakeholders are siloed while the ecosystem becomes more integrated. NASA can play a convener role, bringing together the aviation and other stakeholder communities and facilitating the communication and collaboration between them.
- NASA supports AAM adoption as a benefit for all. In addition, PAX mobility may lead into innovative advancements in aviation beyond AAM as it looks to close the transportation gaps between communities.

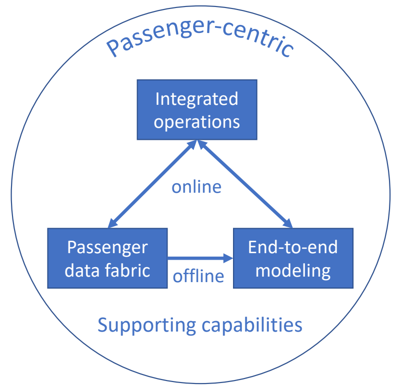
PAX mobility is a timely undertaking for the following reasons.

- Some regions are already planning AAM infrastructure. Planners require AAM integration research now to meet development needs and ensure correct long-term decisions based on proper assessments of passenger-oriented total mobility impacts.
- Air transportation integration is outpaced by other modes. Integration of AAM is an opportunity to close this gap and establish a less-siloed culture.
- Some stakeholders have recently adopted passenger-centric approaches and similar practices are gaining momentum. NASA should be at forefront of this wave.

As is often the case when taking the first step toward solving a wicked problem, there are several potential approaches. Research can begin immediately by weighting and combining one or more solution vectors that point toward the solution.

Potential solution vectors

Minimum viable prototype (MVP) models and simulations can be developed to answer the research question. The MVP models integrated operations on top of two supporting capabilities, a passenger-level data fabric and end-to-end modeling, illustrated at right. The combination of these supporting capabilities with each potential integrated operations solution forms several potential solution vectors (research directions). Four potential solution vectors are described in the next sections.



1. Resilient, integrated, end-to-end multi-modal planning
2. Seamless mobility through transition nodes
3. Network autonomy across multi-modal networks
4. Dynamic multi-modal infrastructure and resource sharing

The MVP models several interrelated aspects of transportation and helps quantify the benefits of PAX mobility vectors. Prioritization of MVP capabilities is done by weighting each solution vector when combining them to form a research plan. How solution vectors are combined also determines the degree of supporting capabilities needed. Two supporting capabilities are:

- A passenger-level **data fabric** provides passenger information to support both **offline** evaluation and **online** decision making.
- Integrated network **models** build on the passenger data fabric and enable development and evaluation of **integrated operations** from a passenger end-to-end perspective.

Note that while the integrated operations vectors are different from each other, they share a common underlying model of an integrated network of aviation and other modes of mobility enabled by a passenger-level data fabric. This underlying integrated network represents a holistic closed ecosystem in which people circulate as they travel door to door. People (passengers) constitute the core element of the ecosystem, which requires the integration of all modes of mobility.

Passenger-level data and integrated-network modeling capabilities underlie reasoning solutions that integrate aviation with other modes for end-to-end passenger-centric operations. Several vectors offer different opportunities for integrated solutions requiring NASA expertise. For all these vectors, NASA is uniquely qualified and positioned to develop specific solutions and study the effectiveness and total impacts of these solutions using the data fabric and modeling capabilities. These vectors are described below along with their desirability, viability, feasibility, and wickedness (DVFW) characteristics. Please see the appendix for descriptions of the data fabric and end-to-end modeling supporting capabilities.

Potential solution vector 1: Resilient, integrated, end-to-end multi-modal planning

In this vector we imagine a future where people can make choices to travel from their origin door to their destination door using aviation as an option as easily as the other mode options such as car, train, ferry, bus, etc. Strategically placed nodes serve as transfer centers where passengers can conveniently transition between modes. Their itineraries allow them to make changes across modes and operators as their needs entail. The passengers are expedited and prioritized in the network to keep the overall travel time and environmental impact below desired thresholds. This future requires building several capabilities that, in turn, require breaking several barriers. Some key ones follow.

- A data fabric that establishes a taxonomy and language among the different modes, including aviation, and to share passenger information among different operators and different service providers. The passenger-level data fabric requires breaking barriers of privacy, propriety, and public-private interoperability among others.
- A network of networks framework and model that integrates the aviation network with the other modal networks to allow seamless dynamic planning across modes, end to end.
- Reasoning and decision making that include the passenger object as the core element circulating through the network. This is a paradigm shift from the flight object being the core element in current traffic management planning in aviation.
- The integration of transition dynamics across multi-modal nodes with the transition dynamics across links between nodes. The former involves passenger connectivity, vehicle turn operations, and fleet management, which are typically handled by operators. The latter involves traffic management which is typically handled by service providers managing the airspace and ground infrastructure resources. The integration of these siloed processes is a paradigm shift that again requires breaking propriety, security, public-private responsibility/accountability barriers, among others.

From the passenger perspective, multi-modal integration of aviation offers more flexibility and freedom of movement. An integrated ecosystem offers better connectivity between communities and better accessibility for underserved communities. For example, tailored mobility options will allow people to take a job or receive a service from further locations or provide more access to passengers with personal or physical disabilities without changing home residence. In addition, added flexibility offers more resilience to many types of disruptions, such as the ability to circumvent weather disruptions with other transport options and greater freedom of movement during disasters such as earthquakes that shut down ground transportation.

NASA-conducted research will answer key research questions and develop solutions to answer wicked questions: Where should aviation be placed within the eco-system to better connect communities end to end and prepare them for disruptions? How do we measure the total impacts of such integrated planning solutions in terms of physical mobility and its effect on the economy, society, and the environment? What information sharing, modeling, and reasoning capabilities are necessary to allocate passengers effectively across the different modes under different conditions and disruptions?

NASA can achieve this vector by demonstrating MVP simulations for resilient, integrated, end-to-end multi-modal planning, including the following.

- Develop concepts, requirements, and algorithms for integrated end-to-end planning while prioritizing passenger needs.
- Demonstrate real-time integration of transition/turn node dynamics (passenger and fleet management typically performed by operators) with link dynamics (traffic management within and across modes typically performed by service providers).
- Apply the integrated planning in both nominal conditions to improve equitable accessibility and in off-nominal conditions to improve safety and resilience to major disruptions.
- Recommend architecture and requirements for secure passenger data sharing across modes.
- Build towards a total mobility operations system (TMOS), which provides a kernel and applications for distributed but cooperative, interoperable, and scalable planning across aviation and the other modes.

