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Implications as to the Identification of Enabling Technologies and Reference Designs for Extreme Short Haul VTOL Vehicles With Electric Propulsion

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September 2017

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Nomenclature and Acronyms

ADS-B	Airborne Dependent Surveillance-Broadcast
AEDT	Aviation Environmental Design Tool
AGL	Above ground level
AHS	American Helicopter Society
ARMD	Aeronautics Research Mission Directorate
ARTCC	Air Route Traffic Control Center
ATM	Air Traffic Management
BART	Bay Area Rapid Transit
BTU	British thermal unit
BVI	Blade vortex interaction
BWI	Blade wake interaction
CDF	Cumulative distribution functions
CFD	Computational Fluid Dynamics
CIMS	Comprehensive Inter-Modal Systems
CONOPS	Concept of Operations
C_P	Rotor power coefficient, $C_P = P/\rho A(\Omega R)^3$, nondim.
C_T	Rotor thrust coefficient, $C_T = T/\rho A(\Omega R)^2$, nondim.
DES	Discrete event simulation
DNL	Day-night average sound level
DWR	Dynamic Weather Routes
ELOS	Equivalent Level of Safety
EMS	Emergency medical services
ESHVL	Extremely short haul vertical lift
E_{sp}	Battery specific energy, W-h/kg
FAA	Federal Aviation Administration
FACET	Future ATM concept evaluation tool
FAP	Fundamental Aeronautics Program
fDist	Flight distance in statute miles (parameter used in the BaySim software tool)
FMS	Flight Management System
GA	General aviation
GPS	Global Positioning System
HIGE	Hover in-ground-effect
HITL	Human-in-the-loop
HOGE	Hover out-of-ground-effect
Hopper	Another term used in this report for ESHVL vehicles
h/R	Vehicle hover-in-ground-effect; ratio of height above ground to rotor radius
HSI	High speed impulsive (noise)
HUMS	Health and usage monitoring system
IADS	Integrated Arrival/Departure/Surface
IMC	Instrument meteorological conditions
IMPLEMENT	Investigating Mission-PLausible-Elements Mandating ENabling Technologies
INM	Integrated Noise Model
IOC	Initial Operating Capability

Nomenclature and Acronyms (cont.)

iPX	Number of passengers on a flight (parameter used in the BaySim software tool)
L/D_e	Vehicle equivalent lift-over-drag ratio
LFO	Level flyover
LOA	levels of autonomy
LOS	Loss-of-separation
McTMA	Multi-center TMA
MIT	Miles-in-trail
NAS	National Airspace System
NCT	Northern California Terminal Radar Approach Control
NDARC	NASA Design and Analysis of Rotorcraft (software)
NextGen	Next Generation Air Transportation System
OASPL	Overall acoustic sound pressure level, dB
PAV	Personal air vehicles
PAX	Number of passengers onboard vehicle
PDRC	Precision Departure Release Capability
PEM	Proton exchange membrane
PST	Pacific Standard Time
RC	Radio-controlled
ROI	Return-on-investment
RPM	Revolutions per minute
RVLT	Revolutionary Vertical Lift Technology
RVSM	Reduced Vertical Separation Minima
SARDA	Spot and Runway Departure Advisor
SBIR	Small Business Innovation Research
SFO	San Francisco International (airport)
STOL	Short takeoff and landing
TBO	Trajectory-Based Operations
TFM	Traffic Flow Management
TMA	Traffic Management Advisor
TSAM	Transportation Systems Analysis Model
UAS	Unmanned aerial systems
UAV	Unmanned aerial vehicle
V	Aircraft/vehicle cruise velocity
VFR	Visual flight rule
VMC	Visual meteorological conditions
VTOL	Vertical takeoff and landing
W	Vehicle weight, kg or lb_f
WEP	Wheel of electric propulsion
x/R	Vehicle hover-in-ground-effect; ratio of lateral separation (to referenced object) to rotor radius
4DTs	Four-dimensional trajectories

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Summary

There are substantial future challenges related to sustaining and improving efficient, cost-effective, and environmentally friendly transportation options for urban regions. Over the past several decades there has been a worldwide trend towards increasing urbanization of society. Accompanying this urbanization are increasing surface transportation infrastructure costs and, despite public infrastructure investments, increasing surface transportation "gridlock." In addition to this global urbanization trend, there has been a substantial increase in concern regarding energy sustainability, fossil fuel emissions, and the potential implications of global climate change. A recently completed study investigated the feasibility of an aviation solution for future urban transportation (refs. 1, 2). Such an aerial transportation system could ideally address some of the above noted concerns related to urbanization, transportation gridlock, and fossil fuel emissions (ref. 3). A metro/regional aerial transportation system could also provide enhanced transportation flexibility to accommodate extraordinary events such as surface (rail/road) transportation network disruptions and emergency/disaster relief responses.

The goal of this study was to develop an integrated system simulation that incorporated models of aircraft, vertiport stations, fleet operations, and airspace management technologies to determine the feasibility of using electric-propulsion vertical takeoff and landing (VTOL) vehicles to serve a metro-regional transportation system. The technical challenges of developing a metro-regional aerial transportation system based on extremely short haul vertical lift (ESHVL) vehicles, aka Hoppers, were examined through these simulations (Fig. 1).

There were three key components to this study. First, an expanded vehicle design space was examined for rotary-wing vehicles incorporating electric propulsion. This design space included not only emerging advanced battery technologies, but also hydrogen-fuel-cell systems and hybrid (turboshaft engine and battery/fuel-cell-driven electric motor) propulsion systems. Additionally, the conceptual design space was influenced by insights gained during this study as to mission

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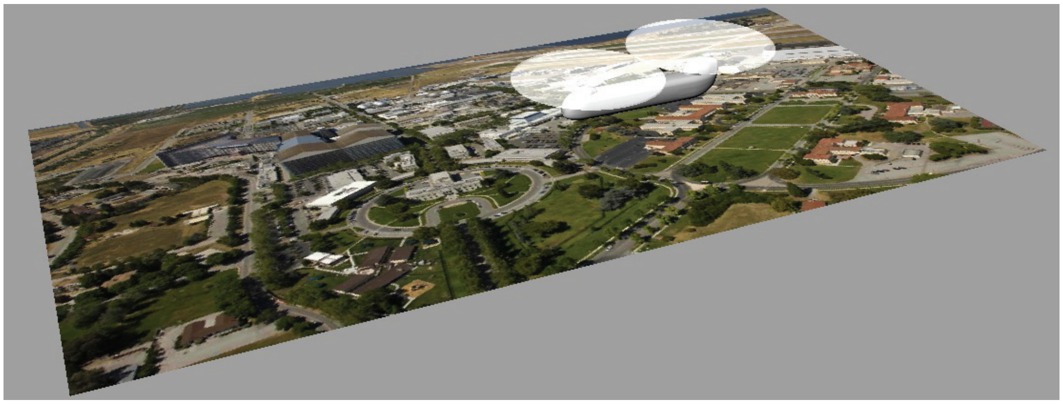


Figure 1. One possible future for metro/regional transportation: an aerial public transit system using rotorcraft.

profile requirements—particularly vehicle range requirements (25–100 nautical miles). The expanded design space was explored with a new, custom-developed (as a part of this study) rotorcraft-sizing software tool. Second, a considerable effort was expended on developing the tools and analysis to support investigation of near- to far-term evolution of the notional aerial transportation network—from simple three-node networks to large multi-node systems. The ability to model/analyze this network evolution begins to capture the nuances of a more realistic potential future implementation of such a metro/regional aerial transportation system. The primary simulation tool used for this investigation was the BaySim software tool, an earlier version of which was developed and discussed in reference 1, and then greatly enhanced as a part of the present study. BaySim was extended to incorporate public domain San Francisco Bay Area population data from Government census/zip code databases (an approach that is readily extensible to other metropolitan areas). BaySim updates also included alternate network topologies, the Dijkstra optimization algorithm (ref. 4), and air traffic management integration via "speed tables" (time-of-day flightpath dynamic routing). And finally, third, a number of operational (and miscellaneous related) issues were explored in a very preliminary sense using computational fluid dynamics (CFD), acoustics analysis, and the analysis of air traffic management issues resulting from interaction of the Hopper fleet with commercial air transport and general aviation aircraft using the well known NASA-developed tool FACET (Future ATM Concept Evaluation Tool; e.g., ref. 5).

Altogether, this study revealed that a mid-term (next 15 to 20 years) solution for electric vertical lift vehicles supporting the Hopper metro/regional aerial transportation system mission might be feasible. Specifically, relatively near-term hybrid propulsion (i.e. turboshaft engines with batteries or fuel cells) technologies can make these short-range vehicles realizable perhaps within the next 10 years. Near-term battery technology (500–600 W-h/kg at reasonable power densities) will satisfy power and energy requirements for these short-range vehicles. To successfully develop rotorcraft with electric-propulsion capability, it is not simply a question of waiting until industry produces a sufficiently advanced battery (or fuel-cell or hybrid system) in terms of specific power and specific energy capability. Clearly, when considering that Hopper vehicle battery packs will be an order-of-magnitude greater in size/capacity as compared to current production automotive electric vehicle batteries, there are aviation-unique aspects to electric-propulsion system development.

With regards to the foundational concept of such vehicles supporting a mission application targeted around metro/regional aerial transportation, large numbers of medium to large aircraft are required to serve assumed passenger levels (which ranged in this study from 5,000 to 30,000 passengers per day). Flying and VTOL are energy intensive transportation modes. While originally conceived as “light infrastructure,” i.e. no new roads or rail lines, Hopper station power requirements and real estate footprints of ramps and terminals will be nontrivial when large numbers of aircraft are involved. Two examples of this secondary but essential infrastructure are: 1) trucks will be required if charged batteries are to be delivered to stations (and discharged batteries removed for offsite recharging), and/or 2) high-power electrical transmission must be provided to stations if charging is onsite. Nonetheless, the simulations and schedule optimization analysis performed during this study support the possibility of Hopper-type vehicles carrying a substantial daily passenger load within the San Francisco Bay Area (and, by extension, other metropolitan areas).

Other operational considerations for operating a large fleet of medium to heavy vertical lift vehicles performing sustained, frequent flights over the urban environment include the issues of noise and emissions. From an emissions standpoint, rotorcraft with electric propulsion are more environmentally benign than turboshaft-engined rotorcraft. However, though the vehicles conceptually designed in this study were required to operate at much lower tip speeds and disk loading than conventional helicopters, rotorcraft noise reduction will still be an important technological challenge. A very preliminary set of acoustic predictions was made during this study. Other important operational considerations include rotor wake interactions in the proximity of vertiports (aka Hopper network stations) as well as airspace management issues inherent in attempting to notionally interject a large fleet of aircraft into an already complex, congested airspace. Emerging technological and procedural advances, currently being proposed under the Next Generation Air Transportation System (NextGen), could be leveraged to facilitate the realization of the Hopper concept. Further, the challenges in integrating Hopper flights and Bay Area commercial traffic can be partially addressed with Hopper aircraft time-of-day dynamic routing in addition to NextGen technologies.

This study directly addressed NASA’s strategic goals to advance aeronautics research for societal benefit. Transportation is a first-order driver to the economy; a cost effective and adaptive metro/regional aerial transportation system would have a first-order effect on regional economies and direct economic benefit to the nation. The immediate anticipated benefit of this study, though, is in providing rotorcraft researchers with a novel electric aerial vehicle reference design and a notional mission/application that can potentially act as an aid in defining future technology development roadmaps for NASA. In this regards, a considerable body of NASA rotorcraft research (most of which focused on conventional rotor configurations) potentially awaits transitioning from the lab, wind tunnel, simulator, etc., to flight demonstration and production. Such research into active rotor control, active flow control, active structures, and many more technologies would transform a vertical lift vehicle, in its most represented form, the helicopter, from an aircraft with electric propulsion to an “electric rotorcraft”—a vehicle that is intrinsically “wired” to drive not only electric motors but a suite of electrically/actively controlled actuators and devices. Such electric rotorcraft could, one day, result in a vehicle with improved performance and passenger/community friendliness.

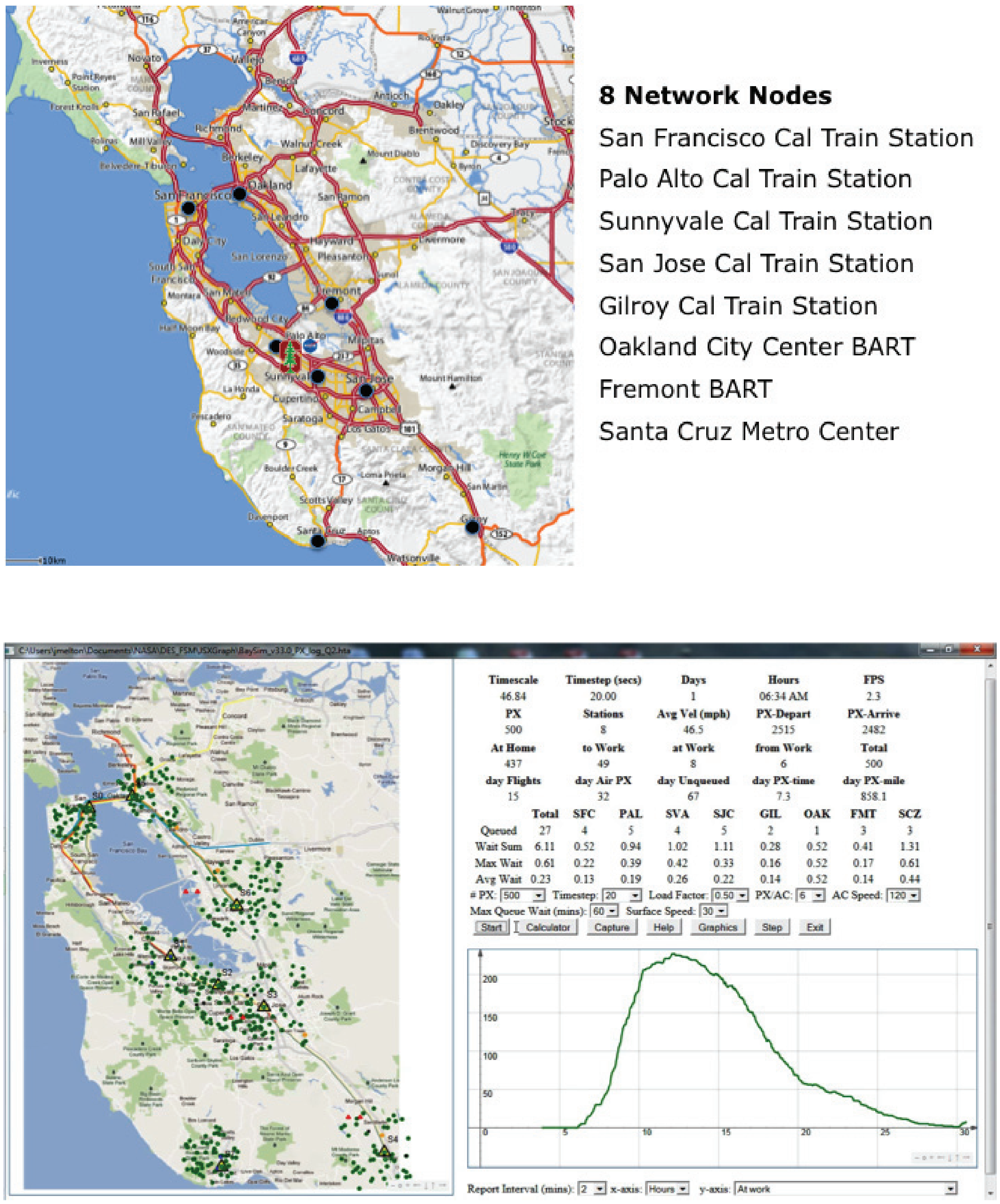
Introduction

There are substantial future challenges related to sustaining and improving efficient, cost effective, and environmentally friendly transportation options for urban regions. Over the past several decades there has been a worldwide trend towards increasing urbanization of society. Accompanying this urbanization are increasing surface transportation infrastructure costs and, despite public infrastructure investments, increasing surface transportation "gridlock." In addition to this global urbanization trend, there has been a substantial increase in concern regarding energy sustainability, fossil fuel emissions, and the potential implications of global climate change (ref. 6). This study—and an earlier companion study (ref. 1)—investigates the feasibility of an aviation solution for future urban transportation. Such an aerial transportation system could ideally address some of these concerns related to urbanization, transportation gridlock, and fossil fuel emissions.

Specifically, this study documents the results of a conceptual design and systems analysis investigation into a notional metropolitan aerial transportation system. The goal of the earlier Phase I effort (ref. 1) was to develop an integrated system simulation that incorporated models of compatibly designed aircraft, stations, fleet operations, and airspace to determine the feasibility of using electric short or vertical takeoff and landing (STOL or VTOL) vehicles to serve a metro-regional transportation system. A baseline system simulation was achieved. It incorporated a newly developed discrete event simulator, modified network optimization algorithms, new electric propulsion modules in NASA's premier rotorcraft design tool, NDARC (refs. 2 and 7), and database expansion of NASA's premier airspace simulation software (FACET). Key findings from Phase I were: 1) aircraft designed for extreme short haul (defined as less than 100 nautical miles per flight leg) could be used to serve tens of thousands of daily commuters in a metropolitan area; 2) aircraft designs are feasible using conventional propulsion and today's technology; 3) aircraft designs using electric propulsion will be possible in 15 years, with larger vehicles possible in 30 years; and 4) the aircraft would likely need to fly below 5000 feet to minimize airspace conflict. The results from both the Phase I and Phase II efforts provide insight into the potential of electric aircraft to serve a unique urban transportation role.

Figure 2a summarizes the Hopper stations/network studied in Phase I; Figure 2b illustrates representative Phase I BaySim discrete event simulation results of the Hopper vehicles/network as a function of time-of-day. Note that in the Phase I effort, aircraft could travel from one station/node to any other node in the network.

Figure 3 illustrates a representative snapshot, using the FACET airspace analysis tool during the Phase I study, of the estimated loss-of-separation (LOS) events—and their spatial distribution throughout the San Francisco Bay Area airspace—resulting from the introduction of the notional fleet of Hopper aircraft. These projected airspace conflicts presented a key technological challenge for the Hopper metro/regional aerial transportation system concept. It was clear from these and similar results that innovative airspace management technologies and techniques would likely need to be implemented in order to support the introduction of a large number of additional aircraft into heavily congested airspace such as that in the Bay Area. Further, this airspace management challenge, though identified in the context of the Hopper concept, would likely include other alternate aeronautics innovations such as small unmanned aerial systems (UAS) platforms, advanced general aviation (GA) aircraft, and personal air vehicles (PAV).



(a)

(b)

Figure 2. (a) Phase I Hopper stations/network and (b) representative time-of-day snapshot of Phase I BaySim output.

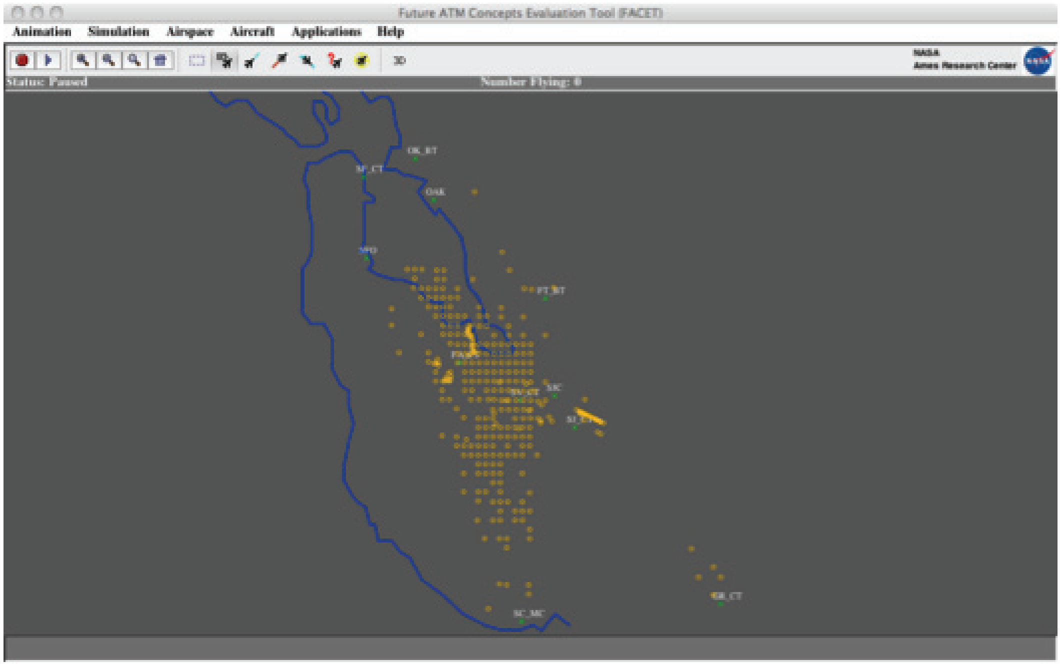


Figure 3. Phase I FACET loss-of-separation assessments (gold circles represent individual unique LOS locations; ref. 1).

Figure 4 is a summary of some of the Hopper vehicle conceptual designs developed during the Phase I study. Three different passenger-size classes of vehicles were studied with a modified version of NDARC: 6-, 15-, and 30-passenger-capable vehicles. Figure 4 presents design sizing results for both a turboshaft-driven design as well as two different variants of a 30-passenger tandem helicopter design. The 65-nautical-mile-range, 30-passenger tandem helicopter Phase I design was carried over as a baseline vehicle design for most of the Phase II simulation and analysis work.

Given the successful development of an analytical framework in Phase I, the Phase II effort set out to take the analytical tools and analyses developed in Phase I and to determine the most feasible approach to one day developing a realizable network of station-to-station VTOL/aerial vehicles—ideally employing electric propulsion—serving the transportation needs of urban metropolises.

A set of Phase II study objectives were defined that addressed four fundamental questions regarding the feasibility of the overall aerial transportation concept. First, can one or more business cases be suggested that might make feasible the proposed concept (in the near-, mid-, and far-term time frames)? Second, beyond the economic considerations of the proposed concept, are there other public-good attributes that may enable its adoption? Third, what are the critical, unique, and NASA-only enabling technologies for such a metropolitan-regional aerial transportation network, including the development of environmentally friendly propulsion systems? And, fourth, can this proposed work be integrated or, rather, transitioned into the

		TS	Electric	
No. Pax	-	30	30	30
Design Range	nm	65	65	40
Design Gross Wt.	lb	20,313	24,148	30,096
Weight Empty	lb	12,364	12,382	14,986
Wt. Empty Fraction		61%	51%	50%
Prop. Grp.+Fuel Wt.	lb	3,723	6,906	10,660
Max Rotor Pwr	kW	1,896	1,834	2,227
Prop. Grp. Spec. Pwr	W/kg	231	121	95
Stored Spec. Energy	kW-h/kg	12.0	0.650	0.350
Conv. Efficiency	-	28.1%	90.3%	90.3%
Storage Volume	gal	858	554	645
Rotor Diameter	ft	53.6	62.0	69.2
Disk Loading	psf	4.5	4.0	4.0
Tip Speed	fps	650	650	650

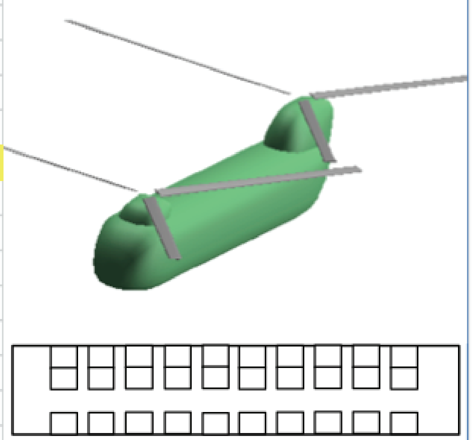


Figure 4. Representative conceptual designs from Phase I.

main Aeronautics Research Mission Directorate (ARMD) projects so as to advance the development of VTOL vehicles with electric propulsion and/or an urban aerial transportation system such as the Hopper concept?