Desirability

- Prioritize passenger equity, affordability, and accessibility needs at individual and community levels.
- More dynamic mobility options increase resilience to disruptions.
- Transportation authorities and academics indicated a need for layering aviation network models with other mobility models and for key performance indicators (KPIs) to quantify total end-to-end benefits and tradeoffs for passengers and society.

Viability

- Regulatory changes will be required in some cases to enable public-private compatibility, data sharing, resource sharing responsibilities, etc.
- Several Bay Area transportation stakeholders are willing to share data (non-reimbursable).
- Some percentage of passengers is likely to share their travel status and intent at low or no cost.
- NASA models and algorithms can be transitioned to stakeholders (industry, government, etc.) for use and maintenance.

Feasibility

- Passenger data fabric and end-to-end models leverage and extend existing architectures and models within and outsides NASA and can be utilized across integrated operations solution vectors.
- Integration efforts for other modes indicate feasibility; adding aviation poses technical challenges due to its dissimilarity to the other modes.

Wickedness

- Integrated multi-modal operations are a larger scale and more complex problem involving system of systems.

- Integrated end-to-end planning requires a data fabric across modes resulting in a very complex data architecture.
- Integration between siloed traffic management problems and operator fleet/passenger management problems requires breaking data sharing and private-public barriers.
- Aviation poses different challenges such as more complex security concerns and procedures.

Potential solution vector 2: Seamless mobility through transition nodes

In this vector we envision a future where the network of multi-modal networks described above includes nodes that allow seamless and frictionless transition of passengers, equitably expediting passengers who are in need while reducing the transition time and uncertainties to desirable targets much lower than in today's operations. While the previous vector focused on integrating the transition point dynamics into the overall end-to-end dynamics, this vector makes this integration more effective by tracking and sharing passenger information through the nodes and understanding the transition point dynamics, which include operator fleet management, vehicle turn around, and passenger connectivity at each transition point. The transition of passengers at multi-modal nodes between multi-modal trip segments is a major pain point where delays occur and propagate, safety and security are compromised, and uncertainties accumulate. For example, in today's commercial air transportation system, on-time performance targets are set at plus-minus 15 minutes of scheduled arrival times because, in part, the standard deviation of pushback times at origin airports is also of a similar magnitude. Therefore, on-time performance will only improve if operators reduce uncertainties of the transition through the airports.

This future requires breaking several barriers enabling the following capabilities.

- The passenger-level data fabric mentioned in the previous vector must include information on passenger status *through* the transition nodes and not just at the inputs and outputs.
- The network-of-networks models mentioned in the previous vector must include high-fidelity models of the transition dynamics through the nodes to reduce uncertainty and improve predictability.
- Concepts and technologies are necessary for circumventing sources of friction at the nodes, such as heterogeneity in security requirements between aviation and other modes, interoperability between private and public services, multi-operator dynamics and interoperability, and others.

NASA can answer key research questions and develop solutions to mitigate key barriers. Planners need to be able to understand and characterize the transition pain points to identify key barriers that make the transition points painful particularly for aviation (e.g., the high security requirements and the heterogeneous public-private services). They must also be able to identify solutions to mitigate these transition pains, which include regulatory as well as technological solutions. Finally, planners will need to develop solutions that respond to passenger needs through the transition point (e.g., prioritizing and expediting late passengers with excessive, unfairly incurred delay).

NASA can achieve this vector by demonstrating MVP simulations for seamless mobility through transition nodes, including the following activities.

- Develop concepts, requirements, technologies, and algorithms for alleviating friction/pain points during transition at multi-modal nodes.
- Improve tracking and information sharing for passengers, operators, vehicles, and services, including energy charging, not only at the input and output of nodes but during the transition through the nodes, to reduce transition/turn uncertainties and propagation effects.
- Incorporate passenger needs at the individual and aggregate passenger levels in expediting passengers through the transition nodes.
- Develop and incorporate novel concepts and technologies for circumventing sources of friction such as heterogeneity in security requirements, private-public services, multi-operator dynamics and interoperability, among others.

Desirability

- Reduce time and effort spent waiting and transitioning at the multi-modal nodes rather than time spent moving.
- Reduce uncertainties at their most significant source – the volatility of transition processes at nodes.
- Reduce propagation of delays and security breaches through transition nodes.

Viability

- Cost saving across modes are expected due to common data fabric, better on-time performance, and higher load factors.
- Regulatory changes may be required to enable public-private compatibility, data sharing, resource sharing responsibilities, liability, etc.
- Several Bay Area transportation stakeholders are willing to share data (non-reimbursable).
- At least some percentage of passengers is likely to share their travel status and intent at low or no cost.
- NASA models and algorithms can be transitioned to stakeholders (industry, government, etc.) for use and maintenance.

Feasibility

- Seamless transition relies on the ability to share passenger level information across different modes, operators, and service providers.
- It also relies on streamlining technologies for security screening, baggage handling, payment, etc., across different modes and across public and private providers.
- Seamless mobility as a service is feasible for other modes, while aviation integration remains a challenging outsider.

Wickedness

- Aviation poses challenges of much higher magnitude, such as security and safety concerns.
- Seamless transition through multi-modal nodes involves wicked dynamics to coordinate diverse operator models, public-private providers, information privacy and proprietary barriers, and liability issues, in addition to technological and logistical advancements.

Potential solution vector 3: Network autonomy across multi-modal networks

In this vector we envision a future in which autonomous operations and processes enable higher degrees of integration of aviation with the other mobility modes. The integration of aviation with the other modes, as described in the previous two vectors, results in a complex network of networks that is very difficult to manage by a human-centric approach. Therefore, autonomy building on the digital transformation are key enablers of the increased integration of aviation with the other modes and the ecosystem. This future requires breaking challenging barriers and enabling several additional capabilities, some key ones are:

- Network-level autonomy applies advanced self-monitoring and self-operation technologies across the interconnected networks of the multiple mobility modes. For example, self-monitoring technology can detect precursor gridlock and hazard onsets and the potential propagation of gridlock and hazards from one mode (such as in the ground transportation network) to another (such as the air mobility network). Network-level autonomy also includes self-mitigation capabilities to prevent these propagation effects and ensure persistent passenger flow circulation through the inter-connected networks.
- As autonomous vehicles become abundant and dominant in all modes (both in the air and on the ground), technology must be developed to enable self-monitoring and self-operation of vehicles and swarms consisting of vehicles of different modalities. The human role becomes supervisory control where one (or a team of) human(s) supervise a multi-modal fleet of vehicles.

NASA can conduct research leveraging its extensive expertise in autonomy to address network level issues such as potential gridlock in multi-modal networks and its mitigation through integration of aviation. NASA can develop capabilities for persistency and resilience of self-operating networks. (This type of research may even scale to multi-modal space operations in space robotic colonies and habitats, where the level of autonomy is necessarily high.)

NASA can achieve this vector by demonstrating MVP simulations for network autonomy across multi-modal networks, including the following.

- Develop concepts and capabilities for increasingly autonomous tracking of passengers and vehicles, automated digital information exchange (machine to machine, multi-modal IoT), and multi-modal network self-management.
- Develop methods and technologies for self-monitoring and detection of the onset of hazards and threats, delay propagation, gridlock instabilities, security breaches, etc., across multi-modal networks.
- Develop methods for self-mitigation and cooperative management of these risks across the different mobility modes.

- Investigate methods and technologies to support the supervisory control of a fleet of vehicles from different modes, including air and ground vehicles.

Desirability

- Managing a multi-modal network of networks is too complex for human-centric operations. A high level of autonomy is necessary for end-to-end monitoring, supervision, and management across mobility modes.
- Transportation authorities in the Bay Area and many other locations are proactive in introducing autonomy for ground vehicles with safety and scalability benefits. The introduction of AAM is forthcoming; these vehicles will be abundant in the envisioned future. More advanced autonomy tools must be developed to manage the interactions across the different mobility modes.

Viability

- Industry is pursuing autonomous air cargo-delivery, which can be extended end-to-end and scaled to passengers.
- NASA algorithms for network-level autonomy, such as precursor gridlock and hazard detection, can be transitioned to stakeholders (industry, government, etc.) for use and maintenance.

Feasibility

- Network autonomy relies on the ability to track and share passenger level information across different modes, operators, and service providers.
- It also relies on integrating automation for security screening, baggage handling, payment, etc., across different modes and across public and private providers.
- Autonomy is proving to be feasible for other modes; autonomy in civil aviation is expected to start with cargo operations and will be a more difficult challenge for passenger operations.

Wickedness

- Aviation poses challenges of much higher magnitude, such as security and safety concerns.
- While autonomy is seemingly within reach for single vehicles or swarm of vehicles, network-level autonomy that self-manages gridlock propagation and ensures persistent flow circulation remains a tough future challenge that is largely overlooked.
- Multi-vehicle supervision is still in its infancy, even for supervising multiple vehicles of a single mode. The military is researching supervisory control of multiple vehicles of different mobility modes.

Potential solution vector 4: Dynamic multi-modal infrastructure utilization and resource sharing

In this vector we envision a future where aviation is used ubiquitously to get anywhere from anywhere. In this future multi-modal air-ground transition nodes can be placed dynamically almost anywhere, providing ubiquitous access to air mobility and its integration with the rest of the mobility modes. The dependence on static and complex infrastructure is reduced to a minimum. New types of multi-modal vehicles, such as planes that can land on roads, on railways or in the water and turn into ground vehicles, are accommodated, and integrated into the total mobility system. In addition, users share vehicles and crews, extending the ridesharing models to air mobility and providing better utilization and mitigating the worsening shortage of these resources. This future offers greater utilization of underutilized infrastructure and induces mobility and travel that is otherwise dormant. A lot of infrastructure and operational resources already exist, such as vehicles and crews that are underutilized. With better utilization, passenger mobility can benefit greatly. In addition to harnessing aviation to reduce congestion and improve connectivity between communities, aviation can be used to induce more people to travel and using aviation. An uptick in travel would have economic, social, and environmental impacts, all of which should be assessed and accounted for from a passenger-oriented perspective in PAX mobility.

This future relies on new capabilities and paradigm shifts that in turn require breaking challenging barriers including the following key examples.

- Paradigm shifts enable sharing of operator resources, e.g., pilots, crews, vehicles, and hubs among operators, requiring new concepts and technologies, as well as appropriate regulatory, certification, and business models as to how resources are owned, shared, and operated.
- Reducing the dependence on a complex and static infrastructure enables air mobility from anywhere to anywhere and futuristic multi-modal vehicles. This includes technologies to enable the dynamic placement of vertiports and multi-modal stations along with appropriate regulatory, certification, and business models.
- Extending the use of infrastructure and resources during idle or night times while leveraging autonomy in conjunction with appropriate regulatory and business models.

NASA can conduct research to answer key research questions, including: what technologies, procedures, and regulations are needed to enable anywhere to anywhere air mobility? How can we simplify landing and takeoff operations to be as independent of infrastructure as possible and thus to be performed at any dynamically located multi-modal node? How can we best integrate multi-modal vehicles that combine air and ground mobility? What technologies, regulations, and business models will maximize sharing of vehicles, pilots, crews, and other resources?

NASA can **achieve this vector by** demonstrating MVP simulations for dynamic multi-modal infrastructure utilization and resource sharing.

- Extend trends in ride and code sharing to sharing of assets (vehicles), operators, and hub/station resources for added flexibility and resilience.
- Extend operations to underutilized or idle resources, including smaller airports, multi-modal stations, and nighttime hours.
- Invoke new or reinvigorate dormant travel by introducing aviation with novel cost structures and business models.
    - Reverse trends in lower transit utilization.

    - Support economic growth with climate awareness.
- Enable and integrate new multi-modal vehicles for anywhere-to-everywhere mobility.
    - Incorporate more infrastructure-independent modes like personal vertical takeoff.
    - Enable new multi-modal vehicle concepts (air-ferry, air-rail, etc.).

Desirability

- Transportation authorities indicated interest in inducing new demand and reversing underutilization trends of infrastructure and resources.
- Dynamic multi-modal nodes and resource sharing will provide a higher level of accessibility and enable anywhere-to-anywhere travel.
- More flexible infrastructure-independent options and shared utilization of operational resources such as vehicles and crews will increase resilience to disturbances.