To meet these study objectives, the following technical tasks were pursued during the Phase II study:

1. Refinement and Extension of Network Design/Tools. This task consisted of refining and extending the network design/tools that were originally developed as a part the Phase I study. Airspace operations and the network design were more fully considered in Phase II. The network topology and its variations were examined from a nominal set of operational conditions. The network analysis tool was the Phase I–developed “BaySim” tool. The Phase I network topology was based on an any-node-to-any-node operation. Phase II examined alternative network topologies including ring and spoke configurations. Ring and spoke configurations might be advantageous for (at least) two reasons: 1) overall throughput, and 2) number of aircraft on station. If the number of aircraft (aircraft footprint) at a given station becomes too large, it will significantly increase infrastructure—including real estate—cost. As a part of this expanded network analysis, the concept of dynamic time-of-day flightpath routing was examined in the BaySim discrete event simulations; this time-of-day routing was driven by complementary airspace analysis of conventional aircraft traffic density in the Bay Area. This air traffic density assessment (qualitatively, at least) led to the defining of look-up tables of altitude and flightpaths of the fleet of aerial vehicles to minimize interference with conventional aircraft (as modeled in BaySim). The tool used for the Phase II airspace work was the Ames-developed FACET tool. Phase I fixed the fleet cruise altitude at 5000 feet; the Phase I airspace simulations using the FACET tool showed a high potential at that cruise altitude for commercial air traffic and Hopper flights interfering with each other for the larger projected Hopper fleets and ridership levels. A

number of potential technological and operational solutions were proposed to address the Phase I–projected high levels of loss-of-separation (LOS) events between commercial air traffic and Hopper aircraft.

2. Refinement and Extension of Vehicle and Fleet Designs/Tools. The network/vehicle fleet designs were revised/updated during this Phase II study. In particular, this study sought to qualitatively capture what a near- to mid-term network/fleet might look like versus a mid- to far-term network/fleet. The Phase II tool was a Stanford University–developed rotorcraft-sizing code incorporating a number of electric-propulsion models. The results from the Stanford tool were validated against the modified (to model battery-powered vehicles) NDARC vehicle-sizing tool used in Phase I. This change in vehicle-sizing tools was, in part, necessitated by the need to adopt new electric-propulsion models (fuel cells and hybrid systems in addition to the battery-only systems studied in Phase I) that were not incorporated in the modified NDARC tool. The risks and benefits and ease-of-introduction of these alternate propulsion systems were considered in this task. As a part of this analysis, a preliminary assessment of total energy requirements of the various vehicle fleet and network options was made.

3. Alternate Business Models. A qualitative discussion of multiple business models for the proposed extreme short haul Hopper concept was summarized.[2] The electric vehicle and the extreme short haul concepts need to be explored somewhat independently from each other—e.g., electric vehicles might not be economically viable in the near- to mid-term time frames but turboshaft-engine vehicles might be viable for such markets. Electric and/or green propulsion concepts could be longer-term goals for implementation. (Results from this study would suggest, though, an introduction of rotorcraft with electric propulsion sooner than originally anticipated.)

4. Aerial Vehicle Station Design and Operations. This task consisted of the conceptualization and assessment of infrastructure and operational requirements for proposed urban aerial transport systems. Key among the issues considered were aerial vehicle station design and operations; in order to drive down the mass of the vehicles, the total energy (fuel) budget should be minimized as much as possible. This dictates a close examination of the maximum distance between (and therefore total number of) Hopper network stations—e.g., a 25-nautical-mile design range would result in a smaller gross weight vehicle than a 65-nautical-mile design range. (However, some interesting design issues are raised when a 20-minute-reserve requirement dominates the total energy budget of the aircraft.) Among the station design issues considered (for the electric-propulsion version of the vehicle fleet) is the need to periodically recharge the vehicles. The initial ideas considered in Phase I were twofold: either using quick-charge equipment or an automated battery swap. (Note that alternate electric-propulsion strategies such as fuel cells or hybrid systems have their own unique station design implications.)

[2] A local AHS chapter seminar was given in which the CEO of a Vancouver, BC, helicopter air taxi (one of the few existent non-EMS/petroleum/tourism-focused helicopter transport service companies) discussed the challenges and opportunities of providing economically viable urban helicopter services. A number of valuable insights relating to the Hopper concept were gained from this informal talk.

5. Technology Roadmap. A high-level technology roadmap was developed for the unique technologies and capabilities required for the success of the Hopper concept. This roadmap includes not only electric propulsion technologies but, additionally, automation and autonomous system technologies and airspace management technologies. (Personnel costs are likely to be a big driver of operational costs for such a network. If the network is dominated by fairly rigid fixed routes, both in a spatial and temporal sense, then Hopper-type flights might require vehicle autonomy as a make-or-break vehicle capability.) Ultimately such a roadmap will hopefully complement, and ideally, be integrated into, the technology portfolios and demonstration opportunities of ARMD.

6. Concept/CONOPS Implementation Roadmap. This task consisted of two parts. First, a notional implementation plan was developed. This notional plan proposes an early network of semi-on-demand and semi-scheduled fleet of conventional propulsion (non-electric) rotary-wing aircraft for high-value point-to-point flights. This network would then evolve to one having higher capacity traffic with more frequent scheduled flights. The later stages of this network would adopt, first, small, and then, increasingly larger vehicles with electric propulsion and, in turn, network topologies more in kind to mass public transit models. Second, the task briefly explored integration of extreme short haul concept business models and CONOPS with the notional Subsonic Rotary-Wing project's "Civil Tiltrotor in NextGen" CONOPS (refs. 8, 9). This notional integration effort would seek to overall improve the door-to-door time and economic competitiveness of both concepts/CONOPS.

Objective of the Current Study and Its Relationship to Earlier Studies

Rotorcraft playing a significant role in commercial transport aviation is hardly a new concept. References 8, 9, and 10, for example, detail past studies directed towards this commercial mission application. From a historical perspective, reference 11, for example, details early civil aviation programs in the United States that were intended to enable such rotorcraft commercial markets, which, it turned out, proved to be unsuccessful. The success of helicopter operators to-date has been limited to tourism, public service missions (including emergency medical services (EMS), police, firefighting, etc.), offshore oil-rig transport, logging and other heavy-lift operations, and corporate/private transport. Helicopter airline operations, on the other hand, beyond the early experiments of the past, never fully materialized. Currently, there are only one or two civil operators known to the authors that conduct regularly scheduled commercial passenger transport operations. There are many reasons why this is the case; they range from simple economics to concerns about community noise and public safety, and restrictions on reliable access to congested, high-demand urban airports. Ongoing research projects within NASA have long been examining rotorcraft technologies that might improve safety and reduce noise (e.g., ref. 12). Such work has sought to improve safety through improvements in structures and materials, advanced onboard health monitoring (both diagnostic and prognostic) systems, and improved analytical tools for vehicle design load prediction.

Electric propulsion for aircraft has to a significant degree captured the imagination of the aeronautics research community and aviation innovators. More than anything, perhaps, it is the difficulty of the challenge that draws in enthusiasts for electric aircraft research. Several studies have been performed in the recent past (e.g., refs. 13 and 14), examining some of the fundamental challenges and opportunities for electric aircraft. Most of this work has focused on fixed-wing aircraft of various types and mission profiles. A key milestone for electric aircraft has been the NASA Centennial Challenge (ref. 15), and rotary-wing vehicles have also met some modest success with regards to electric propulsion (refs. 16–18). But beyond technology demonstrations, with the high hover-power requirement and low forward-flight lift/drag ratios of most rotary-wing platforms, there are limitations on the type of missions a passenger-carrying vertical lift vehicle might perform. (Note, on the other hand, that there are many potential missions/applications for small electric rotary-wing unmanned aerial vehicles (UAVs); refer for example to reference 19. The success of small electric radio-controlled (RC) hobbyist helicopters and quadcopters over the past few years is one small example of this potential emerging market.) Among those missions that rotorcraft with electric propulsion, greater in size than small UAVs, might perform include: 1) experimental/kit/sport helicopters for the aviation enthusiast who does not mind flying only tens of minutes for the sake of flying electric; 2) self-deploying, flying battery-pack charging stations for fielded warfighters; 3) short-range tourism flights over and into extremely environmentally/ culturally-sensitive natural preserves and historical sites where a minimized noise/emissions footprint is highly desirable; 4) passenger/freight-carrying vehicles for small interconnected rural (or developing world) village/township networks underserved by roads and, yet, having large potential solar energy availability (as a counterpoint (rural/remote vs. urban transportation networks) to the Hopper mission); and finally 5) the Hopper concept as to extremely short haul metro/regional aerial transport. The notional Hopper mission outlined in this report (and the precursor work in references 1 and 2) is, perhaps, the definitive "electric rotorcraft" mission as to potential positive societal impact.

Vehicle Fleet and Fleet Introduction Profiles

Three different vehicle sizes (6-, 15-, and 30-passenger vehicles) were conceptually designed and studied in Phase I of this study (ref. 1); refer to Figure 5. Both turboshaft-driven and electric-propulsion vehicle designs were generated. The bulk of the work in Phase II, though, has been focused on a 30-passenger tandem helicopter with electric propulsion.

Phase I of the Hopper project focused on the design of battery-powered helicopters designed to carry up to 30 passengers a distance of 65 nautical miles, coupled with a 20-minute reserve time requirement. Phase II efforts expanded on this, in particular, looking at the design of rotorcraft in terms of power and energy tradeoffs for a variety of different propulsion systems, including not only battery-electric designs, but also fuel-cell-powered designs, turboshaft/battery parallel hybrid designs, and, finally, battery-fuel-cell serial hybrid designs. The design process is as follows: each configuration is broken down into fixed weight (assumed to be roughly constant with increasing scale), structural weight (assumed to scale with overall gross takeoff weight and includes components such as the transmission), and the propulsion system weight, and is sized based on some assumptions that will be elaborated on later in this report. Diagrams of the energy flow of the design, along with some sample propulsion system characteristics, are shown in Appendix F. A sample weight breakdown for a 65-nautical-mile-range turboshaft configuration developed from NDARC (ref. 7) is shown in Figure 6. Note that the overall gross takeoff weight of this particular design is 20,300 lb.

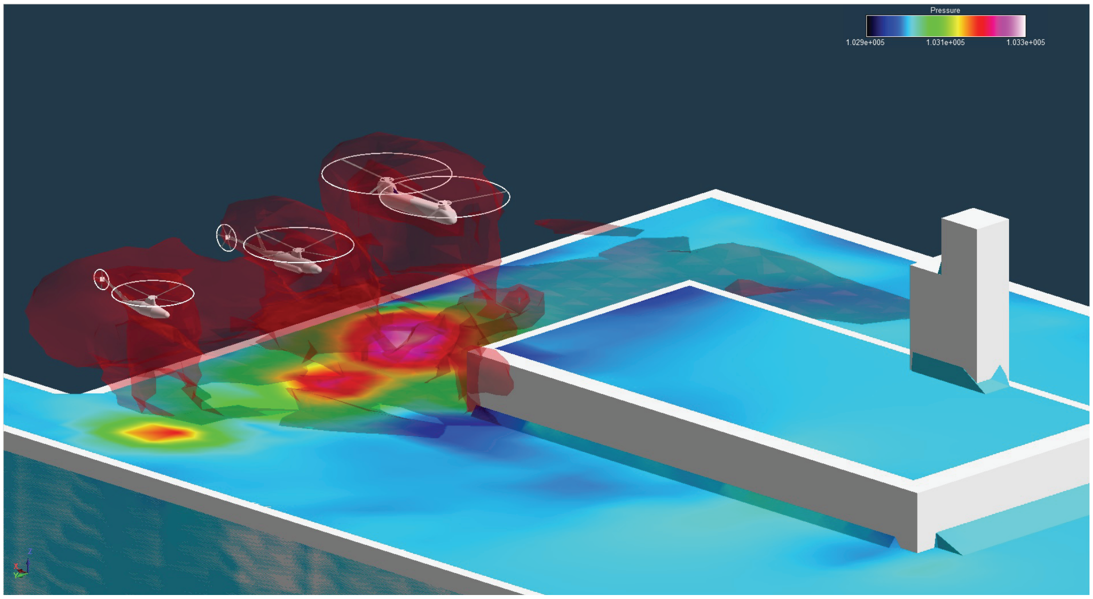


Figure 5. Phase I study Hopper fleet in the vicinity of a vertiport/station.

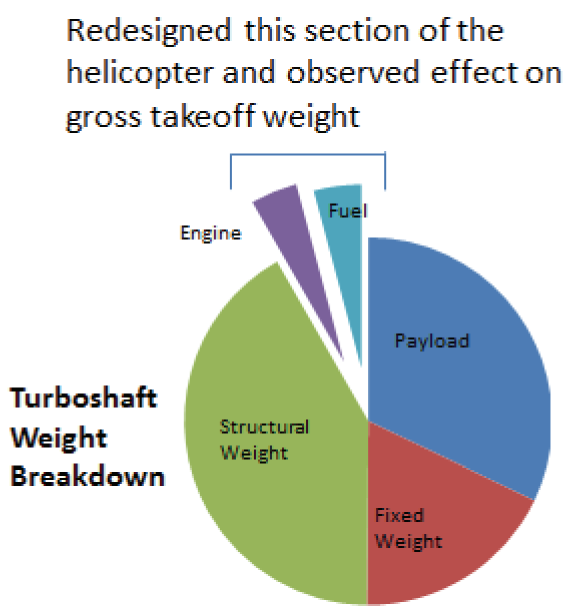


Figure 6. Rotorcraft sizing code sample weight breakdown.

A new modular rotorcraft sizing code, referred to in this report as the Hopper sizing tool, was developed in MATLAB for the Phase II study. This new tool was used to “size” a tandem helicopter design based on a specified mission; in this case, the set of missions specified conformed to the overall metropolitan/regional aerial transportation system concept (i.e. short ranges and low-altitude flight). Given the mission profiles, power and energy requirements were computed, and electric-propulsion equipment such as fuel cells, batteries, and fuel tanks were sized using assumptions that are specified later in this report, and a new aircraft design was created. Figure 7 illustrates the basic architecture behind the Hopper software tool. A Newton fixed-point iteration scheme was used to converge to an overall aircraft design. Electric motor scaling was determined based on a 90-percent state-of-the-art air-cooled motor correlation developed in Phase I and summarized in Appendix F. Resulting Hopper sizing tool–based designs were validated against NDARC-based designs, which closely matched each other with respect to overall gross takeoff weight and component weights.

Each vehicle is sized using essentially the same assumptions in aerodynamic performance (L/D_e, disk loading, hover figure of merit, etc.), with the set of missions varied primarily based on the required range and number of passengers. Note that the aerial transportation network defined in Phase I employed a maximum range of 65 nautical miles. Phase II efforts, on the other hand, began with a smaller network requiring only a 25-nautical-mile maximum range, which significantly reduced the weight penalty associated with some of the electric-propulsion

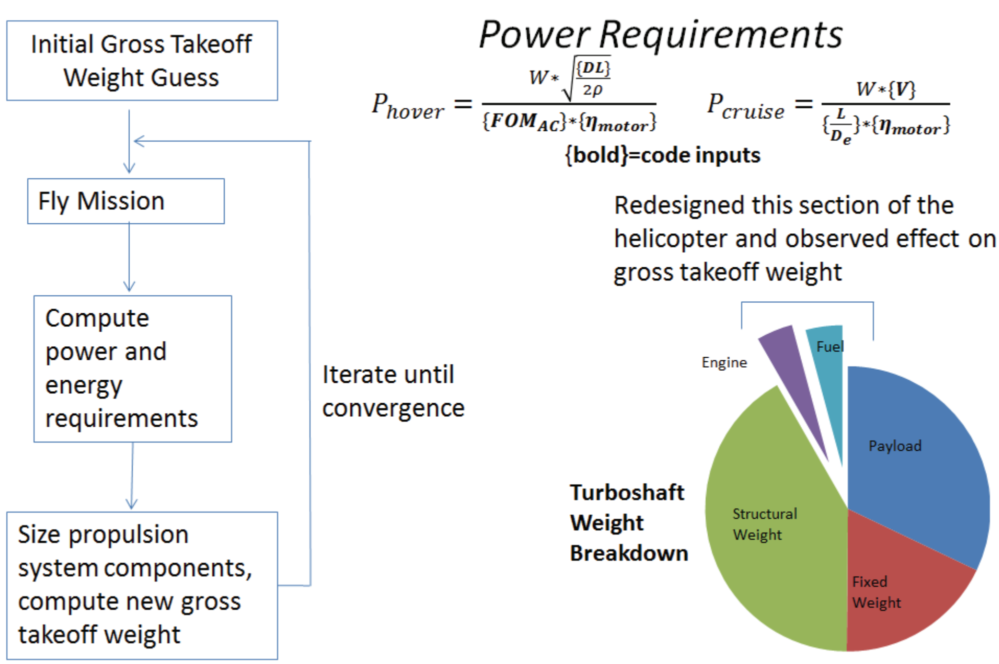


Figure 7. Hopper vehicle sizing tool architecture.

equipment. Note that there is currently a Federal Aviation Administration (FAA)–mandated[3] reserve segment requirement of 30 minutes of flight time, which would significantly increase the energy requirements in the design, particularly compared to the mission segment. The vehicle designs studied in this report, though, were subject to only a 20-minute reserve in recognition of the very extreme short haul nature of the aerial transportation system. This reserve segment should more than account for any networking conflicts or scheduling problems that may arise in a large-scale Hopper network, as a 65-nautical-mile mission only requires around 35 minutes of flight time. Table 1 details the overall mission requirements, as well as the aerodynamic properties of the design. The aerodynamic properties are consistent with respect to tandem helicopter designs and are generally conservative.

Each vehicle uses slightly different assumptions in terms of fixed weight and structural weight fraction to converge on an overall design. The assumptions employed in the sizing analysis are shown in Table 2.

Table 1. Mission Requirements

Cruise Velocity	130 kt
Cruise Altitude	3000 ft
Disk Loading	4 psf
L/De	4.2
Aircraft Figure of Merit	0.5
Number of Passengers	30
Range	25–65 nm (with 20-minute reserve)

Table 2. Hopper Vehicle Sizing Assumptions

	Turboshaft	Battery	Hybrid	Fuel Cell	Fuel Cell Hybrid
Structural Weight Fraction	0.42	0.331	0.37	0.42	0.37
Fixed Weight	3710	2660	3000	3200	3200

[3] Refer to FAR Part 121, Sec. 121.639, "Fuel Supply: All Domestic Operations;" specifically the current 30-minute requirement is for visual flight rule (VFR) operations under visual meteorological conditions (VMC) and not instrument meteorological conditions (IMC), in which a larger reserve for 40 minutes of flight would be required. The all-weather operations of a metropolitan aerial transportation system would suggest a significant fraction of flights under IMC. Consequently, to seek/impose a 20-minute reserve for Hopper aircraft operation would require some future reexamination of the FARs.

The difference in the structural weight fractions for the different concepts can be explained as follows: the transmission, as well as other such components for the turboshaft design, are included in both the structural weight fraction and also partially in the fixed weight. Such drive-system mechanical components generally do not need to be included in the electric-propulsion designs. This is not always a clear-cut situation, though. Note that hybrid-electric-propulsion systems retain some of these drive-system mechanical components and, furthermore, that fuel-cell-powered designs typically require a compressor. In addition to the 25-nautical-mile designs presented herein, Appendix F also presents results for 65-nautical-mile designs.

Fundamental to this electric-propulsion design process is the concept of a Ragone plot—a plot of specific power vs. specific energy—usually plotted on a log-log scale, which may be applied to any number of different energy storage/conversion devices. For batteries, though, Ragone plots tend to have certain characteristic curve shapes that depend significantly on the intrinsic technology and overall design of the battery. These curve shapes stem from a number of factors—in particular, though, they are heavily influenced by the design of the battery anode and cathode. For example, if the anode and cathode have larger exposed surface areas, then the battery can transmit electricity at a faster rate, but at the expense of having a harder time "holding on" to that electricity (i.e. it has a higher specific power but a lower specific energy). A sample Ragone plot of a lithium-ion battery—a lithium-sulfur battery using 2005, 2008, and 2013 technology—is shown in Figure 8, using data obtained from reference 20.

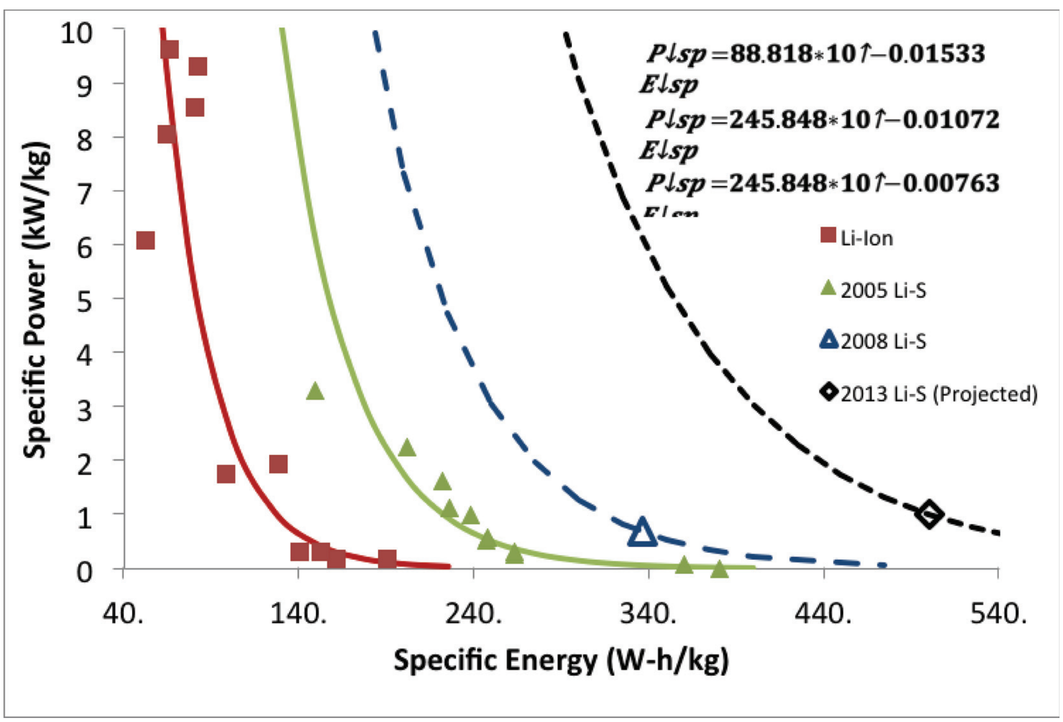


Figure 8. Battery Ragone plot.

To gain a sense of the relative specific energies involved, with respect to Figure 8, Tesla automotive batteries (circa 2013) have a specific energy of around 125 W-h/kg (ref. 21), whereas Jet A fuel for aircraft has a specific energy of around 12,000 W-h/kg. Note that, as shown in Figure 8, even though the 2008 and 2013 lithium-sulfur batteries have only one data point each, the general shape of their curves can be extrapolated based on the fact that they have the same chemistry as the 2005 battery and, thus, are very likely to have similar characteristic Ragone plots. With such battery characteristic curves available, as well as the power and energy requirements of a vehicle for a given mission, there is a near-optimum design point within the Ragone plot where the battery weight will be minimized while at same time satisfying the mission requirements. Many of today's battery applications tend to be more energy-limited than power-limited and, thus, most battery research is applied towards increasing the specific energy. For instance, a great deal of research is going into the development of lithium-air batteries, which are projected to have a specific energy of 1300 W-h/kg and a specific power of 0.66 kW/kg (ref. 22). Hopper-type aviation application batteries tend to be more power- rather than energy-limited. Accordingly, the short-range mission requirements of Hopper vehicles may only require battery technologies close to current technology levels.