Viability

- New, potentially disruptive, business models may emerge, e.g., sharing pilots and assets among airlines and operators.
- Regulatory changes will be required to enable public-private compatibility, resource sharing responsibilities, liability, etc.

Feasibility

- New technological developments are needed to better collocate modes at multi-modal transition nodes, make air-ground transition nodes easy to locate dynamically, and make infrastructure easier to use for landing/takeoff sites or landing/takeoff more independent of infrastructure.
- Simplified ubiquitous takeoff and landing procedures that can be applied almost anywhere rather than at dedicated ports may require new standards.

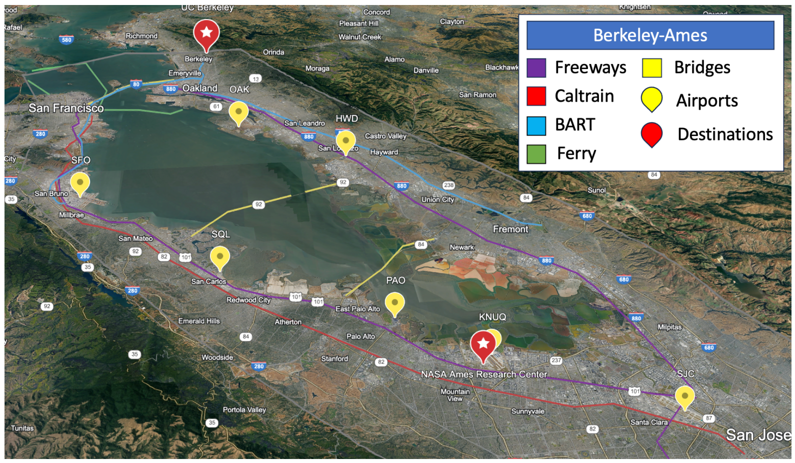
Wickedness

- Some solutions are quite disruptive and require regulatory and even cultural adjustments, such as public acceptance of frequent air travel, pilots as freelance agents shared across operators, autonomous flight, etc.
- Integrating multi-modal vehicles is challenging – imagine exiting the highway to a bridge to take off into the airspace or landing on rails.

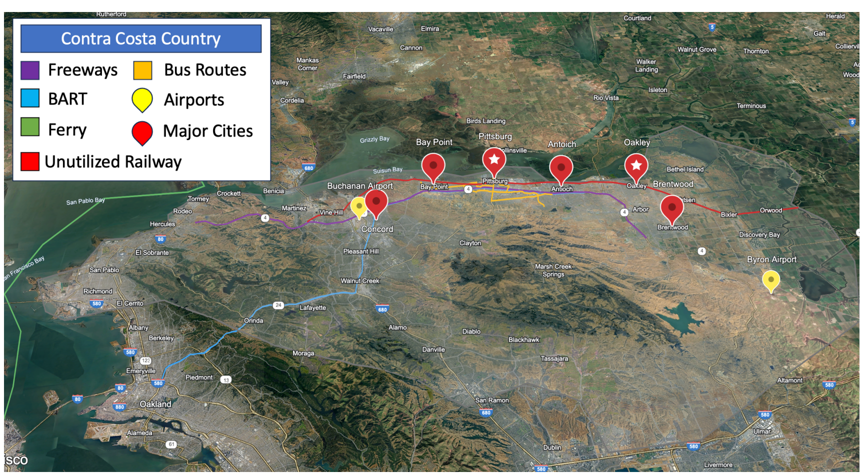
Road to demonstration

Because of the high complexity and potential wide scope of the Pax mobility problem, the research plan takes small steps, starting with a small problem size and gradually expanding in a scalable manner. To ensure scalability, each problem, even the initial smallest, will represent a real problem that is complete and self-contained. The following is a potential graduated plan, based on Bay Area scenarios.

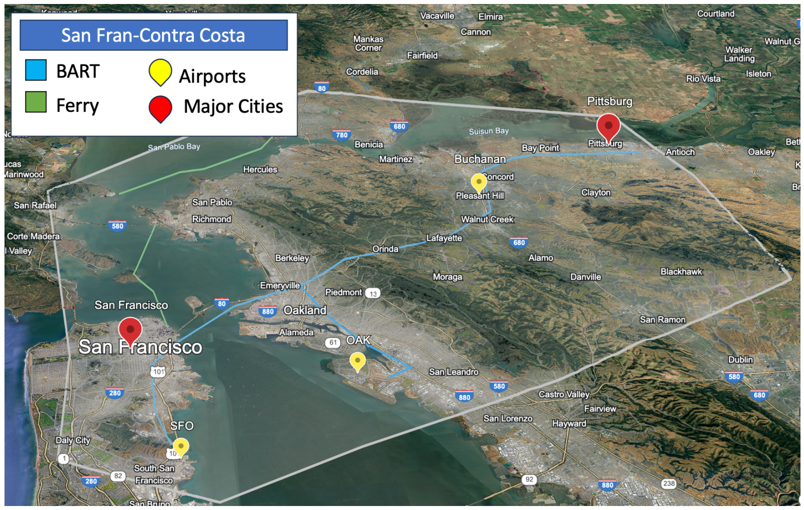
1. **Smallest (mini) scenario:** Start with modeling the passenger door-to-door journey between UC-Berkley campus and NASA Ames Research Center (ARC) (see figure below). Include all (or several) modal options including general aviation (GA) and electric vertical takeoff and landing (eVTOL) considerations. Use passenger data to ensure validity of the model. Study how GA and eVTOL AAM can be made effective in this journey, particularly for low-income students. Include effects of some of the solutions under different conditions such as closure of 101 disruption, travel overnight, etc., and include environmental impacts as well as timeliness and access.



2. **County scenario**: Select a county such as Contra Costa and model a scenario, e.g., closing the transportation gap between the four towns along the railway and Highway 4 (shown in the graphic below) with aviation eVTOL jumpers (other scenarios are also possible). Again, use passenger data to ensure validity of the model. Work with the county planning team to leverage their models and data and layer aviation with these models. Study potential solutions with various models of transition point dynamics, sharing resources, autonomy levels, etc. Study impacts on physical mobility and access as well as economic wellness, societal , and environmental impacts.