Figure 9 is a contour map of vehicle sizing results for a 25-nautical-mile (with a 20-minute-reserve segment), battery-powered all-electric 30-PAX tandem helicopter design. The contour color-scale indicates the gross takeoff weight in lb_f as a function of battery specific energy and specific power. Ragone plot curves from Figure 8 for specific batteries are also superimposed on

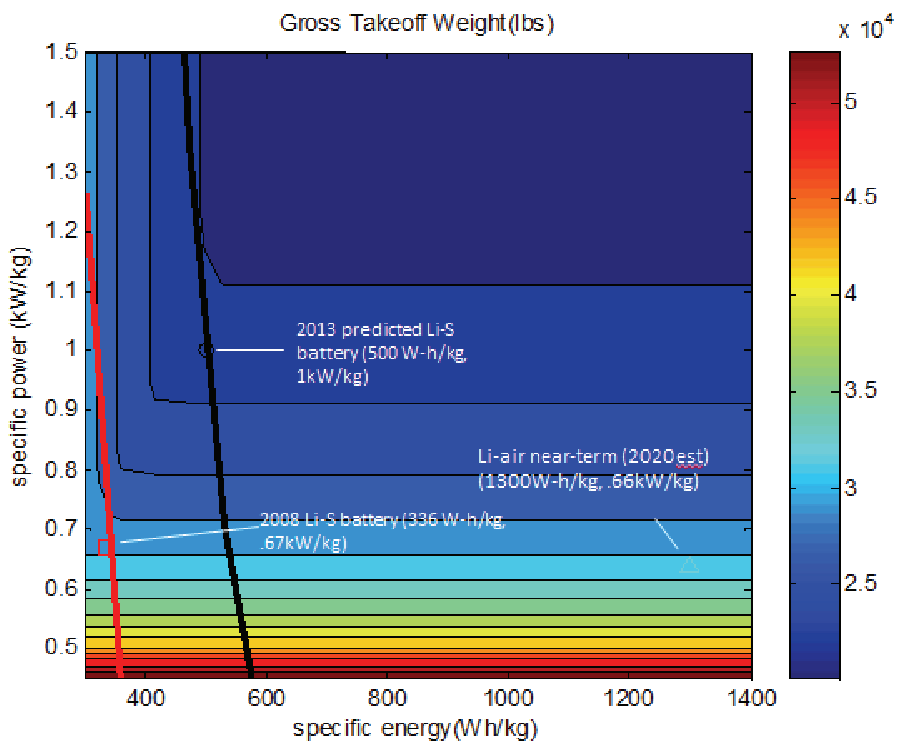


Figure 9. Battery sizing results (25 nautical miles).

Figure 9. Note that vertical near-asymptotic trend lines in the contour plot indicate energy-limited designs, while the horizontal near-asymptotic trend lines indicate power-limited designs—i.e. improvements in battery specific energy will not yield any further significant improvements in the corresponding gross takeoff weight. Additionally, one may follow these Ragone plot curves to find a near-optimum design point/region for that technology level. Furthermore, looking along the positive x- and y-axis directions, one can see these localized regions on the plot where the vertical and horizontal trend lines meet, where the gains in battery-specific energy and specific power begin to have decreasing benefits. Of particularly notable interest is that the target design of a 2013 lithium-sulfur battery (ref. 20) is very close to one such near-optimum design point, and in fact, actually results in a lighter design than a nominally more advanced lithium-air battery with an estimated release date close to 2020 (ref. 22). This is a very significant result, as many previous investigations regarding integration of electric-propulsion technology into aviation concepts have suggested that all-electric battery-based technology will not be feasible for at least another 10–20 years. For missions with as short of range and as specialized as the Hopper concept, there are no apparent major advantages to waiting for new battery technology to develop, as the main focus of battery research is in increasing specific energy, often at the cost of specific power. Thus, it may be advantageous to begin development of flight demonstrators in the near term, rather than waiting for advanced lithium-air battery technology to mature. Comparable sizing results for a 65-nautical-mile-range design are shown in Appendix F.

In addition to purely battery-based designs, hybrid turboshaft-battery schemes are investigated, with the thought that they may be implemented using nearer-term technology rather than a completely electric concept. A sample diagram of the propulsion system is shown in Appendix F and explained as follows: a turboshaft engine is run at its design point, and sized to provide a specified percentage of cruise power, continuously throughout the mission. A battery is then sized to provide the remaining power and energy requirements for the mission, and the whole process is iterated upon until the code converges on a design. This scheme was chosen to take advantage of the fact that turboshaft engines tend to run most efficiently at a specific design point, whereas battery-electric systems can be run at a variety of operational points with comparatively low losses. Sample results for a 25-nautical-mile mission are shown in Figure 10, and results for a 65-nautical-mile mission are provided in Appendix F.

Figure 10 can be explained as follows: the gross takeoff weight is plotted in the y-axis, while the x-axis represents the degree of hybridization. As might be expected, power and energy tradeoffs become more and more important as the turboshaft engine accounts for more of the power requirements. Furthermore, like the case of a pure-electric design, the lithium-air-based design results in heavier rotorcraft than its lithium-sulfur counterpart, with even 2005 lithium-sulfur technology yielding lighter rotorcraft than the advanced lithium-air concepts as the turboshaft accounts for more and more of the power. Again, this is due to the comparatively low energy demand on the system because of the short mission range. The discrepancy between the weights of the fully electric hybrids and the battery-electric design are based on the differing assumptions going into the fixed weight and structural weight fractions outlined previously in Table 2.

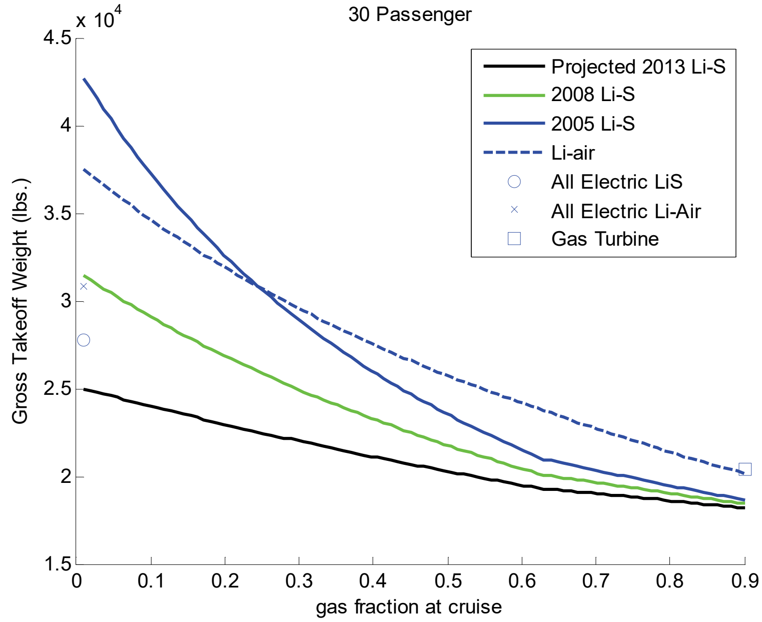


Figure 10. Hybrid sizing results (25 nautical miles).

Fuel-cell-based designs also appear very encouraging (based, in part, on subsystem technology information from references 23–35 and the early rotorcraft fuel-cell-based propulsion conceptual design work of reference 36). The design methodology is taken such that a hydrogen proton exchange membrane (PEM) fuel cell is assumed to have a certain specific power and efficiency (usually taken from the state of the art in automotive technology), and the rotorcraft is run through the mission. From the mission characteristics and conversion efficiency, gaseous hydrogen and fuel tank mass are determined based on an input-tank pressurization criteria (700 MPa tanks were primarily used). Simple Tresca failure criteria with a factor of safety calibrated to match the current 12-percent state of the art in pressurized tank technology were used. A diagram of the notional propulsion system is shown in Appendix F.

Note that, like in the case of a battery, there is a tradeoff between energy and power in fuel cells, although the mechanism is somewhat more complicated, due to the presence of the membrane, and is largely dependent on how the device is discharged. As a result, interpretation of fuel-cell-based vehicle gross takeoff weight curves is perhaps not as straightforward as interpretation of battery-based vehicle gross takeoff weight curves. Nonetheless, Figure 11 does suggest a tradeoff between operating efficiency and specific power; this figure also shows results for some fuel cells produced by Nissan and Honda (refs. 28–29, and 30, respectively). A similar plot for the fuel-cell-based vehicle gross takeoff weight, sized for a 65-nautical-mile mission, is presented in Appendix F.

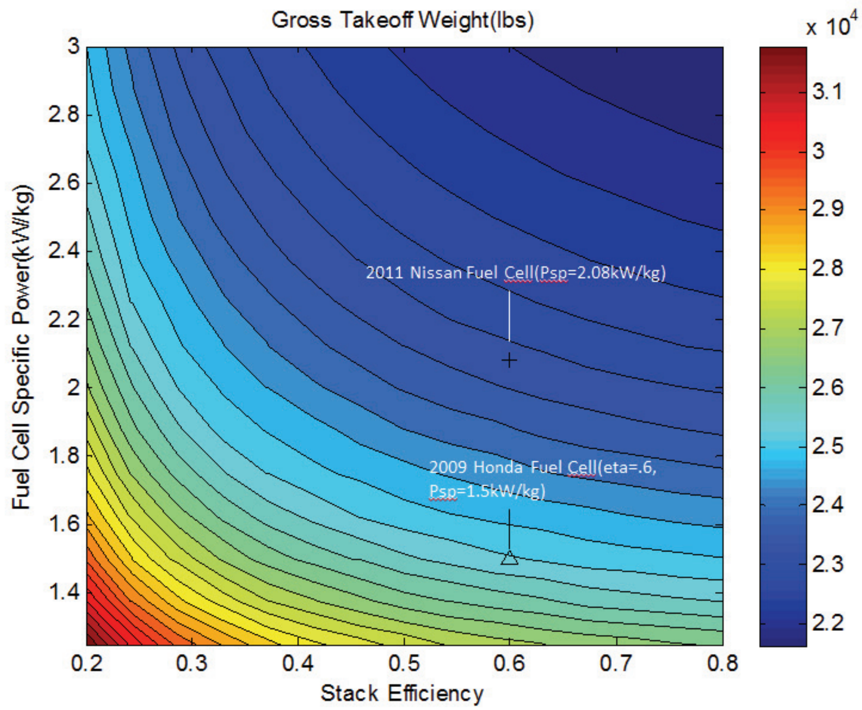


Figure 11. Fuel-cell sizing results (25 nautical miles).

There are considerably less data published for fuel cells than for batteries, although the data from Honda and Nissan (refs. 28–30) suggest that there has been substantial improvements in fuel-cell technology in the past 5–10 years. By way of comparison, a Honda fuel cell circa 1999 only possesses a specific power of around 0.3 kW/kg, which would result in impossibly large designs. Whereas a rotorcraft designed for the same mission using 2011 fuel-cell technology yields a gross takeoff weight of 24,500 lb, while a gas turboshaft design of the same range has a gross takeoff weight of 20,800 lb. Fuel-cell technology appears to have overcome a major hurdle, thus making progress with fuel-cell-based rotorcraft design potentially promising.

The last configuration investigated in this study is the fuel-cell serial-hybrid design, which possesses several advantages over a standalone fuel-cell concept. The first advantage is that batteries often have a higher specific power than fuel cells, thus the propulsion system can be designed so that one component can provide power for shorter, higher-intensity segments (such as hover), while the fuel cell (which is normally power-limited), can be used for the longer, lower-power cruise segments. Second, the benefit to connecting the devices in a serial arrangement is that fuel cells may have a somewhat sluggish response to changes in power demands, particularly in “cold” conditions; the presence of the battery may eliminate this lag.

The analysis of a fuel-cell serial hybrid entails assuming the battery requirements are constrained such that it can power all flight conditions, while powering 5 minutes of cruise flight after takeoff by itself (a large constraint considering the scope of the mission), and is connected directly to the motor. From these assumed constraints, a battery is chosen based on the given power and energy requirements, and a near-optimum point found from the Ragone plots shown in Figure 8. The fuel cell is then sized to provide the remaining energy requirements of the mission. A schematic of the mission power requirements and the state of charge for a 65-nautical-mile design are shown in Appendix F. Additionally, a diagram of a 65-nautical-mile design with the relative volumes of the fuel cell, the fuel tank, and the battery, are shown in Figure 12.

For many hydrogen-based designs, volumetric constraints can be an issue. The relatively short range, coupled with the high-power requirements of Hopper-based missions, result in correspondingly small tank volumes, as Figure 12 demonstrates. Thus, tank volume does not appear to be a limiting factor in the design of the fuel-cell-based rotorcraft sized for the Hopper mission application. Weight, however, is a much more important figure of merit in these fuel-cell-based Hopper designs. To illustrate, Figure 13 displays a breakdown for each of the electric-propulsion system designs, by subsystems or weight groups, calibrated for the 25-nautical-mile scale, while in Appendix F a similar chart is presented for the 65-nautical-mile-range design. Note that for all rotorcraft conceptual design sizing cases using a battery, a near optimum battery was found from the 2013 Li-S Ragone plot shown in Figure 8.

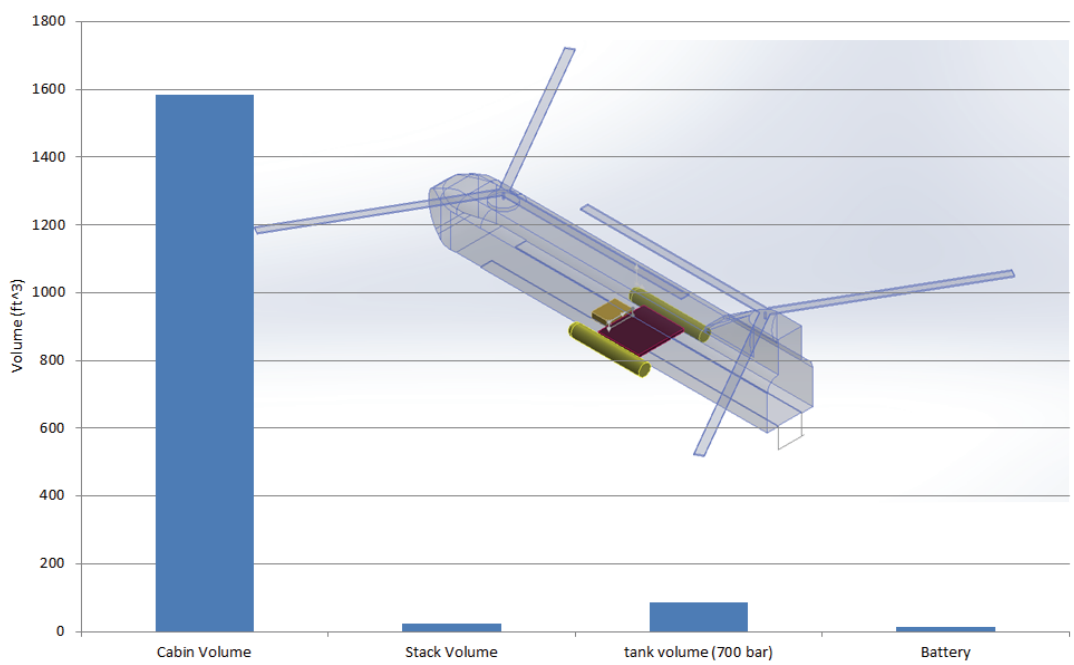


Figure 12. Fuel-cell serial-hybrid 30-passenger rotorcraft volumetric sizing diagram (65 nautical miles).

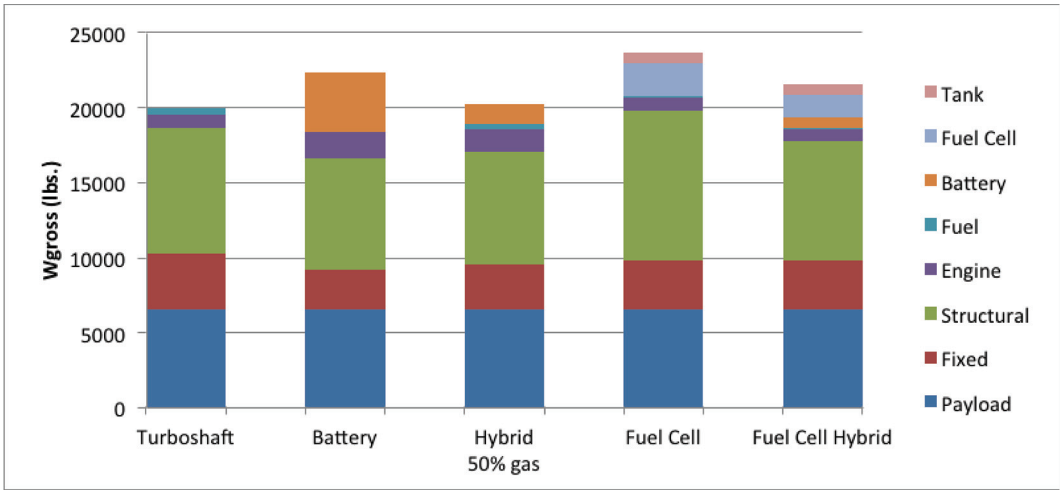


Figure 13. Design weight breakdown (25 nautical miles).

Figure 13 shows that, at the 25-nautical-mile mission range, many of these all-electric configurations appear to be quite competitive with turboshaft-based designs. Moreover, each of them uses current or near-term technology, such that a demonstrator vehicle may be constructed relatively soon. Additionally, the very short range of these missions makes the battery option particularly attractive, in part because of their relatively simple operation and their often higher efficiency, as well as the relatively low cost of electricity compared to hydrogen. The fuel-cell designs, for instance, require the implementation of a hydrogen network, which is a much larger startup cost. When scaling up to larger missions, the battery-electric design becomes less attractive from a weight perspective, as Figure 14 illustrates.

Figure 14 indicates that, when increasing the mission range from 25 nautical miles to a 65-nautical-mile range, the battery size becomes substantially larger (yielding a vehicle gross weight of ~28,000 lb vs. ~22,000 lb) and, thus, may not necessarily be an acceptable propulsion choice for that increased mission range—at least with near-term battery technologies.

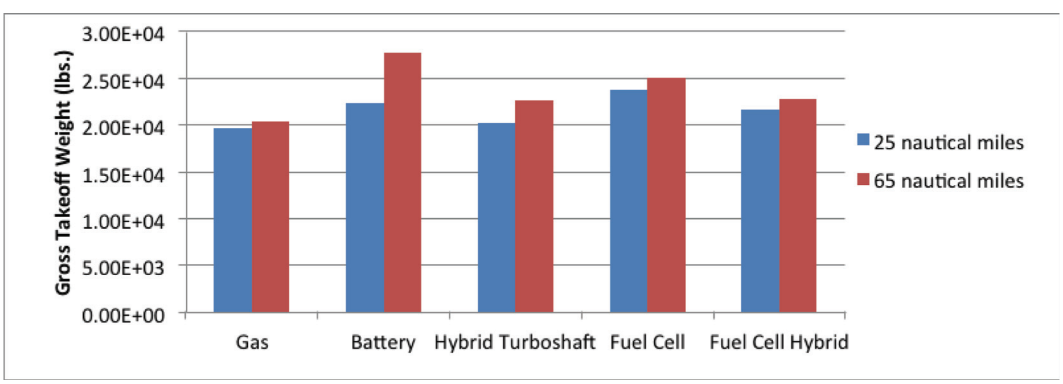


Figure 14. Gross takeoff weight range comparison.

In looking at integration of these design results into the Hopper transportation system network, energy usage for each vehicle design can be modeled in two parts. The first is the energy used for takeoff, climb, and landing, which is computed at takeoff. The second part is an additional energy usage per unit distance, based on the design cruise velocity. A chart of these two sets of energy requirements is shown in Figure 15 for the 25-nautical-mile cases. The energy estimated for cruise is 27.1 kW-h/nautical mile. The reason for the large difference between the gas (turboshaft engine) and electric vehicles is a reflection of the relative conversion efficiency of the different systems. An all-electric system is much more efficient than a conventional turboshaft system.

Both the energy for takeoff as well as the additional energy per nautical mile is scaled based on the number of passengers being transported. The resulting total energy usage is factored into the Hopper network total daily energy expenditure estimates. Two additional key relative energy usage contributors are: first, the gross takeoff weight, in that heavier systems require more energy and, second, the energy conversion efficiency, in that the battery discharge losses tend to be small compared to the other systems, while fuel cells tend to be more efficient than traditional combustion methods.

The issue of electric-propulsion system scaling should be further addressed in follow-on detailed studies, particularly for battery-based electric-propulsion designs. To illustrate this issue, by way of comparison, the 25-nautical-mile design uses a near-optimum battery that possesses a total capacity of 866 kW-h while the largest Tesla Model S automotive battery only stores 85 kW-h of energy. Thus, even for these exceptionally short ranges, the power and energy demands and overall size of a Hopper battery are quite large, and may require new engineering solutions to address issues like battery heating. However, one should note that lithium-sulfur chemistry

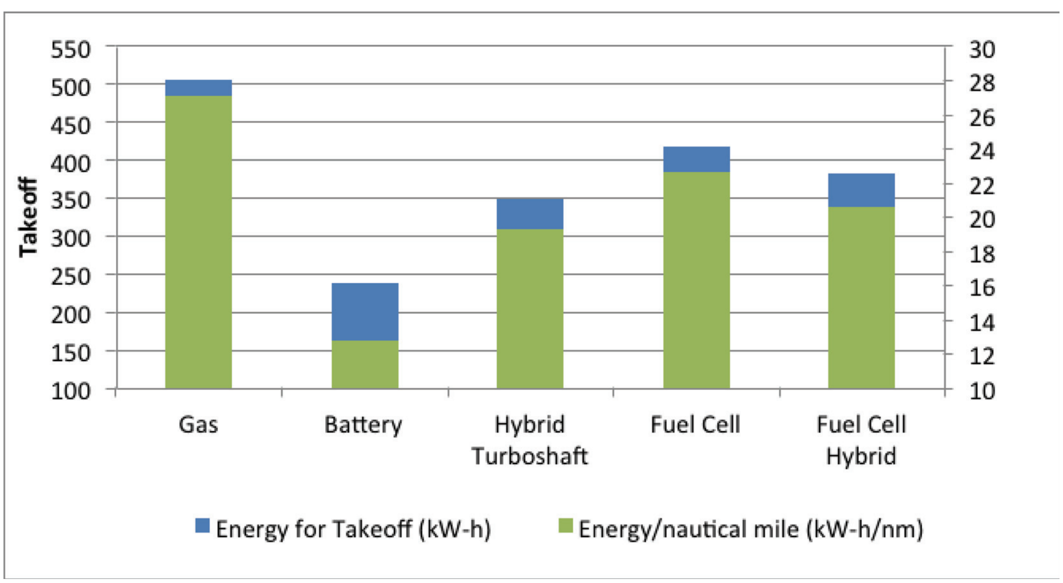


Figure 15. Hopper energy usage (25-nautical-mile range).

is inherently more stable than the lithium-ion battery, so the risk of a lithium-sulfur battery fire is much less likely than for a lithium-ion battery of comparable size.

The discharge cycle life of Hopper-sized batteries is another design characteristic that merits more detailed investigation. By way of reference, the battery design used for the Hopper sizing plots has a lifecycle of over 500 cycles, which compares favorably to a normal lithium-ion battery life of around 400–1200 cycles. Given the repeated charging of batteries necessary to support a Hopper transportation system network, old batteries will have to be replaced frequently with new batteries. Finally, considering the mission that the rotorcraft is designed for, the recharging characteristics of lithium-sulfur batteries are largely unknown; the potential benefits of designing the vehicle such that the battery is replaced with a fully charged battery at each "hop" vs. charging the battery upon landing needs to be analyzed in more detail in future work. Figure 16 presents a first-order projection of the solid waste disposal challenge of expended, or more correctly "consumed," Hopper batteries at a few different discharge cycle lives and different daily ridership levels. Note that the number of daily flights and mean distance traveled between stations follows from BaySim simulation results presented later.

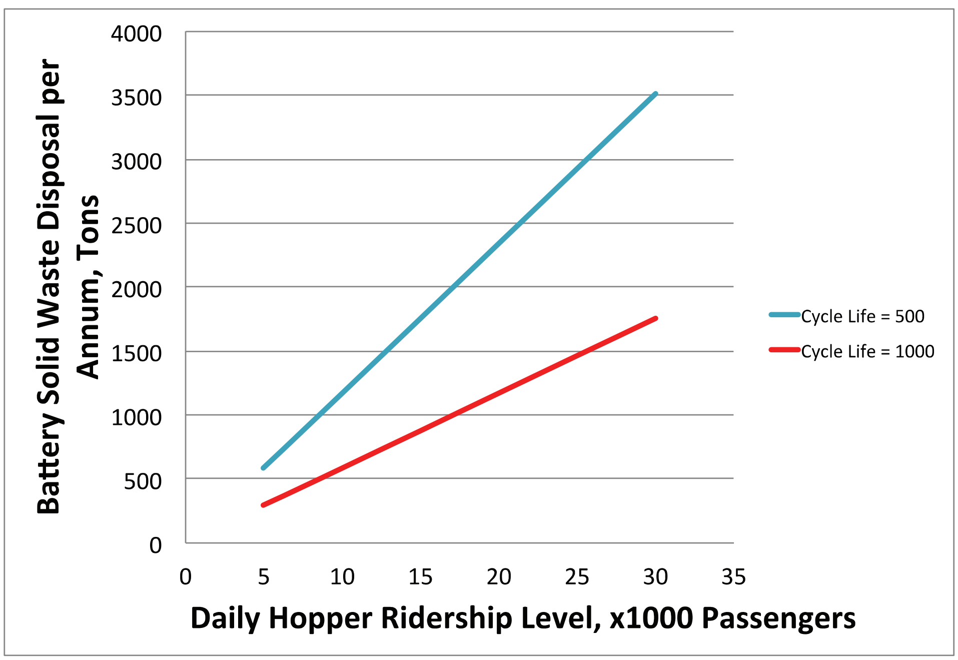


Figure 16. Solid waste disposal challenge for Hopper batteries.

Network Models

BaySim Metro/Regional Aerial Transportation System Modeling

Only one network topology was examined in Phase I; this was an on-demand station-to-station (any-node-to-any-node) network. Alternate network topologies were examined in this Phase II effort in the pursuit of more efficient flight operations as well as minimizing air traffic management concerns. The network topologies examined in this study are, in one sense, tailored to the San Francisco Bay Area, but similar networks are likely applicable to other metropolitan areas throughout the country.

The current study is focused on defining refined network topologies for a metro-regional VTOL aerial transportation system centered in the San Francisco Bay Area. One particular new refinement to the network design effort is to consider a notional evolution/build-up of such an aerial transportation system from a very small (single city-pair) system to a full regional network (Fig. 17a–d; network connections highlighted with purple lines).

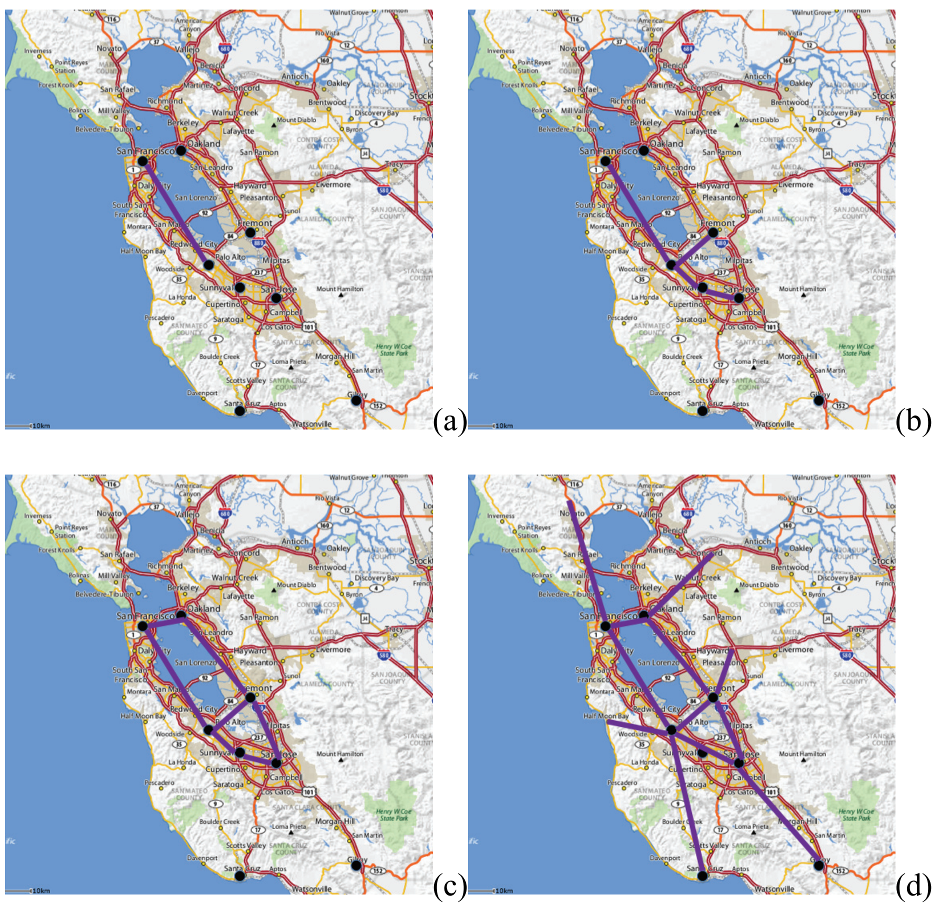


Figure 17. Aerial transport system network topology design/evolution: (a–d) one notional sequence of network implementation/evolution over time.

The BaySim discrete event simulation for the Hopper network problem was developed as a part of the Phase I effort. Details of the initial version of BaySim are reported in reference 1. Additional extensions/enhancements were made to BaySim for the Phase II effort. BaySim was an essential element to not only the Hopper vehicle conceptual designs but the network design(s) as well. Through BaySim simulation result metrics the speed, range, and cruise altitude for the Hopper vehicles was iteratively specified with the vehicle sizing tools used. Through the BaySim simulations the network layout (number and location of vertiports/stations) was also iterated upon several times for various different prescribed ridership levels.

BaySim: a discrete event simulator

The computer simulation of individual human behavior is (and will always be) an imperfect science. An individual's choices and daily behaviors are often complex, usually irregular, and sometimes illogical. But when a large group of individuals is aggregated to form a population, the behavior of that population can be conveniently modeled by statistical averaging over the individuals. This process is commonly referred to as a "microsimulation." A common example of a microsimulation would be the study of highway traffic patterns, with gross characteristics of the traffic flow extracted from the statistical aggregation of individual autos. Inside a microsimulation, the variation in the behaviors of individuals is commonly modeled with a relatively small set of stochastic mathematical functions that create appropriately bounded and distributed randomness in individuals (usually subject to Gaussian-like distributions). This is especially true for actions that all individuals perform with some amount of regularity. The transportation models used herein assumed that during the work week, the demand for transportation arises from the need of individuals to travel from home to workplace and back again, with this cycle repeating for each individual once every 24 hours. Once the rules that govern daily passenger decisions and behaviors are described in software, they become the framework for a discrete event simulation (DES) of the demand for transportation in an extended metropolitan area. In this case, the daily demands on a metro-regional transportation network are derived from analysis of the aggregate behavior of passengers as they move through the network. This demand for transportation is provided as input to a fleet optimization process (described in detail in Appendix E), which is used to determine the total number of vehicles required to satisfy the transportation demand while minimizing the overall cost of transportation. Note that this approach to transportation network analysis does not start with either a predefined vehicle concept or a preset schedule. Instead, every attempt was made to develop a bottoms-up demand model from the two most basic elements: realistic passenger behaviors and the geographic characteristics of home, air terminals, and workplace. Somewhat surprisingly, vehicles in the BaySim DES need not be initially described beyond the most basic performance characteristics of capacity (passenger count) and speed.

BaySim, the custom DES simulation tool developed for this study, has several noteworthy features, including the modeling of individual passengers and aircraft. Each passenger transitions through nine different states during a 24-hour day, and each aircraft transitions through four states during each flight. Transition between states is governed by a finite-state machine using combinations of time of day, random numbers, and queuing/scheduling strategies. Currently, the population is segregated into three primary shifts (day, evening, and night), and geographically distributed around the major population centers of the Bay Area. On-screen graphics provide animations of both passenger and aircraft states and motions, and real-time plots of network statistics (delays times, queue lengths, departure and arrival counts, etc.) are available. A screen capture from the BaySim DES is shown in Figure 18. The left pane of the image provides a graphic display of the status of all population members. Solid green dots represent individuals who are at their home or traveling along the surface toward their home air terminal. Red triangles indicate passengers who are currently grouped together aboard an aircraft and flying toward their workplace air terminal. Black squares show individuals moving along the surface from their workplace air terminals towards their worksite. Blue dots show workers who have finished their workday and are returning along the surface to their worksite air terminal. Blue triangles represent passengers who are aboard return flights that will take them to their home air terminal, and green open dots show individuals who have arrived back at their home air terminal and are moving along the surface to return home at the end of their workday.

Note that adapting the BaySim DES to other geographical areas of interest and/or station network topologies should be straightforward, but would require geographic information about home and worksite locations as input. Aircraft speed, capacity, and minimum required load factors are all available as inputs, allowing for aircraft of various capacities to be simulated.

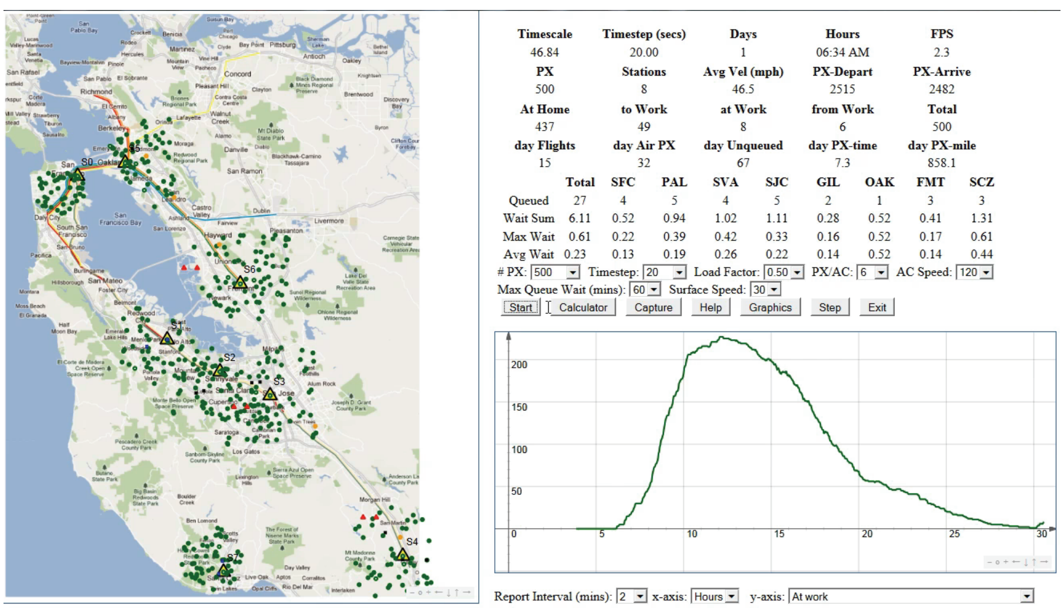


Figure 18. Another screen capture of BaySim DES animation.

To quantify the passenger throughput metrics, understand vehicle-sizing needs, and provide a system simulation upon which optimization can be performed, a daily passenger movement model was developed. BaySim is a DES (see reference 37 for more details) that models passengers' behavior and their interaction with the Hopper air vehicles. The passenger agents in the model move through a series of discrete states over a 24-hour period, simulating their daily routine of arising, preparing for work, traveling to work, working, and returning home. The passengers' homes and worksites are distributed around the Bay Area population centers. Each passenger's movement through the transportation network is simulated. A set of queuing algorithms and flight-generation heuristics are used by BaySim to generate Hopper flights between stations, based on the presence of individual passengers at each station. This results in a flight history logfile containing flight departure and arrival times and the associated passenger load for the entire period of simulation. (The detailed modeling features of the BaySim simulations are discussed in Appendix A.) A daily Hopper flight schedule was derived from this data for subsequent input into fleet assignment optimization and air traffic simulation. It is important to note that BaySim does not do "tail-number tracking" of individual aircraft, but attempts to intelligently create the potential passenger demand for flights by assuming that aircraft are always available to meet the departure demand. Subsequent fleet optimization tries to meet this demand for flights in an efficient way while minimizing the number of aircraft and the number of repositioning flights.

Passenger population

The range of potential ridership levels was developed using some general San Francisco Bay Area statistics. The Bay Area Rapid Transit (BART) system supports approximately 370,000 riders on weekdays, while the number of Bay Area "tech industry" workers in 2008 was reported to be approximately 386,000 (https://en.wikipedia.org/wiki/Bay_Area_Rapid_Transit; last accessed 2017). The peninsula railroad service (Caltrain) between San Jose and San Francisco serves over 40,000 passengers per day (http://en.wikipedia.org/wiki/Caltrain; last accessed 2014), and this level of ridership (spread out across the entire Bay Area) was deemed by the team to be a worthy end goal for Hopper passenger service. With these considerations, 6 ridership levels of 5,000, 10,000, 15,000, 20,000, 25,000, and 30,000 passengers were chosen for study so that trend information would be available. No attempt was made to determine ridership level by other practical considerations (such as ticket prices, convenience, flexibility, point-to-point travel speed, etc.); such an effort would require extensive specific demographic studies and was therefore out of scope with respect to the primary objectives.

The workdays for passengers were distributed such that 65 percent of a population would work a "day" shift that started between 4:00 AM and 10:00 AM, lasting 7 to 9 hours. Twenty percent of the population was assigned to a "swing" shift, which started between 1:00 PM and 6:00 PM, and also lasted between 7 to 9 hours. Five percent of a population was placed into a "night" shift that started between 9:00 PM and 2:00 AM, and lasted between 7 to 9 hours. The starting times for the remaining 10 percent of the population were then randomly distributed between 8:00 AM and 3:00 PM, with workdays lasting between 4 to 5 hours. These workday start times and durations were not based on any specific demographic data, but were chosen through group consensus within the study team.

Short recap of Phase I BaySim work

Figures 19 and 20 are representative Phase I BaySim simulation time history results. In both figures, the passenger states are captured in an hour-by-hour basis. Figure 19 shows the passenger count for passengers at home and at work. Figure 20 shows the passenger count for passengers traveling to and from work.

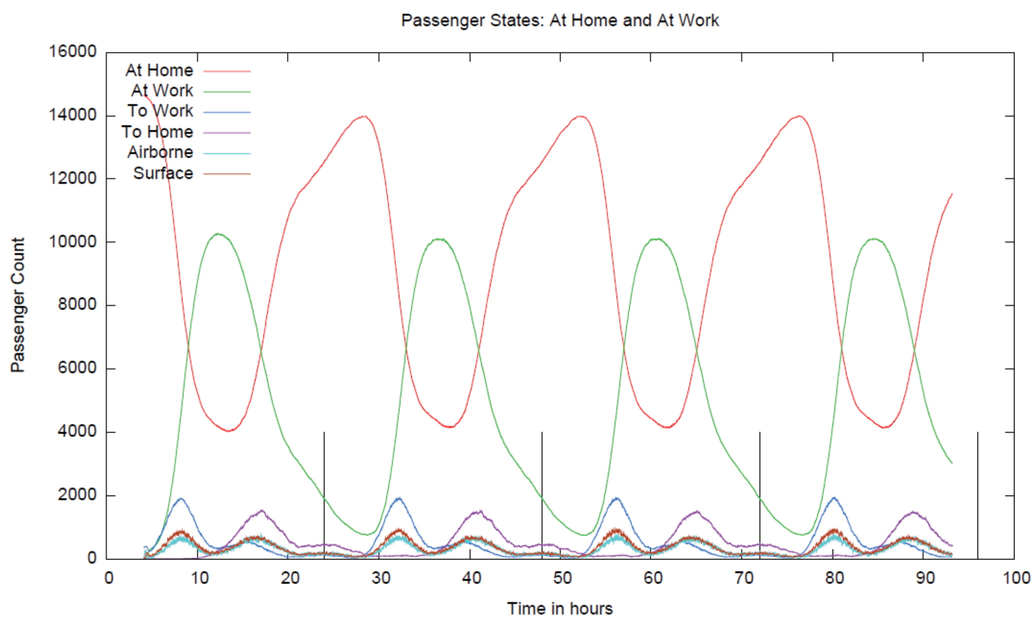


Figure 19. BaySim passenger count estimates of passengers at home and at work.

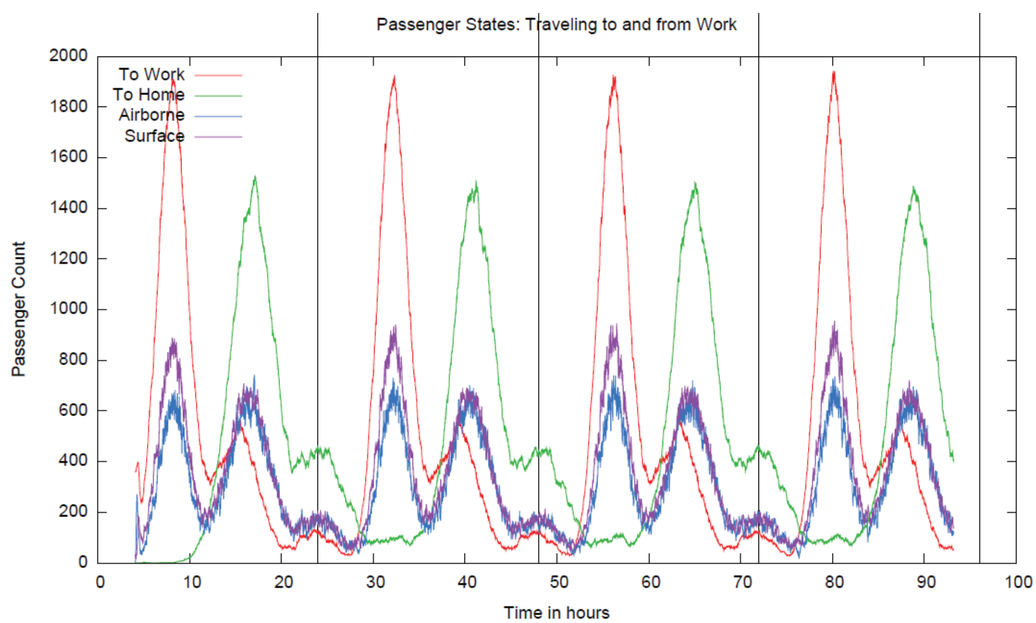


Figure 20. BaySim passenger count estimates of passengers traveling to and from work.

Table 3. BaySim Results Summary

Population	(minutes) MBD	Daily Flights	(maximum) Simultaneous Flights	(preflight) Max Delay	(daily) PX-Miles
5K	3	1940	40	10	270K
15K	3	3140	47	15	834K
15K	1.5	4010	71	6	836K
45K	1.5	6250	84	13	2494K
45K	1	6850	100	3.5	2498K

BaySim analysis for the initial Phase I study yielded the following insights: average trip length was 28 statute miles; average time in air per flight was 14 minutes; at the maximum assumed ridership level of 45,000 passengers per day supported by the aerial transit system, 1712 operations per day per station (assuming 8 stations) would be carried out. By way of comparison, San Francisco International (SFO) airport currently supports approximately 1100 operations per day (arrivals and departures) for 112,000 passengers per day (PX/day). Table 3 provides additional details for all assumed ridership levels studied.

Numerous Hopper network metrics and estimates were made possible with the BaySim simulation. For example, initial BaySim results allowed the following estimates to be made: 1) At the 5K per day passenger level, the estimated energy expenditure for the aerial transit network was 6,700 BTU/PX-mile, with an average 5.1 PX per vehicle; 2) at the 15K per day passenger level, the energy expenditure was estimated at 4,530 BTU/PX-mile, with an average of 7.5 PX per vehicle; and 3) at the 45K per day passenger level, the energy expenditure estimate was 2,570 BTU/PX-mile, with 13.2 PX per vehicle.

Phase II BaySim enhancements

Table 4 summarizes several key differences between the Phase I and Phase II versions of BaySim.

Table 4. BaySim Differences Between Phase I and II Studies

	Phase I	Phase II
Stations	8	3 to 14
Networks	Fully connected	Multiple topologies
PX Routing	Direct	Dijkstra Multi-Hop (ref. 4)[4]
PX Queuing	FIFO (first in–first out)	FIFO
Population Sizes (K)	5, 15, 45	5, 10, 15, 20, 25, 30
Air Travel Times	Constant	Minimize los-of-separation (LOS) events
Population Data	Assumed	Census/zip code

[4] The Dijkstra algorithm was published in 1959 by E. W. Dijkstra and is used to find the shortest paths between points in a network. It was adopted/adapted for use in the BaySim modeling of various potential Hopper networks in the San Francisco Bay Area.

In order to improve the modeling of the potential commuter population and its movements throughout the San Francisco Bay Area, several sources of demographic data were investigated. Identifying and selecting appropriate demographic dataset(s) is a challenge, as the final collection must seek a balance between availability, usability, geographic coverage and granularity (i.e. the coarseness or fineness of the geographic expanse of the demographic data), and availability of correlated data (such as commute and employment information). 2010 census data organized by zip code (including geographic, commuter, and employment data) provided a workable balance, and is freely available online in a format that is straightforward to read via software with good coverage of the populated regions of the United States. The freeware toolset ShapeLib (available from http://shapelib.maptools.org) was used to extract the zip code polygonal geography and population data (from http://www.census.gov/geo/maps-data/data/tiger-data.html under the "2010 Census Demographic Profile" tab). Four custom data extraction software tools were written to extract the polygonal boundaries and demographic data for every zip code with a centroid located within a bounding box used to define the greater Bay Area. Business employment data (including the number of businesses and employee counts) for the identified Bay Area zip codes were extracted from 2010 census data (http://www.census.gov/econ/cbp/download/10_data/index.htm). Finally, the percentage of the resident population of each county that commutes outside of the county for employment was extracted using web tools and census datasets available at http://onthemap.ces.census.gov.

Given an initial total population of commuters, the population distributions of commuter residences and employment worksites within each zip code can be created using simple ratio scaling laws and an estimate of the local number of residents that are long distance commuters. The specific geographic location of homes and worksites is distributed randomly within a specific zip code, but the number is scaled according to the 2010 census data for each zip code. Each home and potential worksite is assigned to a network station based on proximity, and each network station is assigned to a city/county pair that reflects local area commute statistics. The final assignment of commuters to jobsites is done using an iterative process that attempts to satisfy the following guidelines:

Rule 1: Each commuter must travel to a worksite that is served by a network node different from the node that serves his/her residence.

Rule 2: The estimated flying time for a commuter must be less than the estimated driving time.

Rule 3: The number of workers at each jobsite is scaled and limited using the employment statistics of the businesses in the local zip code.

Rule 4: Candidate residents and worksites must be within user-specified distances from station nodes.