3. **Multi-county scenario**: Select two counties (such as San Francisco and Contra Costa counties shown in the graphic below, possibly include more counties) and study the super-commuter journey across counties. This tests scalability of the model to multiple counties. Introduce regional aviation models for the increased scope.

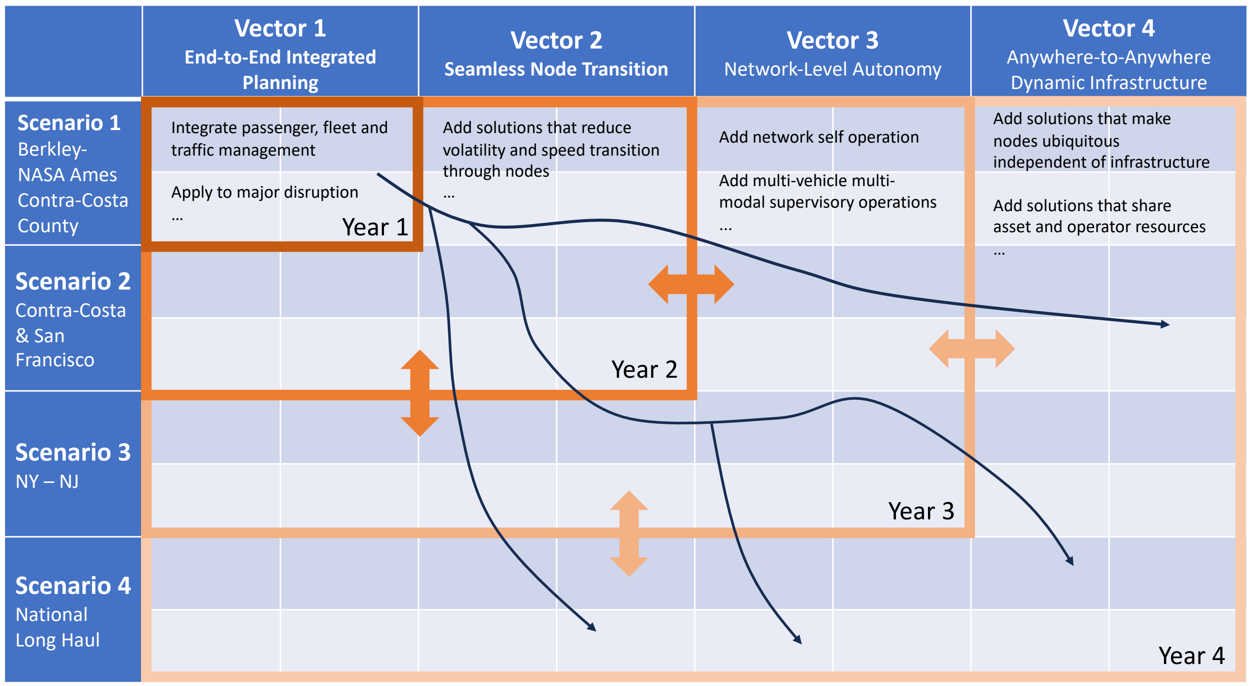


4. **Scenarios outside of the Bay Area**: Expand the model to other regions such as NY/NJ. Select a scenario such as the PATH rail system connecting NY and NJ with a network of small airports in the region. This test scalability to other regions.

5. **Wider scope scenario**: Expand the model to a wider region involving larger airports. In the Bay area this can include SFO, SJC, in NY/NJ this can include LGA, NEW, TEB.

Potential CAS execution efforts and partners

The chart below depicts a potential execution plan. The chart combines the solution vectors on the horizontal axis with the operational scenarios on the vertical axis, defining a two-dimensional space for potential efforts over multiple years. The scenarios and vectors are listed in order of increased complexity. Potential yearly efforts are suggested with rectangles bounding progressive combinations of vectors and scenarios. The rectangle boundaries can be moved to showcase different possible combinations for each year. Multiple paths are depicted showing possible execution paths and pivot points.



The suggested potential execution plan starts in year one with applying vector 1, end-to-end planning to the simplest of scenarios, namely the UC-Berkley-to-ARC journey and the Contra Costa County transportation gap. Starting simple recognizes that the initial effort entails development of the passenger-centric data fabric and modeling which is foundational to every vector. This solution vector explores the challenging problems of integrating passenger, fleet, and traffic management and applying integrated solutions to both nominal and disruption conditions. Optionally the first-year effort can add some limited aspects of the second vector involving seamless transition of passengers through the nodes of the network as well as extending to the multi-county super-commuter scenario.

In the second year, solutions from the second vector are investigated whereby we develop and demonstrate concepts and technologies to speed up the seamless transition of passengers through the multi-modal nodes. In addition, solutions are applied to more complex scenarios involving super-commuters across multiple counties. While these additions may be initiated in year one, their demonstration in simulation will not take place until the second year. The team will pivot and redirect as needed or desired based on the progression of the research and insights gained, following the CAS Execution process.

The third and fourth vectors--adding network autonomy, dynamic infrastructure, and resource sharing—are more challenging and futuristic. Therefore, we suggest that they are tackled in the first two years only at the conceptual, analytical, and requirement development levels. With simulation and demonstration reserved for the third and fourth years respectively, after transitioning from CAS.

Execution will include and be based on partnerships between NASA and potential government, academic, and industry stakeholders. The PAX mobility team has performed considerable outreach, and the following potential partnerships (or similar) are proposed.

- Local transportation authorities, such as the Bay Area Metropolitan Transportation Commission (MTC), Contra Costa County and San Francisco County transportation planning teams. Conversations were also conducted with the Port Authority of New York - New Jersey and with authorities in Washington State, Alaska, and Texas. These authorities will provide NASA with links to modes of transportation other than aviation, including train, ferry, and road, in addition to links to higher DOT and FAA participation. The authorities will also share with NASA, when feasible and appropriate, relevant data, models and metrics, and access to observational research efforts in their communities

- Academia will be a major partner in the execution effort. The PAX mobility team has conducted significant outreach, particularly with UC-Berkley, in addition to MIT, UT-Austin, and UM, among others. The foundational and futuristic nature of this effort lends itself to supporting student innovations and building their careers. Academia can provide state of the art subject matter expertise, student innovation, data science, modeling, and metrics research and tools, in addition to supporting outreach and publication.