A sample image of an initial population of 5000 commuters using a network of 5 stations is shown in Figure 21. The first image (Fig. 21a) shows residents as white dots, with worksites shown as black dots, and stations as white squares with black borders. The second image (Fig. 21b) shows the travel paths for each worker after assignment to a jobsite. The dark gray lines show the path of each commuter from their residence to the nearest network station, and light gray lines connect each station to the worksite it services.

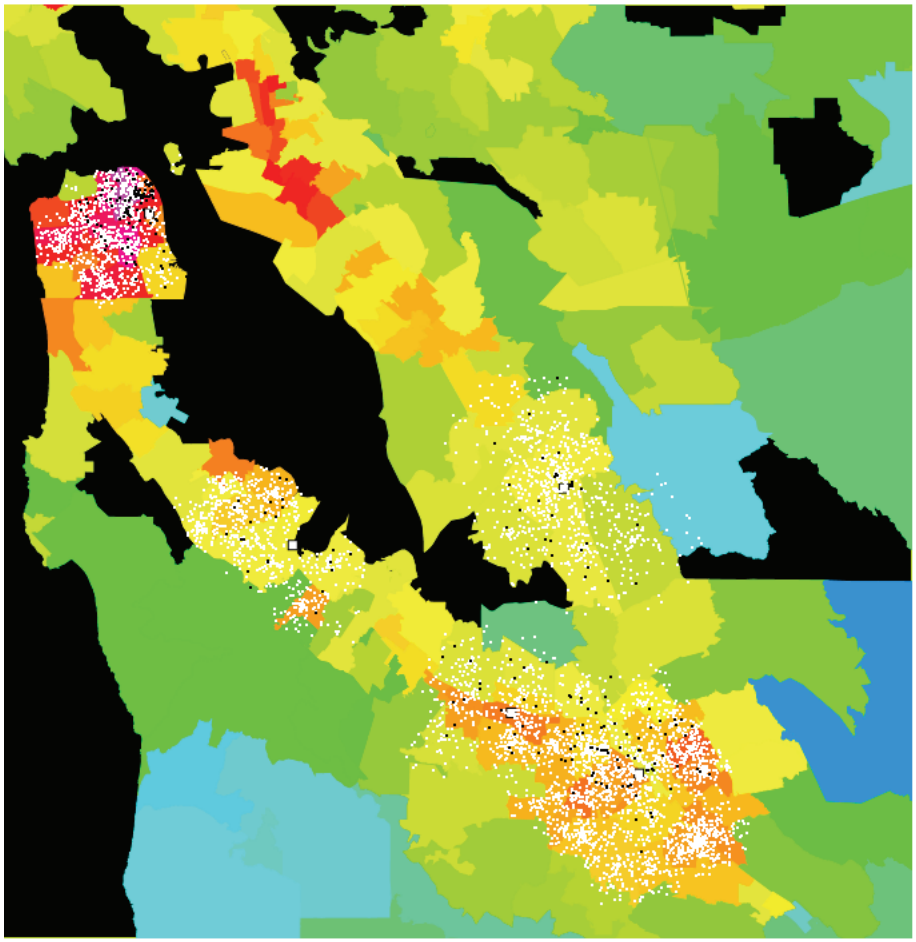

(a)

Figure 21a. Census data in support of BaySim modeling.

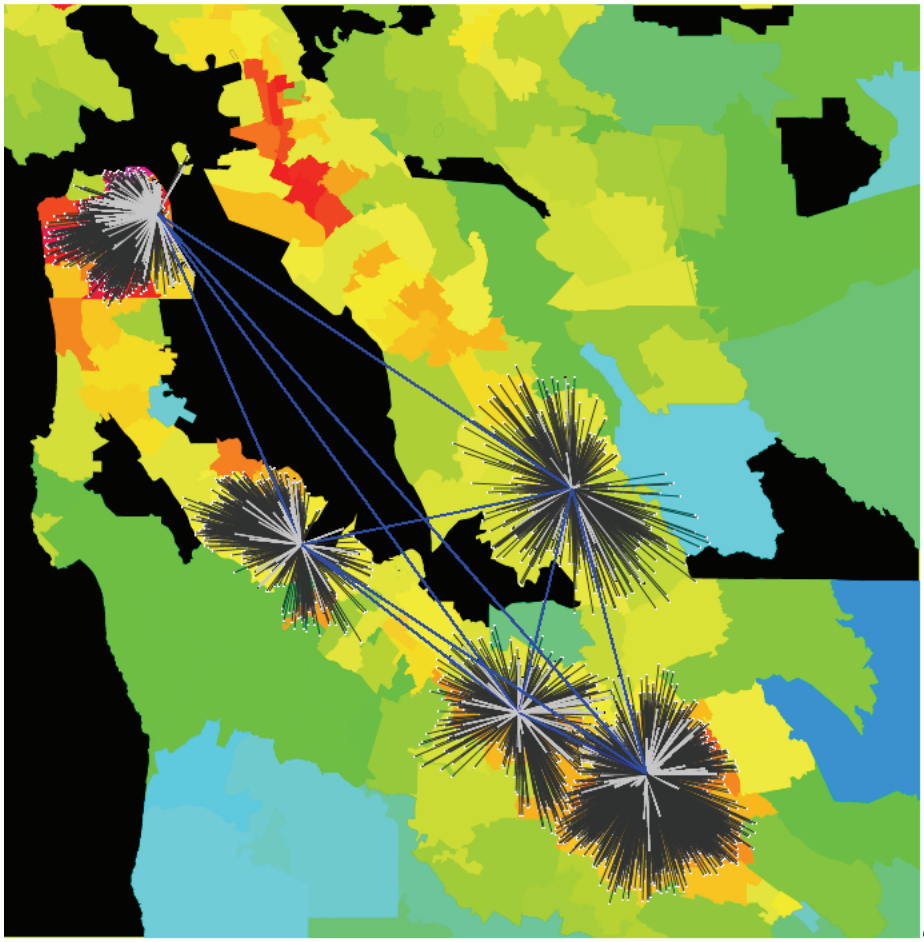

(b)

Figure 21b. Census data in support of BaySim modeling.

This new data-driven approach for initial distributions of commuter residences and worksites is much more representative of current and future populations than the initial, simple approach used during the Phase I Hopper study. It is also easily adaptable for other parts of the United States, as it relies only on readily accessible 2010 census and zip code data.

The networks used during the Phase I Hopper study assumed that each commuter would be willing to wait for a direct flight from residence station to worksite station. The rules for the queuing of passengers and the departures of flights were the same for both Phase I and II, except for one very important distinction. While Phase I queued each passenger for a direct (non-stop) flight from origin to ultimate destination, the network topologies of Phase II required many passengers to take multiple flights in order to reach their destination. Upon arrival at a station (and before queuing for their next flight), a Dijkstra evaluation (ref. 4) using current network statistics for the remaining possible flight legs was used to select routes and queue passengers in an attempt to minimize the remaining travel time. These evaluations were performed immediately upon arrival at a network node using the most recent queue and transit times for each network leg.

Candidate networks also assumed a more practical ring topology with additional spokes to outlying suburbs. This helped to avoid direct overflights of the San Francisco Bay and restricted hopper traffic to non-interfering sky lanes (aka flow corridors), but made nonstop direct connections between some of the most distant nodes impossible.

Incorporation of realistic flight constraints

Realistic Air Traffic Management (ATM) traffic avoidance considerations were implemented by updating flight times for each network leg by a table look-up. The BaySim flight times were harmonized to dynamic time-of-day flight planning analysis results (detailed later in this report) to those flightpaths that minimize ATM conflicts. These dynamic time-of-day flightpaths were defined in terms of, and updated hourly to reflect, traffic density analysis to minimize conflicts with commercial aircraft traffic.

Evolutionary network buildout to mimic possible deployment

During Phase I of the Hopper project, the network configuration assumed that direct flights would be available between any pair of station nodes. The second phase of the Hopper project assumed that an actual network would likely grow over time, and that the simplistic NxN network would likely be replaced by something resembling a ring and spoke configuration that would reduce passenger queuing delays, improve load factors, and avoid overflights of San Francisco Bay. The network evolution is shown in Figure 22, starting with a two-leg (three-station) network serving San Francisco, San Carlos, and Palo Alto. It was assumed that this network would eventually grow to five stations that would serve the peninsula, then expand to the East Bay to include Oakland and Fremont. In the final stages, a complete ring would be created to encompass both sides of the bay, and would eventually be followed with feeder spokes to the outlying communities of San Rafael, Concord/Walnut Creek, Dublin, Gilroy, Santa Cruz, and Half Moon Bay. All stations were co-located with BART, Caltrain, or existing local airports when possible. As these networks were purely notional, no considerations were given to the intricacies of local politics, zoning, neighborhood acceptance, no-fly areas, etc.

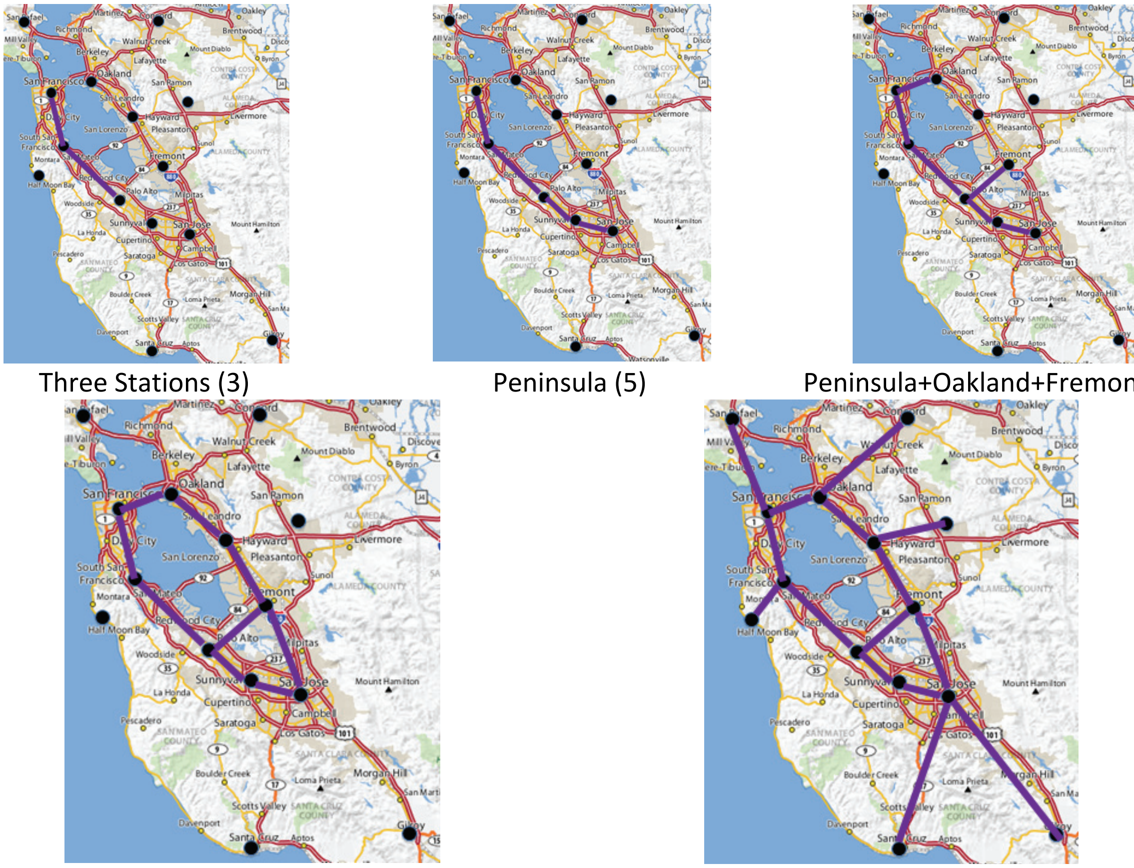
Calculating energy consumption at the vehicle and system levels

The calculation of total daily energy use and energy intensities (in kW-hours/(PX-mile)) were performed using energy regression formulas provided by the vehicle design team. Expressions for the various power systems technologies contained terms dependent on both distance flown and passenger count, and were computed as:

Energy_Battery = 167.96 + 2.351 * iPX + fDist * 0.868976 * (9.0248 + 0.1263 * iPX)

Energy_Gas = 335.28 + 5.6688 * iPX + fDist * 0.868976 * (17.982 + 0.3040 * iPX)

Energy_BatteryGasHybrid = 236.14 + 3.7871 * iPX + fDist * 0.868976 * (13.06 + 0.2095 * iPX)



Three Stations (3) Peninsula (5) Peninsula+Oakland+Fremont (7)

Ring (8) Ring+Spoke (14)

Figure 22. Ring-spoke network evolution.

Energy_FuelCellHybrid = 265.14 + 3.8843 * iPX + fDist * 0.868976 * (14.339 + 0.2101 * iPX)

Energy_FuelCell = 302.17 + 3.885 * iPX + fDist * 0.868976 * (16.337 + 0.2101 * iPX)

In the preceding expressions, the energy required for a flight is in kW-hours, iPX is the number of passengers on a flight, and fDist is the flight distance in statute miles. The first two terms of the expressions were used to create estimates of the energy used during VTOL (takeoff, climb, descent, and landing) operations; terms including fDist are used to estimate energy required for cruise.

Additional software

During Phase II of this study, several additional software tools were created for extracting zip code polygon corner points and for the preprocessing of the population and business census datasets. A new flight visualization tool allows for quickly replaying BaySim simulation logfiles and developing relevant output metrics without requiring entire simulations to be rerun.

Initial study on the effect of departures per hour

Initial Phase II BaySim simulations with 30K commuters quickly showed that in order to avoid a massive backlog of queued passengers, flight departures at any one station would sometimes need to exceed one per minute. The study team group consensus suggested that one per minute was an aggressive upper limit for the departure rate at any station (even for a future automated departure control system), so all Phase II simulations were subject to this one-per-minute departure restriction. No similar restriction was placed on the number of arrivals per minute at a station, i.e. unconstrained arrivals per minute were allowed in the simulation.

Summary of networks results

Results for the simulated networks with the various population sizes are presented in Figures 23–51. The simulation results in these figures encompass the complete set of multiple (over 30) BaySim simulation runs performed during this Phase II study. These BaySim results provide valuable insights into the overall performance and operational efficiency of the various network topologies, given the assumed daily ridership population.

Figure 23 presents results for the estimated number of flights per day being flown by the Hopper fleet. In all results presented it is assumed that a single vehicle type is employed in the Hopper fleet—a 30-PAX tandem helicopter configuration. The vehicle performance characteristics used in the BaySim simulations are drawn from the Phase I NDARC and Phase II Stanford conceptual design/sizing tool results. As anticipated, Figure 23 shows a relatively linear relationship between ridership population size and number of Hopper flights. Figure 23 also reveals that there are critical thresholds whereby the smaller Hopper networks are not able to sustain/support the larger ridership population sizes. For example, it would appear, given these BaySim results, that in order to support ridership levels in excess of 25K passengers per day, a Hopper network with at least 7 stations would be required. Further, the estimated large number of daily flights required to support various ridership levels reinforce the criticality of developing innovative urban airspace air traffic management solutions to accommodate this projected increase in number of flights above and beyond the current commercial air travel levels.

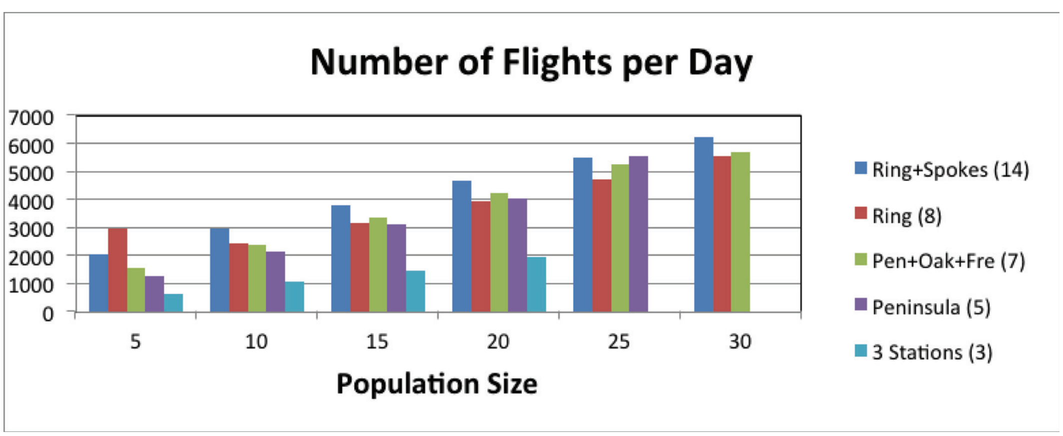


Figure 23. Number of Hopper flights per day.

Figure 24 presents the estimated average load factors for the Hopper flights. Note that the maximum allowed queue delay has a direct influence on the minimum load factor; i.e. if the projected queue delay exceeds the prescribed threshold, then the Hopper flight is released irrespective of load factor. The load factor results also substantiate the earlier presented results wherein large ridership populations, in excess of 25K daily passengers, cannot be supported by the smaller network topologies. The opposite is also true, though—i.e. larger network topologies tend to drive down average load factors for a given assumed ridership level.

Figure 25 presents the BaySim results for the estimated average passenger queue delay while waiting for a single Hopper station-to-station flight leg. (The more flights/legs per a given residence/work commute means more commulative between-flight delays at the vertiport stations per commute.)

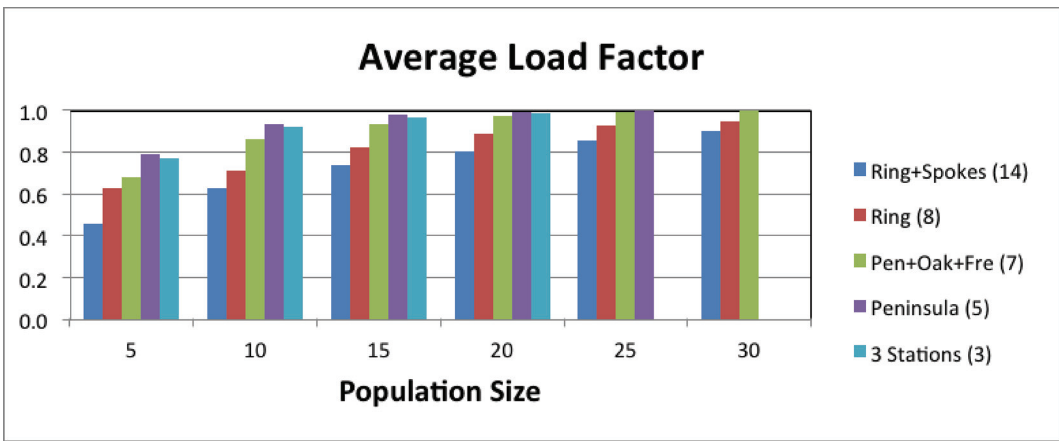


Figure 24. Average estimated Hopper load factor (assuming a uniform fleet of 30-PAX tandem helicopter Hopper vehicles).

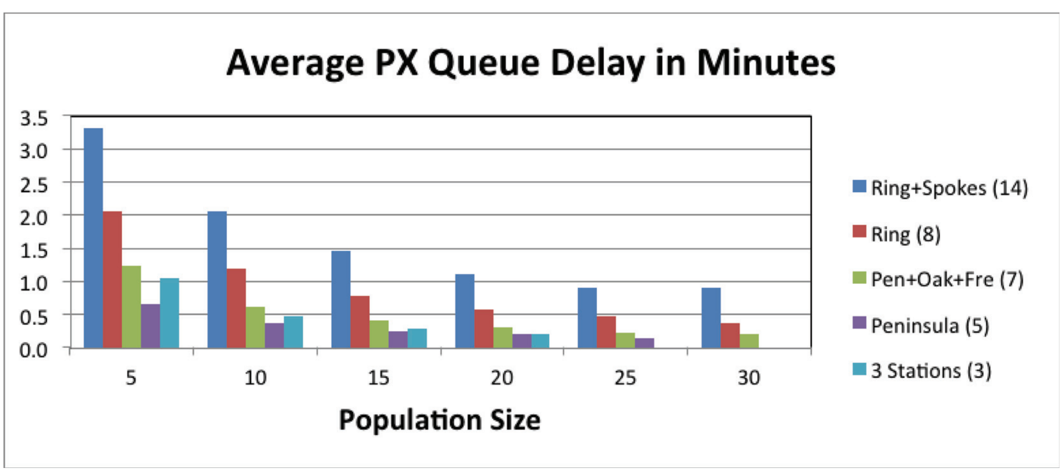


Figure 25. Average estimated passenger queue delay as a function of ridership population size.

Correspondingly, Figure 26 presents results for the estimated average flight departure spacing delay. This component of overall Hopper network commute delay is dramatically aggravated by the assumed daily ridership population levels. As overall ridership increases, the number of flights also increase; this, in turn, increases the congestion at vertiport stations and therefore requires an increase in delay to accommodate acceptable spacing of flights into and out of the network stations. This again reinforces the premise that innovative air traffic management technologies will be required to reduce separation delays in order to sustain the larger ridership populations. Otherwise, as overall Hopper residence/work commute time increases, the viability of the concept, as compared to automotive and other competing surface transportation options, decreases.

In addition to estimating average vehicle load factors and commute delays as a function of ridership levels and network topologies—given vehicle performance numbers derived from the conceptual design tools employed during the study—estimates of overall Hopper aerial transportation system energy consumption for San Francisco Bay Area operations were projected from the BaySim simulation results. These daily energy consumption estimates were made for five propulsion-system configurations—a baseline turboshaft-engine vehicle and four different electric-propulsion system alternatives. These four electric-propulsion configurations were: battery-based, hybrid battery and turboshaft engine, fuel-cell-based, and hybrid fuel cell and turboshaft engine.

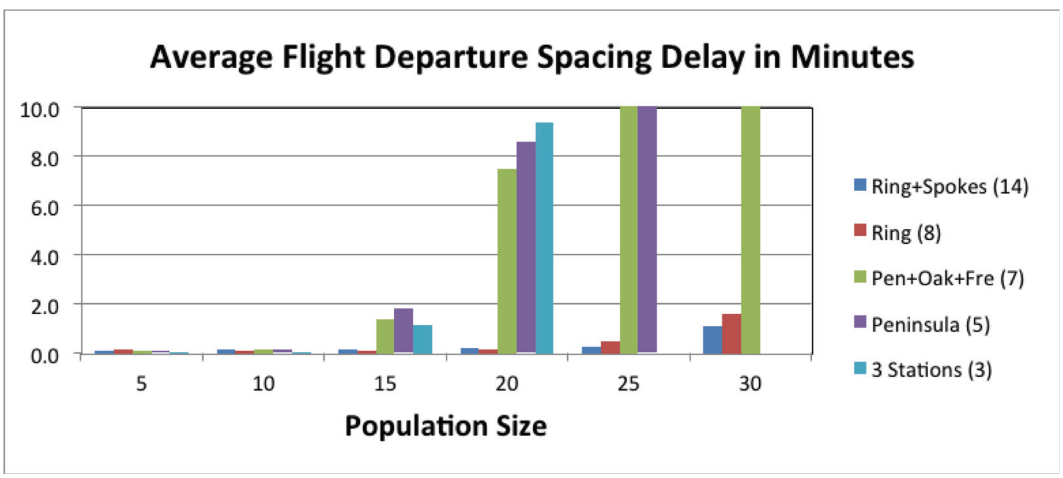


Figure 26. Average flight departure spacing delay.

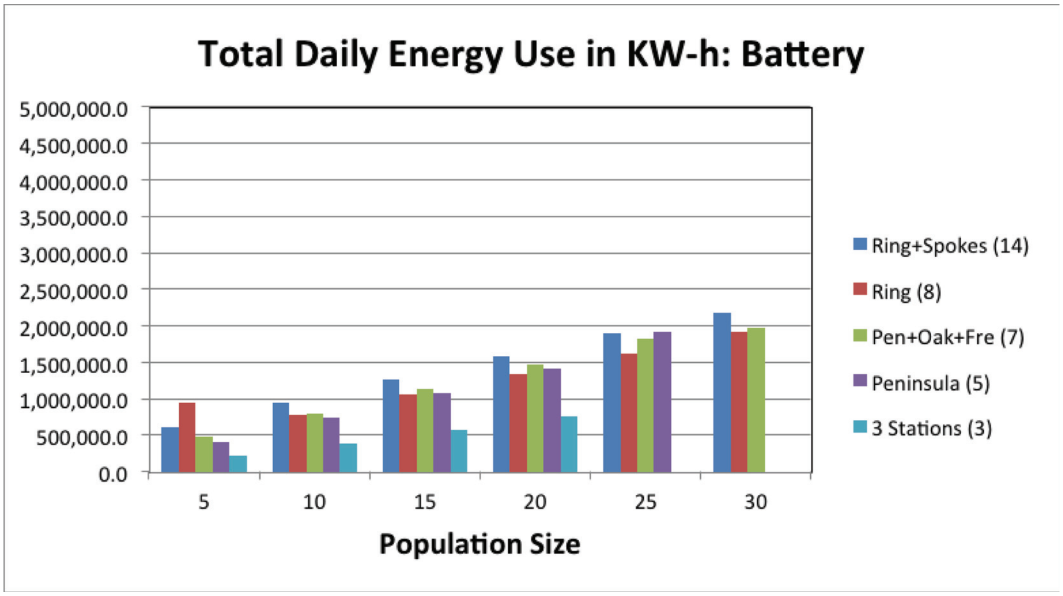


Figure 27. Hopper network total daily energy use (battery-based electric-propulsion 30-PAX tandem helicopters).

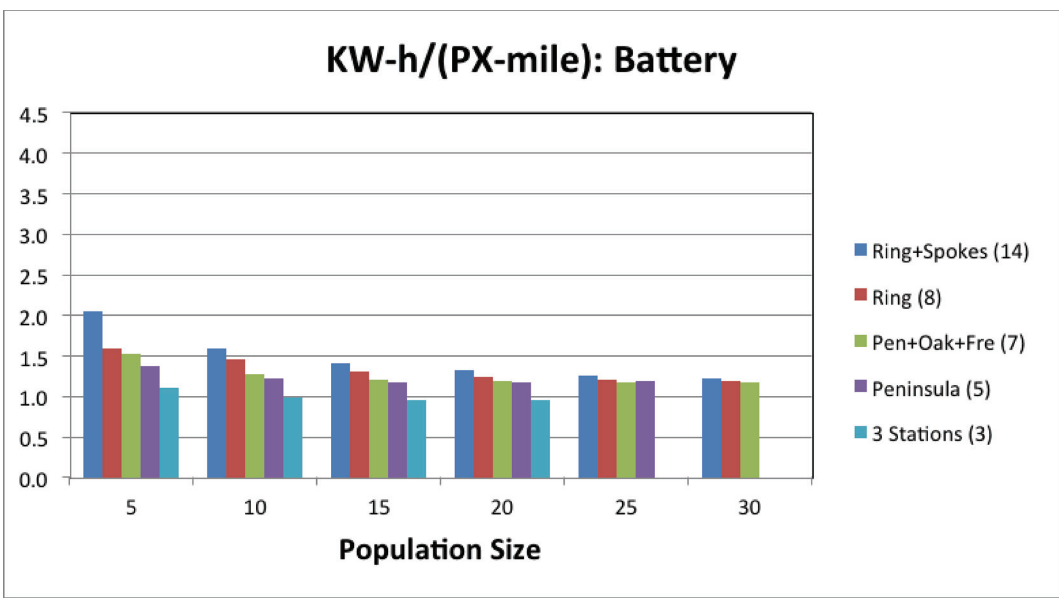


Figure 28. Energy expenditure per passenger-mile for various potential Hopper networks (battery-based electric-propulsion 30-PAX tandem helicopters) and ridership population sizes.

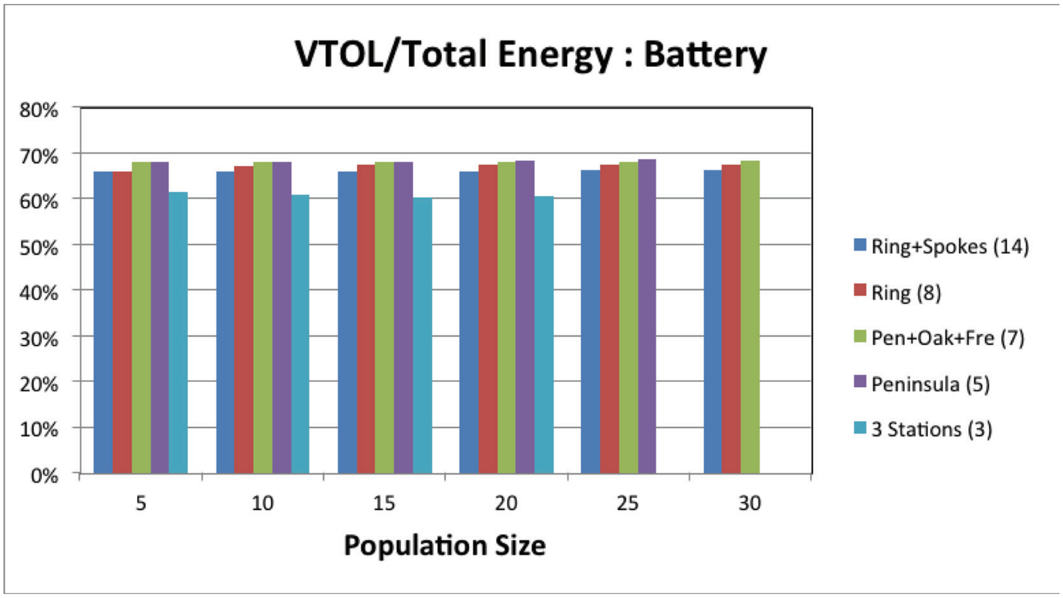


Figure 29. Percentage of energy expenditure for just the vertical takeoff and landing phases of flight versus the total energy expended for the complete flight for various potential Hopper networks and ridership population sizes.

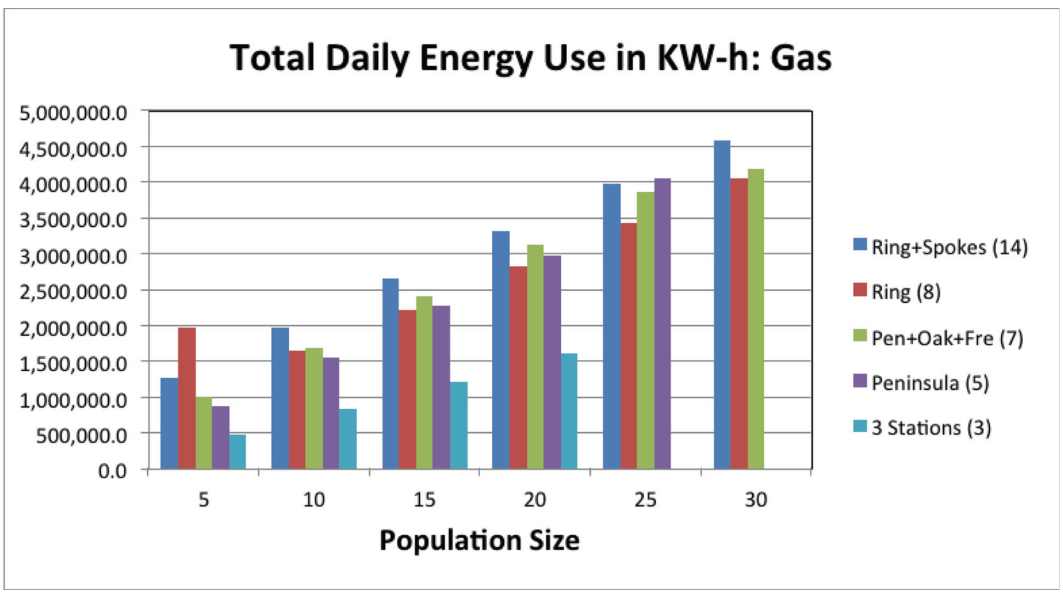


Figure 30. Hopper network total daily energy use (turboshaft-propulsion 30-PAX tandem helicopters).

Figures 30–32 show the comparable energy consumption levels for turboshaft-engine-based Hopper vehicles.

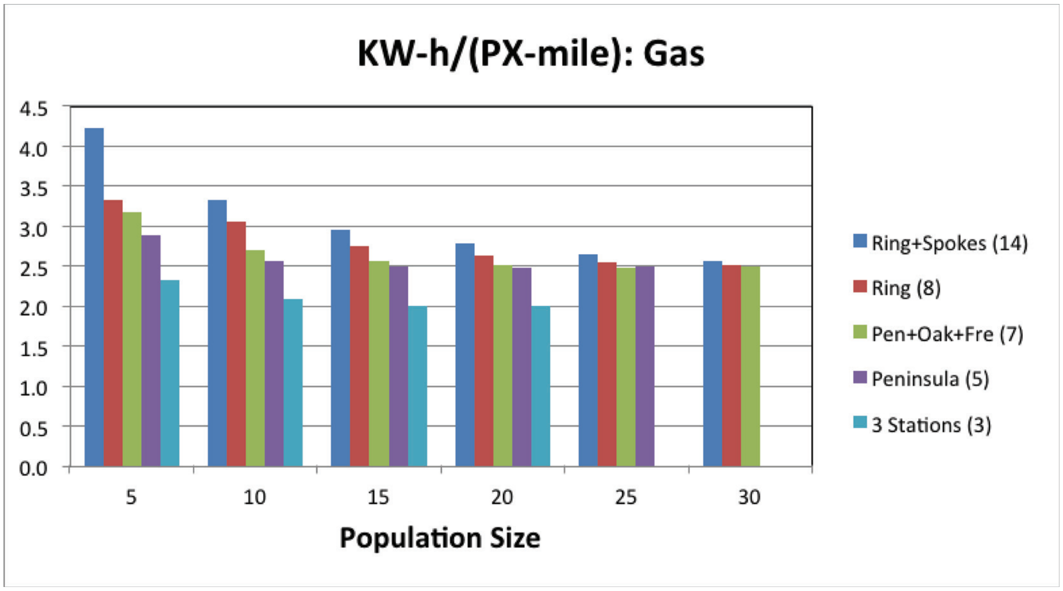


Figure 31. Energy expenditure per passenger-mile for various potential Hopper networks (turboshaft-propulsion 30-PAX tandem helicopters) and ridership population sizes.

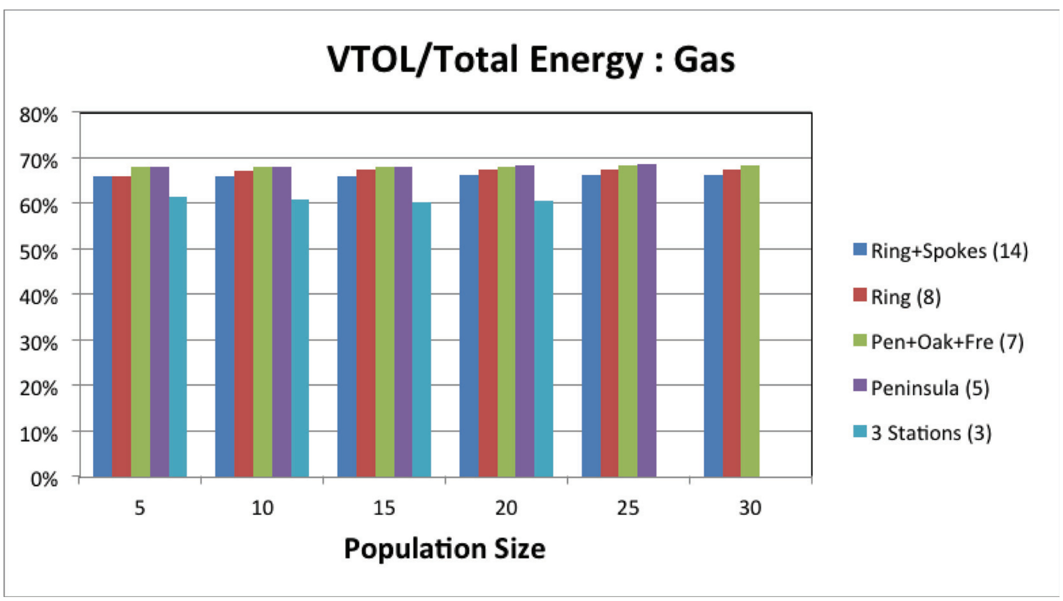


Figure 32. Percentage of turboshaft energy expenditure for just the vertical takeoff and landing phases of flight versus the total energy expended for the complete flight.

Figures 33–35 provide energy consumption estimates for an alternate hydrid propulsion system for Hopper vehicles: a hybrid system of batteries/electric propulsion used in conjunction with conventional turboshaft engines.

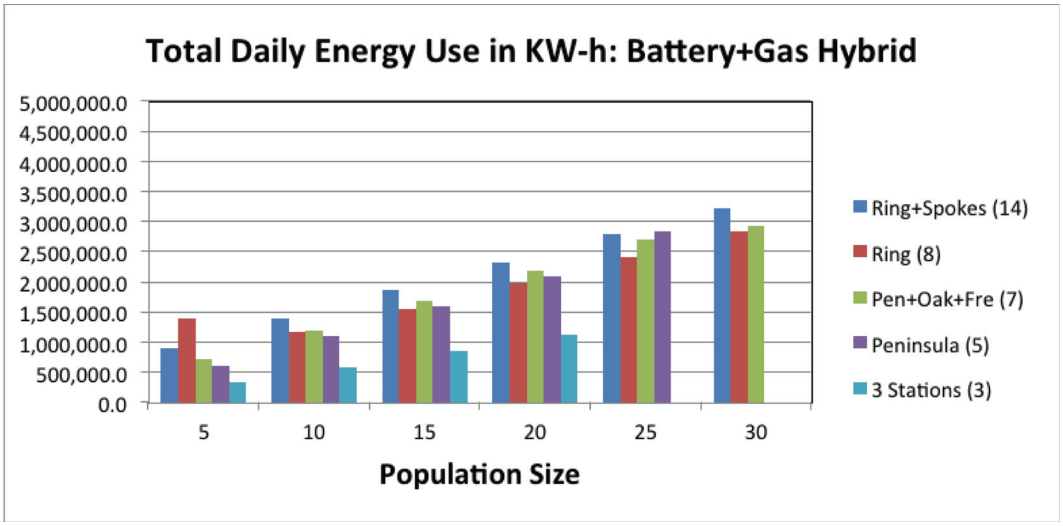


Figure 33. Hopper network total daily energy use (hybrid electric propulsion).

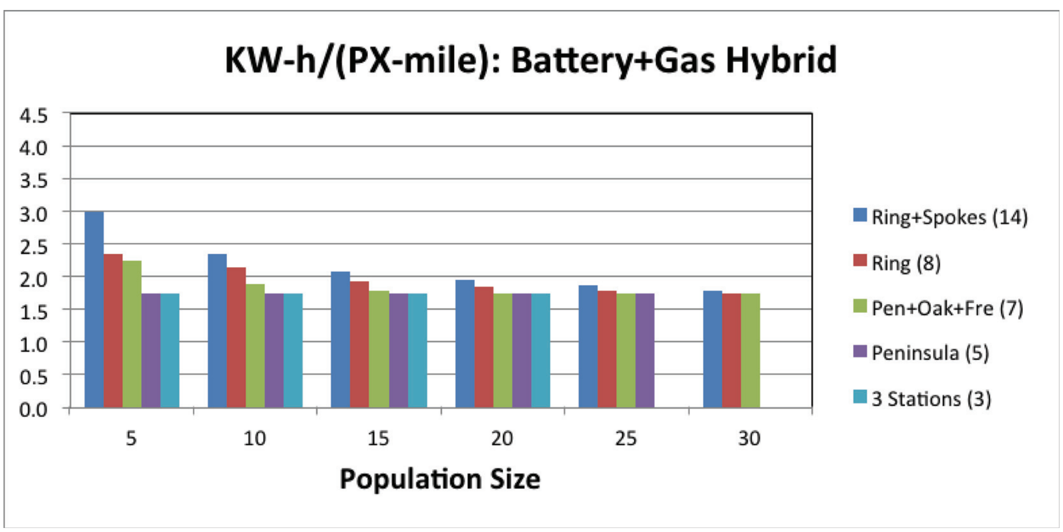


Figure 34. Energy expenditure per passenger-mile for various potential Hopper networks (hybrid electric propulsion) and ridership population sizes.

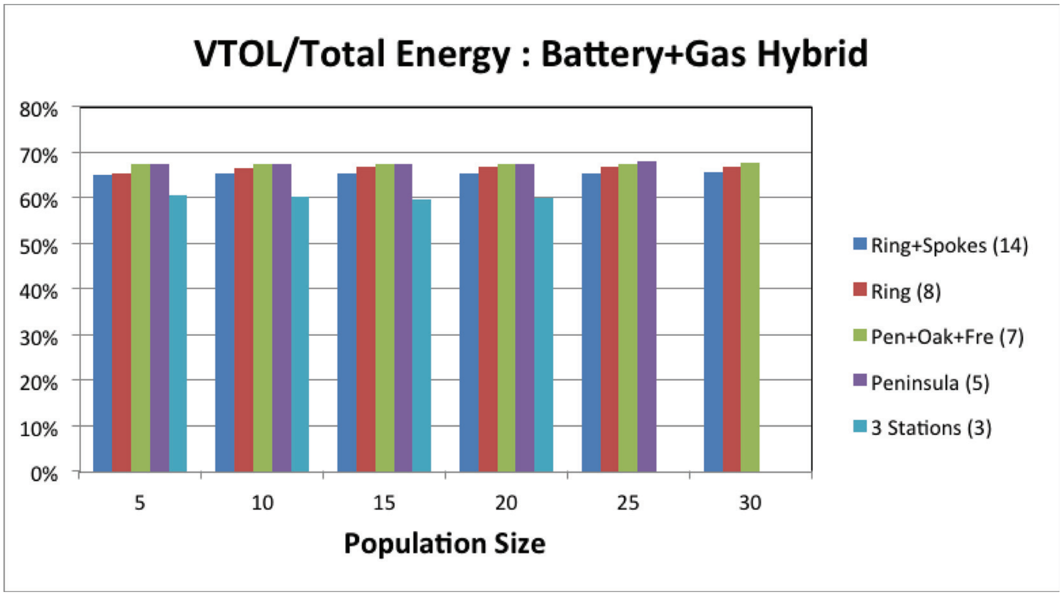


Figure 35. Percentage of hybrid-electric-energy expenditure for just the vertical takeoff and landing phases of flight versus the total energy expended.

Hopper network daily energy consumption estimates for a third electric-propulsion option—an all-electric fuel-cell-based system—are shown in Figures 36–38. A similar examination of the influence of ridership population size and Hopper network configuration on system energy consumption metrics is presented for a fuel-cell-based Hopper as was performed earlier for the battery-based and hybrid-electric-propulsion Hopper versions.

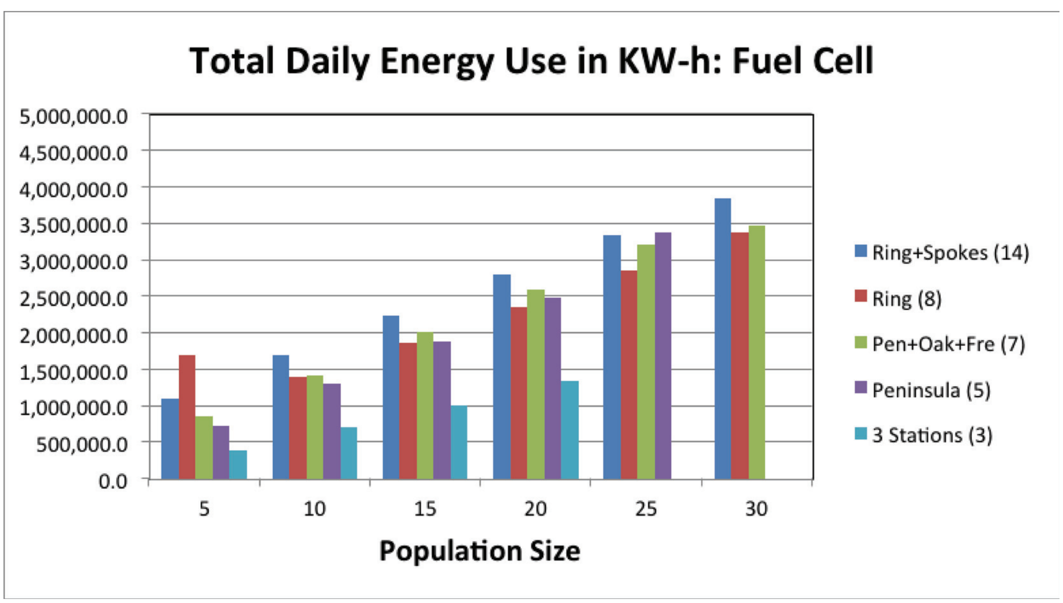


Figure 36. Hopper network total daily energy use (fuel-cell-based electric propulsion).

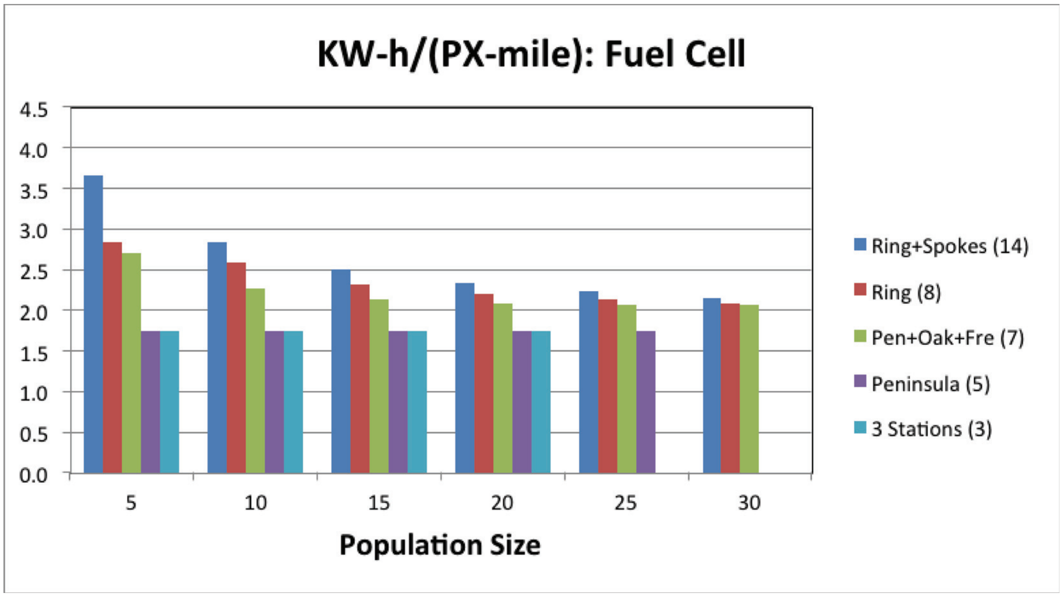


Figure 37. Energy expenditure per passenger-mile for various potential Hopper networks (fuel-cell electric propulsion) and ridership population sizes.