- As a partner, AIAA will provide the widest and most diverse outreach community for this effort. The AIAA AAM multi-modal working group, initiated and led by the PAX mobility PI, provides a platform to access academic, industry, and government participation. For example, the working group is leading a joint special journal issue between AIAA's Journal of Air Transportation, INFORMS's Transportation Science, and IEEE's Intelligent Transportation Systems. AIAA is also considering a shark tank student activity for the 2025 Aviation Forum using a multi-modal scenario to bring together all the stakeholders in infrastructure, certification, and sustainability, among others. This is a potential opportunity to use the scenarios to gather student innovations into the CAS activity. In addition, the AIAA working group has initiated an effort to develop a multi-modal taxonomy study, which can be leveraged for the passenger-centric data fabric proposed in this effort.

- The German Aerospace Center (DLR) is another partner that is active in the domain of total mobility. The PAX mobility team has conducted outreach and established connection with DLR and desire to collaborate is mutual. DLR has started developing an open-source modeling capability with passenger objects, which is synergistic with what is proposed in this effort and establish the ground for great international collaboration.

- Industry partners will be important although outreach has not yet been as significant. Industry partnership will include several types: (1) operators such as airlines and urban air mobility providers, (2) passenger travel services such travel agencies, (3) passenger data warehouses such as Google and Uber, (4) modeling and digital twin outlets, and any others that may be identified. Industry partners are expected to be very interested in this effort as there are many cases where industry is pursuing leveraging passenger data for their on-demand services. One challenge will be the proprietary nature of these efforts. While some proposed activities may be considered for contracting to industry partners, they are typically more expensive than academia, especially for such low TRL effort. Partnership with industry may be limited to provision of data and leveraging modeling and simulation tools if deemed cost effective.

- Airports and port authorities will also be important partners as multi-modal integration of aviation is largely focused the transformation of airports, especially small airports, into more effective multi-modal nodes.

Potential impacts

PAX mobility plans to produce several profound and transformative impacts.

- The main goal of PAX mobility is to cut down the door-to-door travel time for passengers by ensuring that the contribution of air mobility is maximized to its fullest potential. Taking a total end-to-end perspective ensures that air mobility is integrated with the other modes to reduce the overall travel time, while balancing the impacts on the environment, cost, safety, and equity. For each of the scenarios, targets will be set for time reduction, like Europe's 2050 horizon target of ensuring 95% of passengers travel door-to-door in less than four hours. PAX mobility will attempt to achieve such targets through integrated solutions, seamless transition, network autonomy, dynamic infrastructure utilization, and resource sharing.
- By prioritizing the passenger-oriented perspective, PAX mobility will connect communities and economies, especially the underserved and disadvantaged ones, providing better accessibility to jobs, medical services, education, and other utilities. Meliorated freedom of movement leads to economic and social mobility, whereby underserved communities can advance their economic and social statuses.
- PAX Mobility solutions are generic and scalable to address mobility concerns across any journey. Passenger-oriented door-to-door solutions connect patients to their doctors, students to educational institutions, super-commuters to jobs, disabled people to services and locations that may otherwise be too difficult to access, or endangered communities to rescue missions and evacuations from emergency situations and disasters.
- Through PAX mobility, the impacts of aviation are computed end-to-end with KPIs reflecting time, cost, equity, environment, etc. End-to-end metrics enable more accurate assessment of the total value of aviation solutions, which helps speed up the adoption of aviation solutions where most beneficial and avoids its application where harmful.
- PAX mobility will improve the utilization of underutilized infrastructure and resources though reduction in waiting times and uncertainties, seamless multi-modal transition, dynamic infrastructure allocation, and adoption of novel resource sharing approaches.
- PAX mobility increases the resilience of transportation to disasters and disruptions through better integration between aviation and the other modes, making air mobility more readily and dynamically available, and increasing the response options in an integrated network of networks.
- PAX Mobility may result in seeding new industries, technologies, and applications (e.g., passenger data sharing and protection, seamless mobility technologies and applications,

innovative business models for resource sharing such as pilots, crews, and vehicles, among others).

- In addition, PAX mobility offers an opportunity for increased collaboration between disconnected and siloed communities and government, academia, and industry, nationally and internationally.

Stakeholders

The following were identified as potential PAX mobility stakeholders.

- People, passengers, and communities, especially the underserved and disadvantaged
- Transportation authorities and planning teams
- Transportation industry (operators, agencies, etc.)
- Infrastructure and urban planning agencies
- Academic community
- Data science and computing community
- Manufacturers

Some of these stakeholders might be interested in partnerships and transition.

Potential transition paths

PAX mobility has identified several transition paths within NASA and external to NASA.

Within NASA

- PAX mobility envisions its data fabric to provide an extension to the digital data and reasoning (DRF) developed under CAS and adopted by other projects, such as the ATM-X DIP subproject. The PAX Mobility data fabric extends DRF with passenger level constructs that enable end-to-end data sharing and reasoning.
- PAX Mobility envisions end-to-end models and metrics will be connected to NASA testbed and digital twin capabilities to enable end-to-end impact assessments of new aviation technologies. As an example, the PAX Mobility team has already reached out to and coordinated with the National Airspace System (NAS) digital twin and testbed for potential future connection and application.
- PAX Mobility seeks to leverage the AAM mission office working groups and engage in discussions on concepts, model, metrics, and technologies. While not a transition plan, this coordination, which the team has already initiated, provides the potential for transition paths through the mission office depending on future directions and undertakings.

- While PAX mobility is focusing on passengers rather than cargo to manage scope, the cargo use case is of great interest and relevance to PAX Mobility, both as a baseline use case where end-to-end methods are more developed as well as a potential user of future PAX mobility products. This vision leads to transitions to NASA projects working on cargo delivery, including the ATM-X Pathfinding for an Airspace with Autonomous Vehicles (PAAV).
- Ultimately, PAX Mobility offers a future vision that affects the whole transportation ecosystem and highlights the integral role aviation plays in its perennial modernization. PAX Mobility leverages and supports work in other futuristic NASA projects, i.e., Sky for All, and can align with forward-thinking initiatives to provide a passenger-centric perspective. PAX mobility's future vision and problem space is very rich and could potentially lead to a standalone project that can have long standing impacts on the future of transportation, personal mobility, and the wellbeing of passengers and communities.