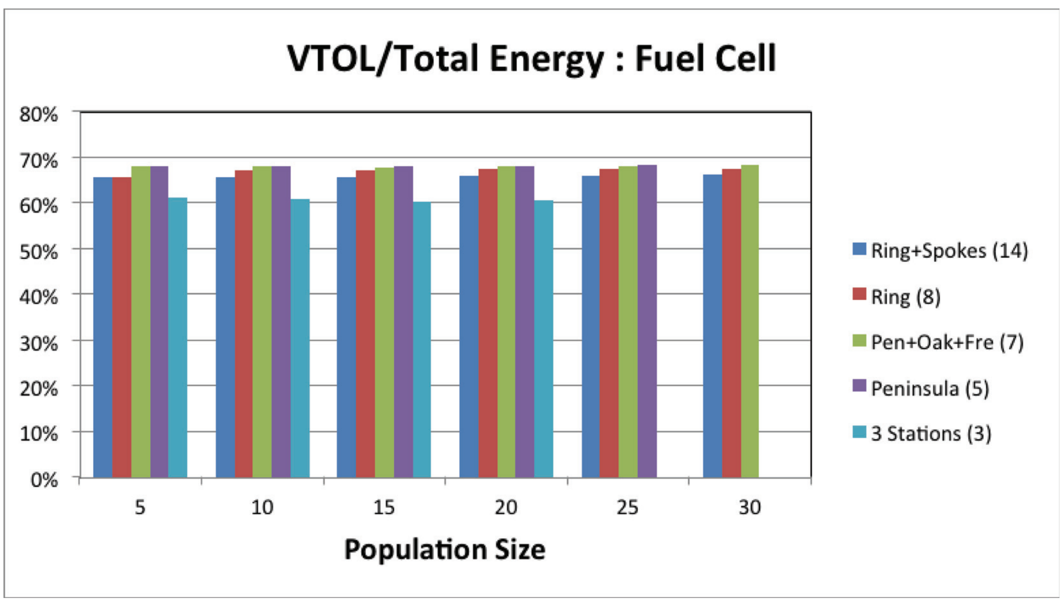


Figure 38. Percentage of fuel-cell-based electric energy expenditure for just the vertical takeoff and landing phases of flight versus the total energy expended.

Finally, energy consumption estimates are provided in Figures 39–41 for a fourth electric-propulsion alternative: a hybrid fuel-cell and turboshaft engine propulsion system. This concludes an initial examination of Hopper network energy consumption metrics for four general electric propulsion configurations: all-electric battery-based, hybrid electric battery and turboshaft engine, all-electric fuel-cell-based, and hybrid electric fuel-cell and turboshaft engine.

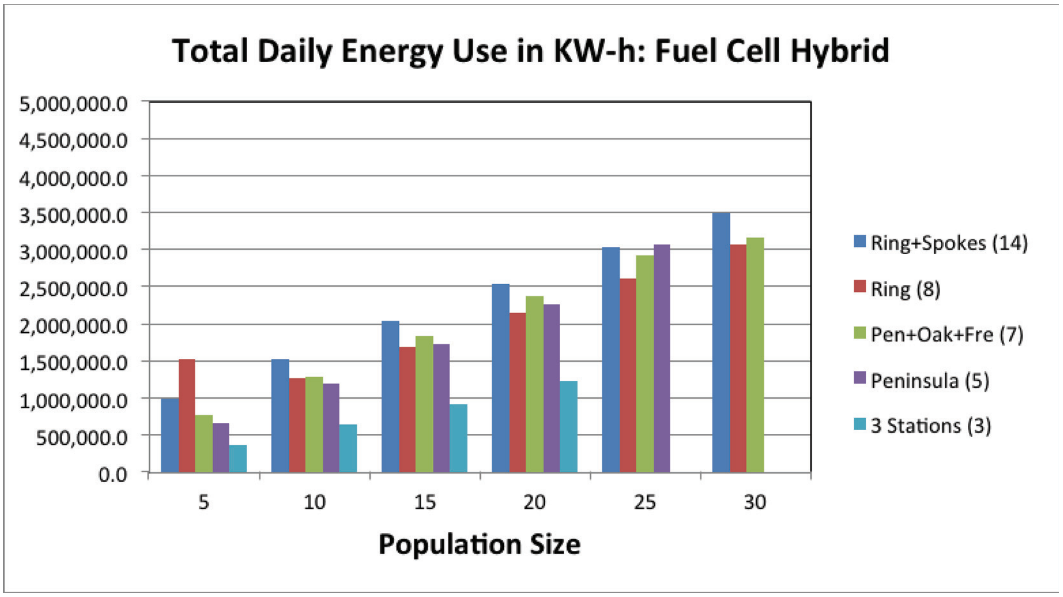


Figure 39. Hopper network total daily energy use (fuel-cell and turboshaft hybrid electric propulsion).

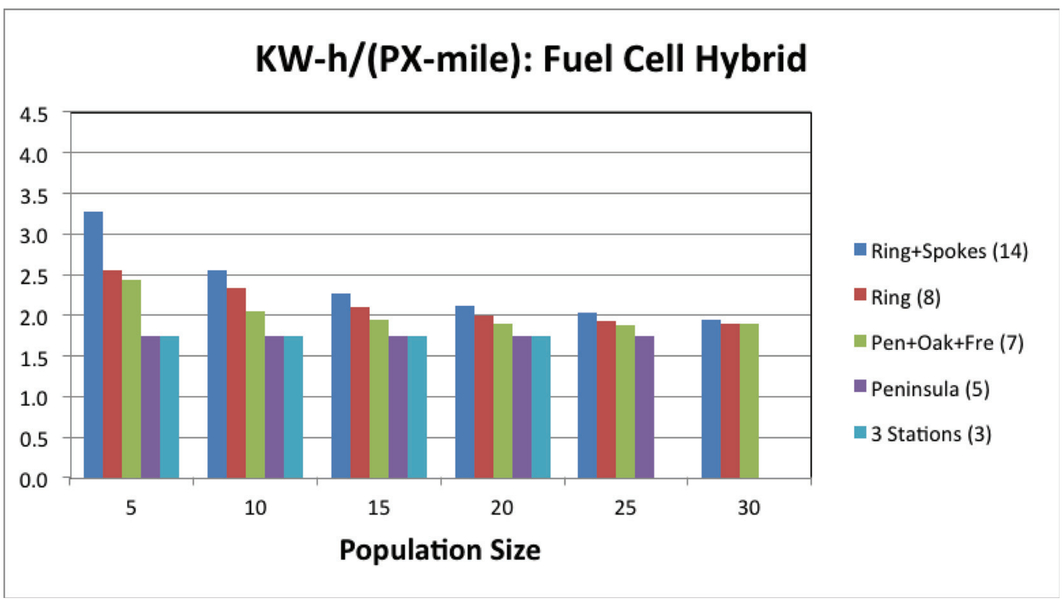


Figure 40. Energy expenditure per passenger-mile (fuel-cell and turboshaft hybrid electric propulsion).

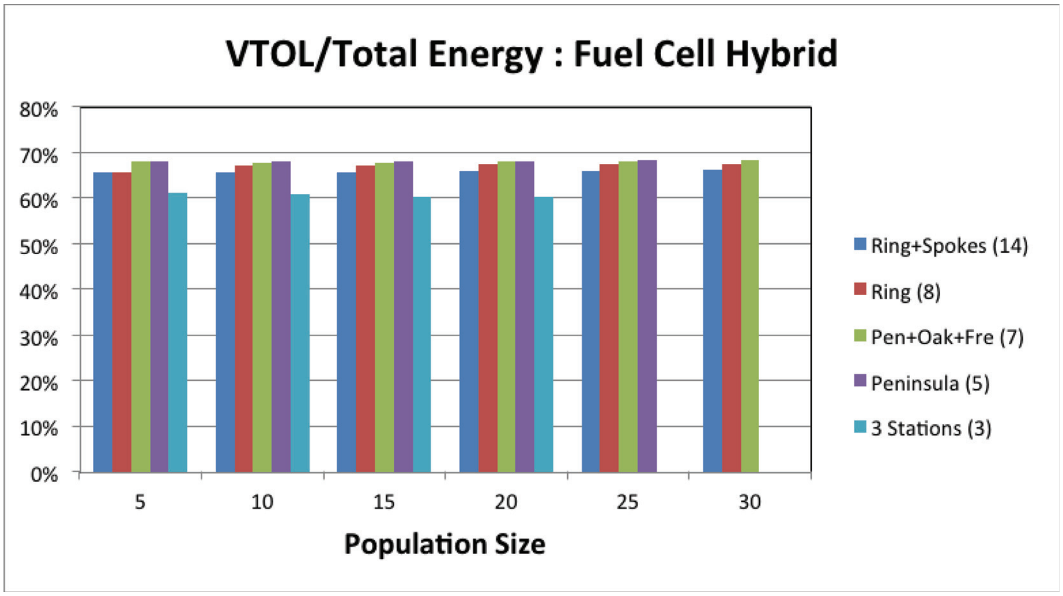


Figure 41. Percentage of hybrid electric (fuel-cell and turboshaft engine) energy expenditure for just the vertical takeoff and landing phases of flight versus the total energy expended.

Transitioning from the preceding consideration of the Hopper network energy consumption metrics, BaySim simulation results for commuter usage/utility metrics are presented and discussed next. Developing efficient combinations of networks and flight scheduling requires a detailed understanding of the interplay between commuter behaviors, aircraft operations, and station node geography. Direct point-to-point and hub-and-spoke should be viewed as nothing more than two points along the possible spectrum of network possibilities. Other potential options might incorporate some elements of near on-demand scheduling, where commuters would indicate their desired origin-destination pairs and desired arrival times (essentially making a reservation some minutes/hours before their flight). A master scheduling system would then reroute aircraft in near real time in an attempt to improve passenger service beyond the scheduled commute and provide as many direct flights as possible. Given sufficient ridership, these types of hybrid services have the potential to significantly reduce multi-hop flights for those commuters that must cross the entire network. Figures 42–51 illustrate the distribution of hops taken per passenger and the cumulative distribution functions (CDF) of the daily commute times for the various networks and populations. The BaySim results are discussed in terms of sets of results for decreasing network complexity (in order of complex to simple networks).

Figure 42 summarizes the projected number of "hops" (successive daily flights with multiple vehicles/stations) that a typical rider might have to take to complete his/her daily commute for a given network configuration (a ring-with-spokes configuration) and for various assumed ridership levels. In this set of results, somewhat independent of ridership level, BaySim suggests that nearly a third of the riders have to take upwards of six "hops" a day to complete their commute; only 15 percent of the ridership would have to take only two "hops." Figure 42 shows that most commuters take between four to eight flights daily commuting to and from work, independent of the size of the population, for the ring-with-spokes network topology. The high level of daily "hops"/flights required for this representative ring/spoke network shows that the Hopper network concept is indeed quite analogous, as originally suggested, to a railway/subway mass-transit-type system.

Figure 43 (daily commute times for the ring-with-spokes network) indicates that 40 percent of the commuters in the 5K and 30K populations have total daily commutes times of less than 80 minutes, and very few total commutes take longer than 3 hours regardless of population size. It is interesting to note the similarities in daily commute times between the two bounding ridership levels. For the 5K ridership, commuters incur delays while waiting for other riders with the same "next-stop" destinations (Fig. 25) to fill flights, while commuters in the 25 to 30K ridership begin to experience growing departure delays (Fig. 26) for flights to the same next stop. Three-hour total daily commutes appear to be the rare upper limit, and this network (with its expanded service area) appears to be viable for ridership levels up to 30K passengers. Given the growing rise in departure delays that are shown at the upper ridership levels (Fig. 26), this network is probably close to its maximum capacity.

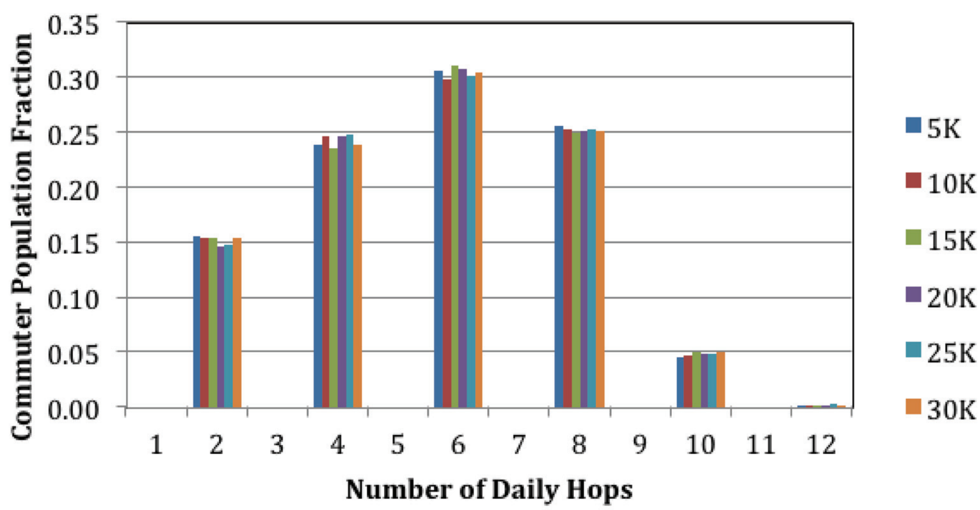


Figure 42. Number of daily "hops" a commuter has to take with a "ring-with-spokes" Hopper network.

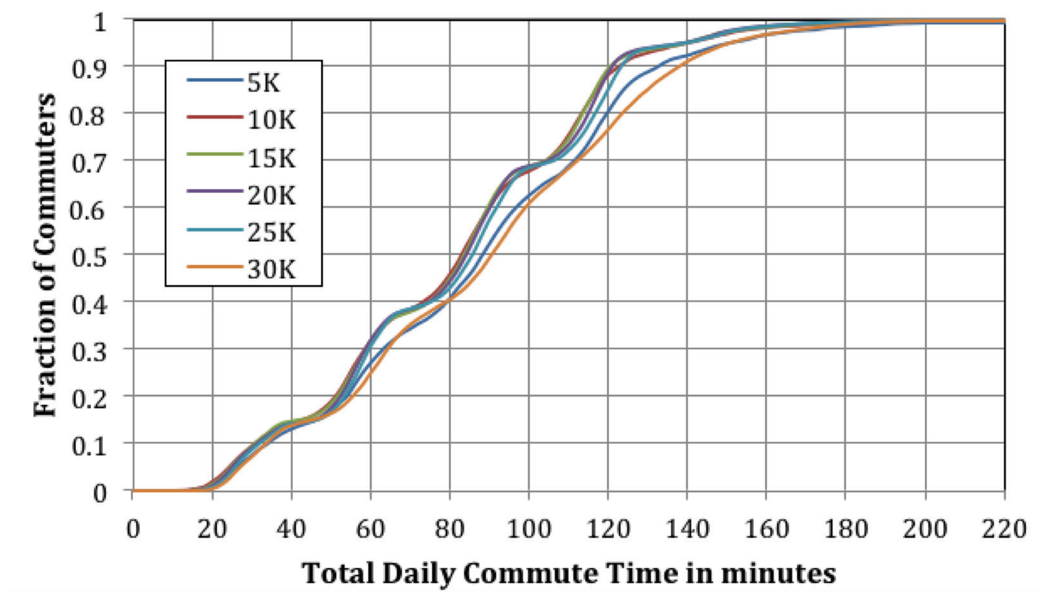


Figure 43. Daily commute times for a "ring-with-spokes" Hopper network for various ridership levels

Figures 44 and 45 show comparable commuter usage/utility results for a ring (no-spokes) network.

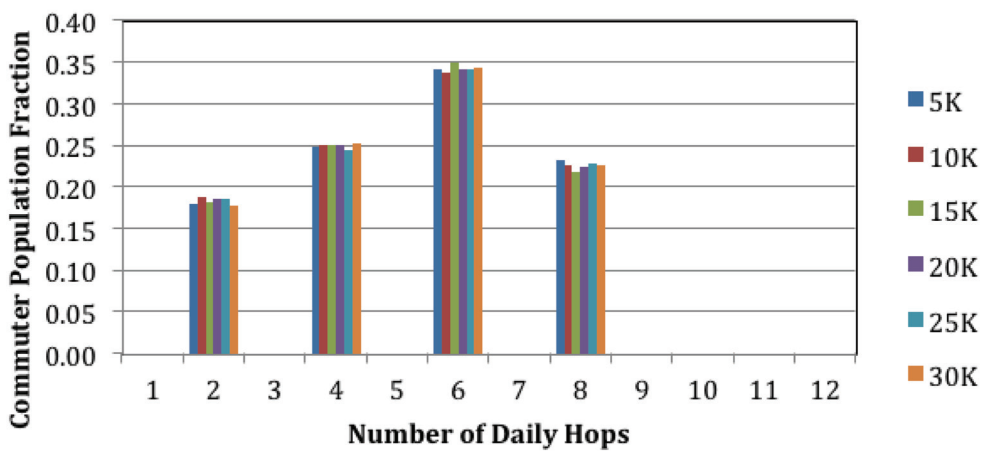


Figure 44. Number of daily "hops" a commuter has to take with a "ring" Hopper network.

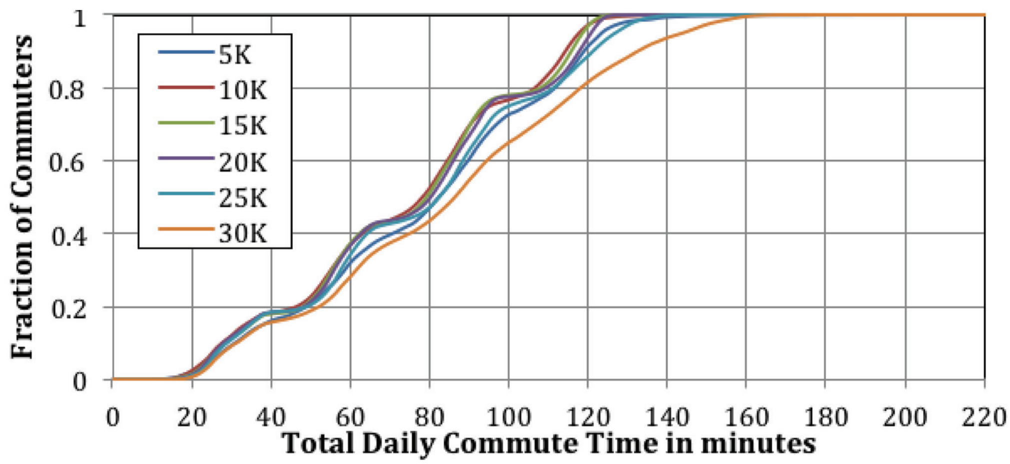


Figure 45. Daily commute times for a “ring” Hopper network for various ridership levels.

Figures 46 and 47 show comparable commuter usage/utility results for the Peninsula plus Oakland plus Fremont network.

Figure 47 indicates that excessive delays have made commutes effectively impossible for many potential riders for this particular network configuration when Hopper commuter populations exceed 15,000 riders per day.

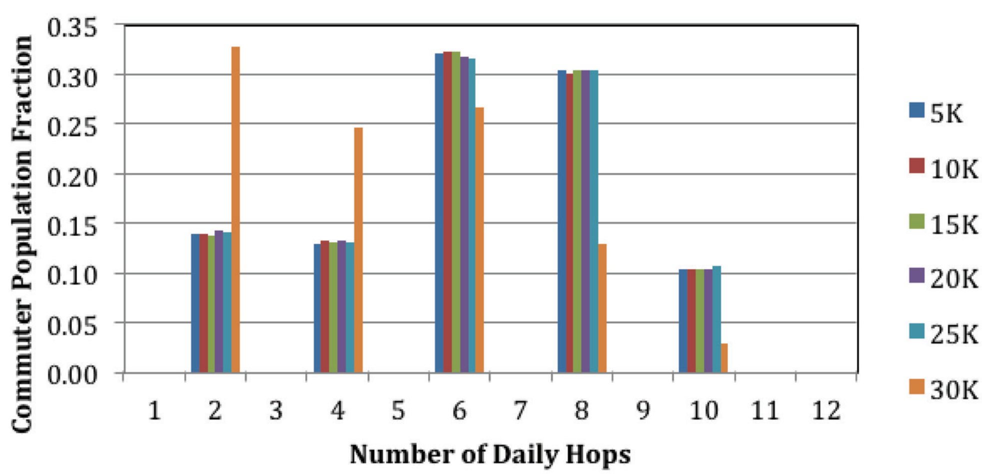


Figure 46. Number of daily “hops” with a “Peninsula+Oakland+Fremont” Hopper network.

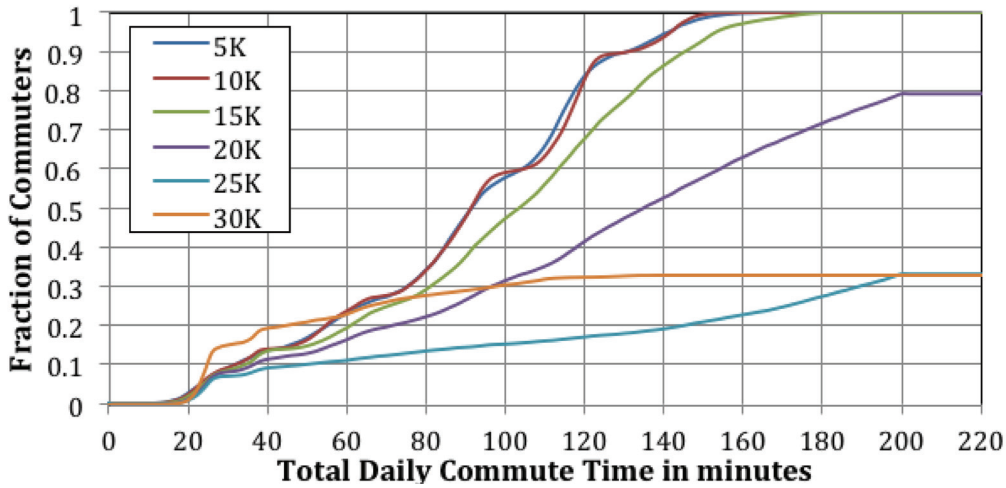


Figure 47. Commute times for a “Peninsula+Oakland+Fremont” Hopper network.

Figures 48 and 49 show BaySim results for a peninsula-only Hopper network.

Similar to what was seen for the “Peninsula+Oakland+Fremont” network, Hopper commutes for the Peninsula-only network also become problematic (effectively impossible in terms of very large delays) for ridership populations greater than 15,000 riders per day.

Finally, Figures 50 and 51 show BaySim estimates of number of daily hops required and overall commute time for the simplest network studied, a three-station network system.

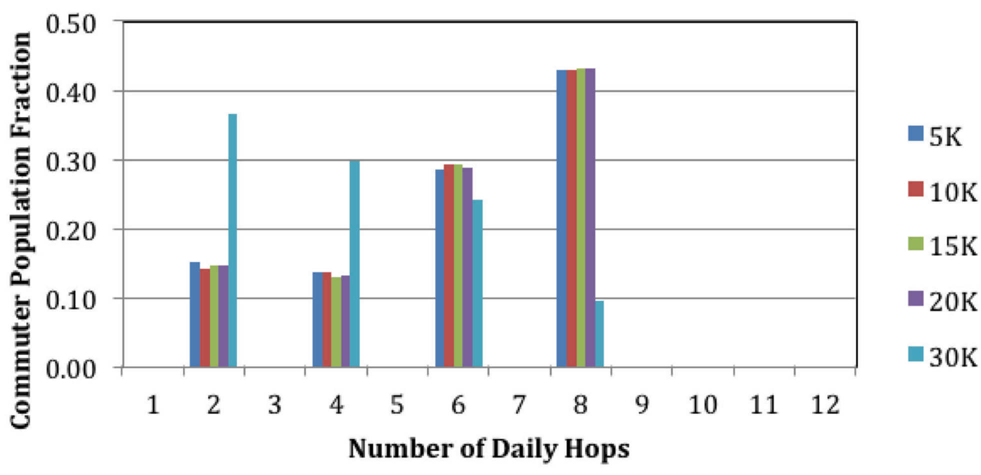


Figure 48. Number of daily “hops” with a “Peninsula-only” Hopper network.