Outside NASA

- Transportation authorities in the Bay Area, such as the MTC and authorities of the different counties' planning teams, have indicated interest in PAX mobility products, including models, metrics, and KPIs that can update and supplement their own capabilities. Technology transfers can be extended to other local and regional authorities through the U.S. as PAX mobility scales its research activities.
- The PAX mobility team expects that the data fabric, the models and metrics, and the reasoning tools will attract interest from companies and organizations investing in multi-modal applications, e.g., operators, service providers, and data science communities, etc. Some futuristic concepts may also plant the seeds for new business models and new types of industries that invest in passenger data sharing and protection, seamless mobility, on-demand mobility, and resource management and sharing.

Conclusion*

The PAX mobility activity, as articulated in this Opportunity Concept Report, represents a pivotal first step towards realizing a future vision where total freedom of movement is attainable for all. This undertaking is a journey towards a more connected, equitable, and environmentally conscious world where every individual has the freedom and ability to move efficiently, reliably, and affordably.

In facing the contemporary challenges of our transportation systems—the congestion, the delays, the inaccessibility, the high carbon footprint, and the inequities—there is a clear imperative for change. Through comprehensive end-to-end modeling that leverages passenger-level data, PAX Mobility addresses these challenges head-on, with solutions designed not just with the passenger in mind but with the passenger at the core.

Throughout this report, we've outlined a constellation of traveler pain points, barriers, and the complex system dynamics that inhibit the seamless flow of people and goods today. The research questions proposed serve to guide our inquiry and challenge our preconceived notions about what's achievable within the realm of contemporary aeronautics and transport.

By foregrounding the traveler experience and harnessing the integrative potential of AAM, PAX mobility is a transformative paradigm shift. It's an activity grounded in understanding that innovation, when driven by genuine needs and equitable access, can profoundly reshape the landscape of transportation.

The potential solution vectors outlined here—resilient multi-modal planning, seamless mobility through transition nodes, network autonomy, and dynamic resource sharing—each contribute to painting a picture of what the future of transportation could look like. These are solutions derived from robust stakeholder engagement, informed by the complexities of the wicked problem space we navigate, and enriched through a lens of desirability, viability, feasibility, and wickedness.

The journey towards demonstration is as methodical as it is visionary, ensuring that each incremental advance is both scalable and reflective of real-world complexity. This gradual, evidence-based expansion ensures that the solutions we pioneer are not only groundbreaking but are also grounded in practical reality, harnessing the best of what technology and collaboration can offer.

The potential impacts are profound. From enhancing day-to-day operational efficiency to bolstering the resilience of entire communities in the face of disaster, PAX mobility is about more than improving transportation; it's about improving lives. The stakeholders identified—all of us who move, who travel, and who rely on the connectedness of our world—are as diverse as they are central to the success of this endeavor.

The transition paths laid out within this report promise to disseminate the fruits of this activity far beyond NASA's remit, informing policy, shaping industry practices, and driving forward a global conversation about what freedom of movement truly means.

In conclusion, PAX mobility is not simply a project or a proposal; it is a beacon that guides us toward a future where total mobility for all is not just a vision but a reality. It is the catalyst for innovation that transcends boundaries, breaks down barriers, and fosters a more connected human experience. As we embark on this journey, we do so with the knowledge that the right first step has been taken, and with the anticipation of the transformative steps yet to come.

References

Tuchen, S. (2020). Multimodal Transportation Operational Scenario And Conceptual Data Model For Integration With Uam. 2020 Integrated Communications Navigation and Surveillance Conference (ICNS), pp. 2C1-1-2C1-15, Herndon, VA, doi: 10.1109/ICNS50378.2020.9223002.

Tuchen, S. (2018). Role of Aviation in Seamless End-to-End Mobility. 2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC), pp. 1-8, London, UK, doi: 10.1109/DASC.2018.8569516.

Cohen, A., & Shaheen, S. (2024). Advanced Air Mobility: Opportunities, Challenges, and Research Needs for the State of California (2023-2030). UC Office of the President: University of California Institute of Transportation Studies. http://dx.doi.org/10.7922/G2JH3JJC Retrieved from https://escholarship.org/uc/item/0656t0dh

Levinson, D., & King, D. (2020). (tech.). *Transport Access Manual: A Guide for Measuring Connection Between People and Places*. Committee of the Transport Access Manual.

University of Minnesota. (n.d.). *Access Across America*. Access Across America | Center for Transportation Studies. https://www.cts.umn.edu/programs/ao/aaa

Idris H, C. Chin, and A. Evans. (2021) *Integration of Network Scheduling Using Accrued Delay Across Vehicle Connectivity*, AIAA Journal of Air Transportation https://doi.org/10.2514/1.D0186

Idris H, (2015) Identification of Local and Propagated Queuing Effects at Major Airports, 22-26 June 2015, AIAA Aviation Forum, Dallas, TX

Appendix: Capability details

The PAX mobility opportunity concept is deconstructed here into two main capabilities that build on each other. At the base, (1) an enabling passenger-level data fabric that provides access to passenger data to support both offline evaluation and online decision making. (2) integrated network models and passenger-level metrics that build on the data fabric and enables development and assessment of integrated solutions from a passenger door-to-door perspective.

Capability 1: passenger-level data fabric

A passenger-oriented paradigm depends on having access to passenger-level data, hence the difficulty in accessing such data is a key barrier. These difficulties stem from several reasons, including: privacy concerns of passengers, proprietary concerns of companies that collect and use passenger data, and technological difficulties in tracking passenger movement and, particularly, intent.

Despite these challenges, passenger data has become easier to collect and access in recent years due to the digitization of mobility as a service using smart devices. Vehicle tracking provides another intermediate medium to generate passenger movement data. Such data has already helped advance sciences, such as behavioral models of demand.

Conversations with transportation stakeholders (see the stakeholder outreach Section 2) indicated the need for such data for planning purposes. For example, the MTC represents nine counties and has collected passenger data from 8,000 households that volunteered to be tracked through an app. In these conversations we identified willingness to share data and a need and desire for NASA to play a role in applying its data science expertise.

This is great opportunity to apply NASA's capabilities and expertise in advancing the ability to collect and track passenger-level data and applying data science to analyze and draw insights from such data. Capabilities include:

a. Offline access to passenger-level data for analysis
   At a minimum NASA works with transportation organizations such as the MTC and Caltrans to access passenger-level data and apply aviation-related analysis

   NASA teams up with companies that collect passenger data such as airlines, travel agencies, Google, Uber/Lyft , etc., to work through proprietary hurdles and create a passenger-level database for analysis.

   NASA starts a national campaign to collect passenger-level data through a "citizen science" approach.

b. Online access to passenger-level data for operation feedback

   Collecting passenger-level data online supports adaptive real-time operation planning as described in the following concepts. The offline data collection provides a skeleton for data needs for real-time operations and decision making. Architecture and data sharing models are created to support such operations.

The PAX mobility team collaborated with transportation researchers to develop preliminary concepts for passenger-level information sharing [Teuchen 18,22]. The core element is a “passenger object,” that becomes a core object for a data fabric that integrates all mobility modes door to door. This construct enables a paradigm shift from the gate-to-gate “flight object” that has driven aviation to date.

Desirability: in many of the use cases analyzed for this effort, people can access services over longer distances because of the remote connectivity. This includes medical services provided from major hospitals to remote areas, education services provided from universities online, and working from home or remote workspaces for many jobs. Physical mobility becomes a bottleneck in these cases where for the times when a physical appointment, course, or meeting is needed, the travel time and cost is prohibitive. Passenger-oriented mobility integrating more options from faster and lower cost travel is very desirable in further connecting these communities and markets.

Viability: Cargo packages and movement are tracked at a much higher degree than passengers. While tracking cargo does not share similar restrictions such as privacy concerns, it provides a reference point. People make decision to trade privacy with utility all the time and it is likely that at least some percentage of passengers is willing to share their travel status and intent for their individual benefit as a well as societal benefits.

Feasibility: Passenger willingness and participation is a key hurdle. Only two percent passenger participation allows google to provide quite accurate predictions of congestion on the roads. This indicates an opportunity that such statistics scale across modes and allow for better predictions end to end. MTC has experience collecting data from eight thousand households is an indication of the feasibility of the approach.

Wickedness: Data privacy and proprietary concerns make this a wicked problem to overcome.

Capability 2: passenger-centric end-to-end modeling

A passenger-oriented paradigm shift depends on building end-to-end models that capture the total impact of mobility solutions from a passenger perspective. Such integrated models are lacking which constitutes another key barrier and another opportunity for NASA to contribute.

Conversations with transportation experts indicated several gaps in integrated modeling to support planning decision making. Often the planning decision making is not based on quantitative data-driven assessments, models that combine demand estimation with supply side services tend to be primitive and lack for example uncertainty modeling. The aviation element is not integrated and accounted for through specialized models that look at airports as origin and destination, with inaccurate and outdated forecasts. Assessments need to account for multiple factors and impacts such as environmental greenhouse effects which is a major concern for MTC and leads to consideration of focused growth of mobility. This poses the risk of limiting economic and societal benefits of increased mobility if the tradeoffs are not accounted for in integrated end-to-end assessments It may also risk limiting and slowing the role of new aviation modes as in some cases it may lead to investments in rail rather than aviation instead of a combined integrated approach.

In these conversations we identified a need and desire for NASA to play a role in applying its expertise in improving the aviation elements of these models, in particular.

a. Integrated models that combine aviation network with other mobility modes to establish end-to-end passenger-level fidelity.

   Building on the passenger-level data, develop integrated models that combine the aviation network with other mobility networks such as trains and highways, to establish end-to-end fidelity.

   Opportunity to work with transportation stakeholder such as MTC to build next generation models that integrate across aviation and other modes end to end. Open-source activity simulations are available and MTC is keen on working to improve on such models using NASA expertise.

   Desirability: In the stakeholder conversations we identified major gaps in integrated models as highlighted above. We also identified a need and desire for NASA to play a role in applying its expertise in improving the aviation elements of these models and in improving the value assessment of different aviation modes and paradigms in conjunction with other modes.

   Viability: NASA can bring in its super computing capabilities among others to open new lines of applications. Many of the existing models are open source, which provides a pathway to contributing to the body of capabilities.

   Feasibility: Building an integrated model is very complex as it brings together multiple systems each is very complex on its own. The complexity of such models has probably been one of the factors that contributed to their lacking. The approach proposed is to focus on minimalistic use cases as outlined in Section "path to demonstration". While complexity is high in considering the combinatorics of different mode options and transition between them, it is compensated for by the small size of the use case. Such a model can then be scaled to larger system while maintaining the complete integrated perspective.

   Wickedness: Building an integrated model is very complex as it brings together multiple systems each is very complex on its own.

b. Establish passenger-mobility metrics and apply machine learning

   Using the passenger-level data and the integrated models that layer the aviation network with the networks of other modes, we apply data science methods to compute and estimate different metrics and performance indicators.

   Examples of such research are numerous including identifying current baselines of mobility and accessibility limitations and identifying desired mobility and accessibility targets for different scenarios (some counties such as contra costa for example have some desired target such as no person should walk more than half a mile to the nearest station). What targets should be set for underserved areas and how does aviation help achieve these targets? What are these targets under off nominal disruptions? What are the Pareto tradeoffs between mobility and accessibility and other important metrics such as environmental greenhouse effects, economic mobility, social mobility, resilience to disruptions, etc.

   Desirability: Conversations with transportation stakeholders indicated that key performance indicators, especially related to the role of aviation in conjunction with the other modes, is an area that is lacking. There is a desire for NASA to contribute to this area.

Viability: NASA can contribute by providing such metrics using its expertise in data science, machine learning and compute capabilities.

Feasibility: PAX mobility PI has conducted several studies to identify choke points in the air transportation network and propagation of delays across different flight segment [Idris 15,21]. The PAX mobility team identified state of the art metrics on accessibility through conversation with SMEs from UC-Berkley [Cohen 24, Levinson 20, University of Minnisota n.d.]. There is an opportunity to extend such metrics and analyses to multi-modal networks identifying choke points and propagation of delays across multi-modal transition points.

Wickedness: modeling transition points and tracking passengers through these points to have data that validate the models are very difficult. The lack of tracking and modeling of transitioning is a major source of uncertainty in estimating and forecasting delay propagation. This is already extremely difficult within the aviation network and will be more difficult across different modes. Identifying key challenges and barriers in what information should be shared through transitions and how to use such information to reduce uncertainties and reduce delay propagation are key contributions to the seamless mobility of passengers through the transition points.