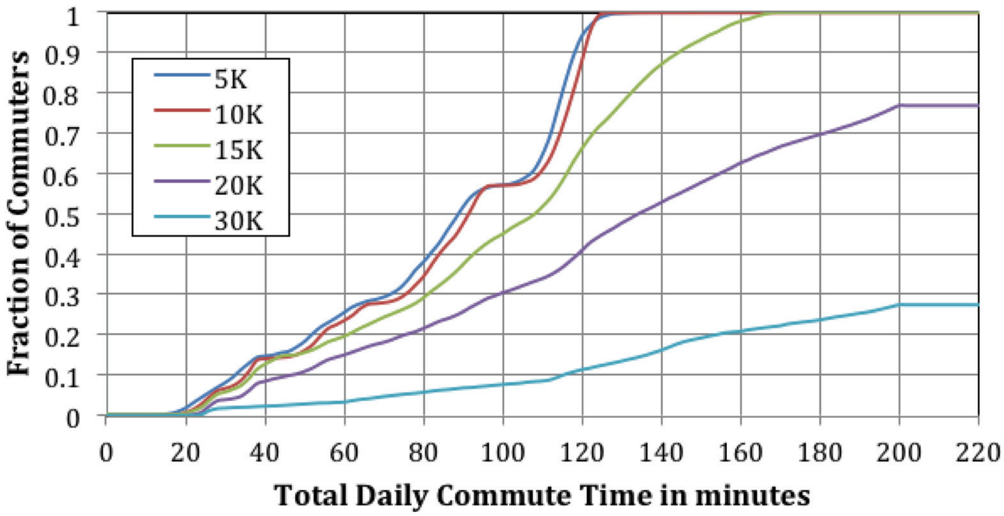


Figure 49. Commute times for a “Peninsula-only” Hopper network.

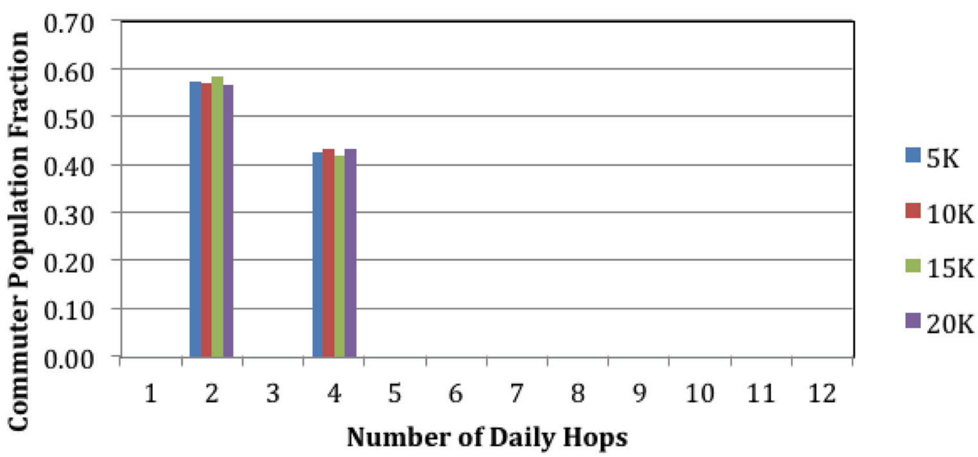


Figure 50. Number of daily “hops” with a “three-station” Hopper network.

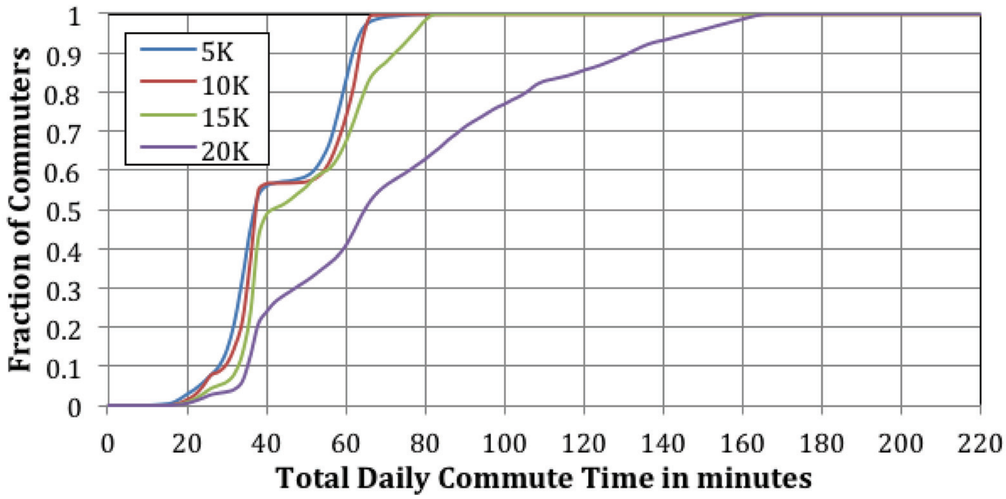


Figure 51. Daily commute times for a “three-station” Hopper network.

The three-station network also has difficulty serving more than 15K to 20K daily commuters under the current assumptions used in the BaySim simulations.

For the current version of the Hopper concept (with the network topologies studied to date), most passengers have to take multi-leg journeys between home to work, and again from work to home. Given 30,000 passengers on the largest network studied, with each passenger making an average of four to six flights (hops) per day (two to three in each direction), one should expect around 30000 * (4+6)/2 = 150000 PAX-flights per day. Assuming 30 PAX per aircraft, there will be approximately 150000/30 = 5000 daily flights.

Each passenger has to make a minimum of two flights per day to go from home to work and back, assuming a perfect point-to-point network (see the comments about some inherent inefficiencies of point-to-point networks below). With 30K passengers, this means an absolute minimum of 60K daily passenger departures (again, likely much higher due to intermediate hops). Assuming that each flight could be filled with 30 passengers, the entire system would have to handle 60K/30 = 2K departures per day. If these departures could be distributed equally across 100 vertiport stations (also an unrealistic assumption in light of workplace and homesite aggregation), one would expect on average 20 departures per day at each vertiport station. With 30 passengers in each departure, this leads to 600 passengers per day departing from each station. Note that an equal number of passengers would be arriving each day as well, so the foot traffic at each station would be more like 1200 people per day per vertiport. If there is one passenger per aircraft, this means that there must be 60K departures per day to serve 30K passengers. Distributing those 60K departures evenly over 100 vertiport stations leads to 600 departures per day per station. Assuming a 15-hour day, this leads to 600/15 = 40 departures per hour, with one flight departing every 90 seconds. Arrivals would also occur at the same average rate. But considering only daily average departure and arrival rates seriously underestimates actual vertiport requirements because it ignores realistic commute traffic patterns consisting of both morning and evening rush hours. At a minimum, public mass transit terminals/stations must be sized to accommodate these daily surges. BaySim was expressly designed to predict these daily changes in commuter demand by simulating actual human behavior via large populations of discrete actors.

At some point, requiring infrastructure support at an ever-increasing number of locations would seem to increase (not decrease) the net amount of infrastructure required. While some nodes might be able to operate without the full ground (recharging/maintenance/terminal/etc.) infrastructure, there is likely some minimum level of support required to handle passengers at any network node. Dealing safely with the needs of all passengers entering and exiting aircraft in a transit system available to the public cannot be done for free, and flying with poor (to zero) load factors to reposition aircraft to provide point-to-point service is economically unviable. There are likely to be some fixed costs for operations regardless of aircraft size, and at some point an ever-increasing distribution of network nodes diverges from the system optimal low-cost/low-energy/low-infrastructure solution simply because it cannot take full advantage of the multiple economies of scale provided by larger aircraft and aggregated infrastructure. Increasing the general distribution of nodes (with a corresponding move to smaller aircraft) necessitates more aircraft, more flights (including repositioning flights), more control automation, more charging facilities, and more net system energy usage. It also comes with a host of increased secondary costs, including an increased real estate footprint (rents/leases), increased insurance and security costs, increased liabilities, increased electrical infrastructure costs, and increased community impacts (emissions and noise). Minimal services and amenities must be present even at “low-infrastructure” nodes, such as parking, ground transportation from nodes to remote final destinations, local air-to-ground communications, and basic emergency services. Developing a transit system that balances multiple objectives is challenging, but because of the above considerations, it currently seems very unlikely that the best fleet balance will consist of mostly very small aircraft.

There are also some serious problems with point-to-point mass transit networks that quickly become obvious upon closer inspection. After unloading passengers at a workplace destination, an aircraft must be returned to the network. In order to avoid return flights with very low load factors, an equivalent number of new passengers with a new common destination must be available to board the aircraft. Unfortunately, many workplace nodes are likely to be located in industrial parks, and will therefore lack the pool of surrounding home sites with commuters looking for their own morning trip to work. It seems clear that a better network solution is to position nodes so that they can serve both home sites and job sites while minimizing the number of non-revenue “repositioning” flights carrying few to no passengers. No viable taxi service can allow its vehicles to move without passengers or sit motionless for hours between fares.

Is there a better distributed mass transit system that might be more “optimal” (however that might be defined) than the largest hub-spoke network investigated in this study? Of course there is, and it probably includes some mix of both larger and smaller aircraft. Is it a system composed primarily of aircraft carrying two to four passengers flying point-to-point? Again, this seems very unlikely, especially if one believes in the economic advantages of aggregating the largest infrastructure and capital expenses, and taking full advantage of economies of scale in both the design of the aircraft (physics) and their operations (economics). Future work will have to be performed to study in more detail the economics, demographics, and business case analyses required to determine the true magnitudes of these costs.

Additional plots illustrating network statistics for various populations and topologies are provided in Appendix D.

Table of network and station operation rates

Developing efficient combinations of networks and flight scheduling requires a detailed understanding of the interplay between commuter behaviors, aircraft operations, and station node geography. Direct point-to-point and hub-and-spoke should be viewed as nothing more than two points along the possible spectrum of network possibilities. Other potential options might incorporate some elements of near on-demand scheduling, where commuters would indicate their desired origin-destination pair and a desired arrival time (essentially making a reservation some minutes/hours before their flight). A master scheduling system would then reroute aircraft in near real time in an attempt to improve passenger service beyond the scheduled commute and provide as many direct flights as possible. Given sufficient ridership, these types of hybrid services have the potential to significantly reduce multi-hop flights for those commuters that must cross the entire network. Extensive tables and figures related to the Hopper operations counts (departures and arrivals) for each of the networks are presented in Appendix D.

Integration of Hopper Flights into San Francisco Bay Area Airspace

A major factor in the feasibility of the Hopper system is the interaction of Hopper vehicles with background air traffic. The Northern California Terminal Radar Approach Control (NCT) controls low altitude and transitioning traffic within the San Francisco Bay Area. This facility handles 4,800 to 5,200 operations per day including major airports, 73 public/municipal airports, and a vast number of private airports. Therefore, inserting Hopper flights into the Bay Area airspace is not a trivial problem.

In order to illustrate the need for new and emerging technology to make the integration of a Hopper fleet with the background traffic feasible, first consider what would be required in order to integrate Hopper vehicles into the Bay Area airspace under *current* operation conditions.

Similar vehicles currently operate within the Bay Area airspace (e.g., news/traffic, police, emergency medical services (EMS), and Coast Guard helicopters). These vehicles are typically routed along a very specific route, avoiding interaction with background traffic, and fly under visual flight rule (VFR) conditions (ref. 38). Hopper flights would cause a significant challenge compared to the current operations of similar vehicles since the frequency of Hopper flights would be much greater. Given a 30,000-passenger estimate, there would be more than 400 Hopper departures per hour at peak commute times. The problem of separating Hopper vehicles from background traffic would result in a substantial increase in controller workload.

In an attempt to segregate Hopper flights from background traffic, Hopper station locations could be chosen and flight plans generated to avoid having Hopper flights enter a region around the arrival/departure paths (3 to 5 miles out from the runways) of the major Bay Area airports. This could make locating Hopper stations at locations convenient to integration with existing ground transportation difficult. The patterns of traffic flow into and out of the major airports changes with weather due to airport configuration changes. Hopper flight plans could be generated for various runway configurations, directing Hopper flights around the arrival and departure streams associated with each configuration. Global Positioning System (GPS) technology (available and in use today) could be used to make tighter, more predictable approaches for traffic arriving at and departing from major airports and for the Hopper flights themselves. Increased flight plan accuracy would shrink the approach corridors and allow for more flexibility in both Hopper station location and routing Hopper flights to avoid entering these corridors.

Additionally, to avoid conflicts with general aviation flights and VFR flights, it might be necessary to block out corridors for use exclusively by Hopper flights (ref. 38). This would basically allow Hopper to operate air traffic control of Hopper flights independently from background traffic. However, the designation of such corridors would be difficult to achieve. Thus, some level of integration of Hopper flights with background traffic will be required.

Given the challenges that would be faced in attempting to integrate Hopper vehicles in current operations conditions, new and emerging technology must be considered to facilitate the realization of the Hopper system.

The problem of integrating Hopper flights into Bay Area airspace is addressed in two ways. First, a method of planning Hopper flightpaths is described to minimize the potential of conflict with background traffic. Secondly, air traffic management technologies and methods are examined—both those currently available and in development—that could facilitate the integration of Hopper flights with background traffic.

Flightpath planning

Flightpath planning was performed to reduce the potential for Hopper conflicts with background air traffic. A loss of separation in the terminal area is defined as occurring when two aircraft come within 3 nautical miles of one another in the horizontal plane and within 1,000 feet of one another in the vertical plane.

Traffic density maps were generated using actual traffic information from May 8, 2007.[5] The region of airspace of interest was divided into a three-dimensional grid of 0.04 degrees latitude by 0.05 degrees longitude (roughly 2.4 by 2.4 nautical miles) by 250 feet vertically. The horizontal grid size roughly matches the 3-nautical-mile horizontal separation requirement. The simulation time step was chosen to be 15 seconds. Using this time step and grid size, each

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[5] Conventional air traffic continues to grow and, in the future, airspace integration of Hopper-like vehicles may increasingly be a challenge.

aircraft spends roughly one to three time steps in a given volume of airspace. Traffic in each grid element is reported as the average airspace use (aircraft dwell time in the grid element) per hour. The average is taken over 1-hour time periods.

Using traffic density maps of this form, various flightpaths were analyzed at different times of day. Each path is described by the origin location, destination location, cruise altitude, and two intermediate waypoints. These paths were compared based on the amount of fuel required to fly the given flightpath and the potential for conflicts with background traffic. In order to estimate the potential for conflicts, a "traffic cost" was calculated for each flightpath. At each time step, the location of the flight along the path is found. The traffic score at that location is the sum of the traffic values of the column of cells 1,000 feet below that location to 1,000 feet above that location. The total traffic cost for the flightpath is the sum of the traffic cost calculated at each time step. This traffic cost is a measure of the density of traffic encountered along the flightpath. Flights traveling through regions of airspace with denser traffic are more likely to come into conflict with another aircraft.

For this work, performance models for gas-turboshaft-powered rotorcraft vehicles of three sizes (6, 15, and 30 passenger) were used. Several different origin and destination pairs were evaluated, with results used as part of the station location and network structure selection process. Here, results are shown for Hopper flights originating at San Jose Caltrain Station destined for San Francisco Caltrain Station using the 15-passenger vehicle performance model. Figure 52 shows the path requiring minimum fuel in black, overlaid on the traffic density map. The cruise altitude of this particular path is 3,000 feet and is thus shown on top of the average traffic density map for 2,000 to 4,000 feet. This range coincides with the vertical separation requirement for an aircraft at 3,000 feet. Figure 53 depicts a path that uses at most 15 percent more fuel than that required for the minimum fuel path with minimum traffic cost. Allowing a 15-percent increase in fuel consumption over the minimum required results in a potential traffic cost reduction of just over 75 percent. Figure 54 illustrates path planning over a range of time intervals, with flightpaths using at most 15 percent extra fuel between Palo Alto Caltrain and San Francisco Caltrain planned for various time intervals between 7 AM and 10 AM.

Traffic cost reduction compared to the minimum fuel path for various values of allowable fuel increase are shown in Figure 55 for hour-long time intervals between 7 AM PST and 10 AM PST. Here, it can be seen that allowing just a 15-percent increase in fuel consumption can lead to a traffic cost reduction of 39–75 percent.

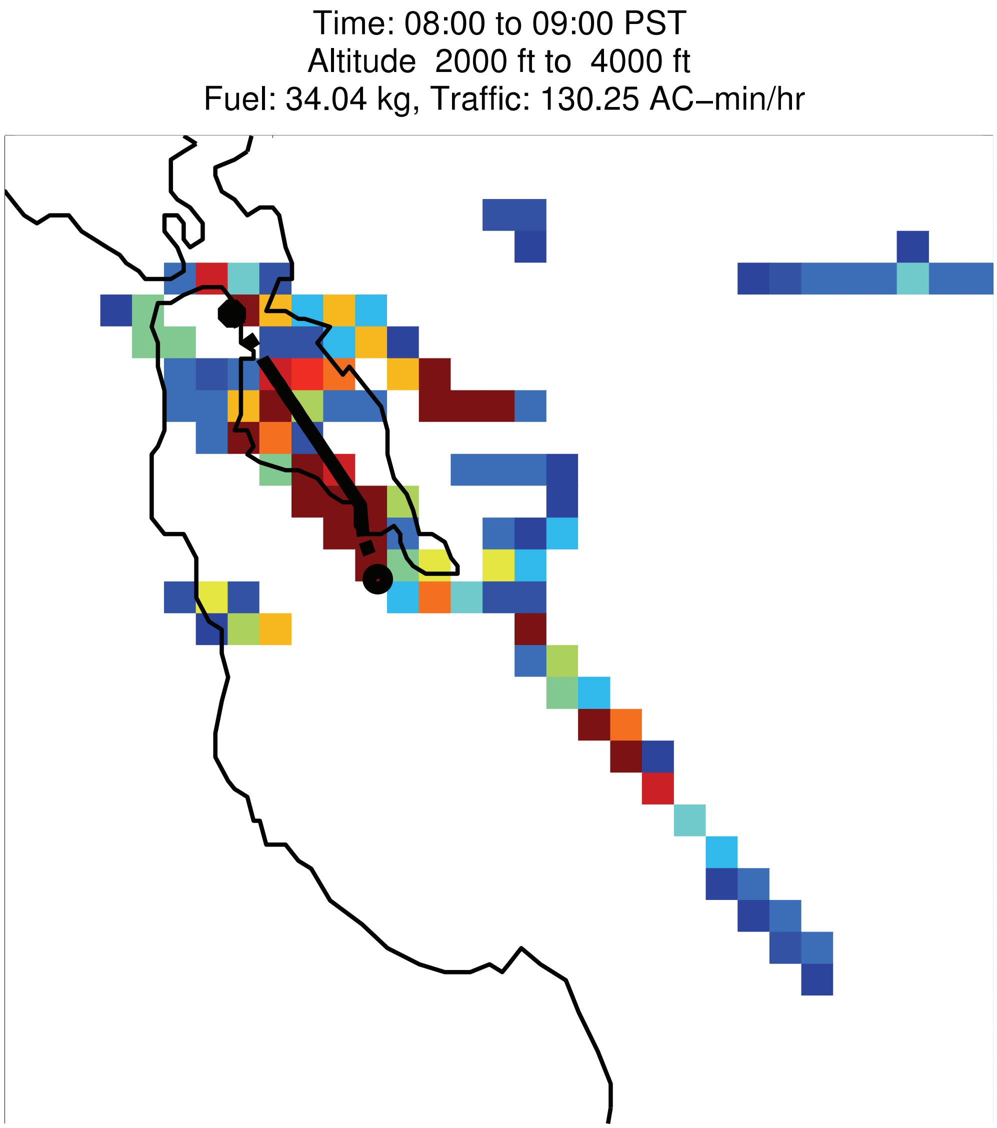


Figure 52. Minimum fuel path.

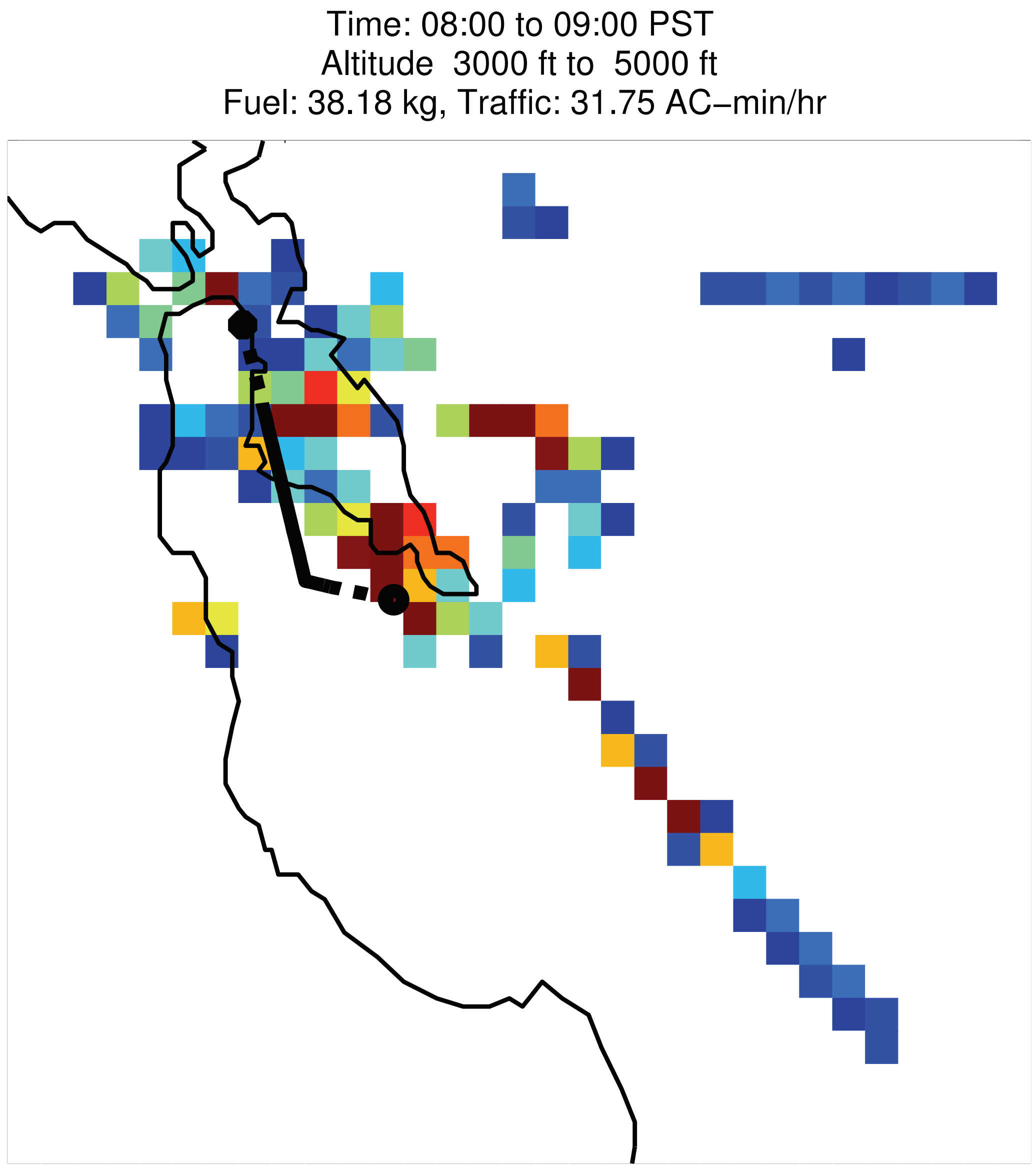


Figure 53. Fuel used within 15 percent of minimum fuel required.

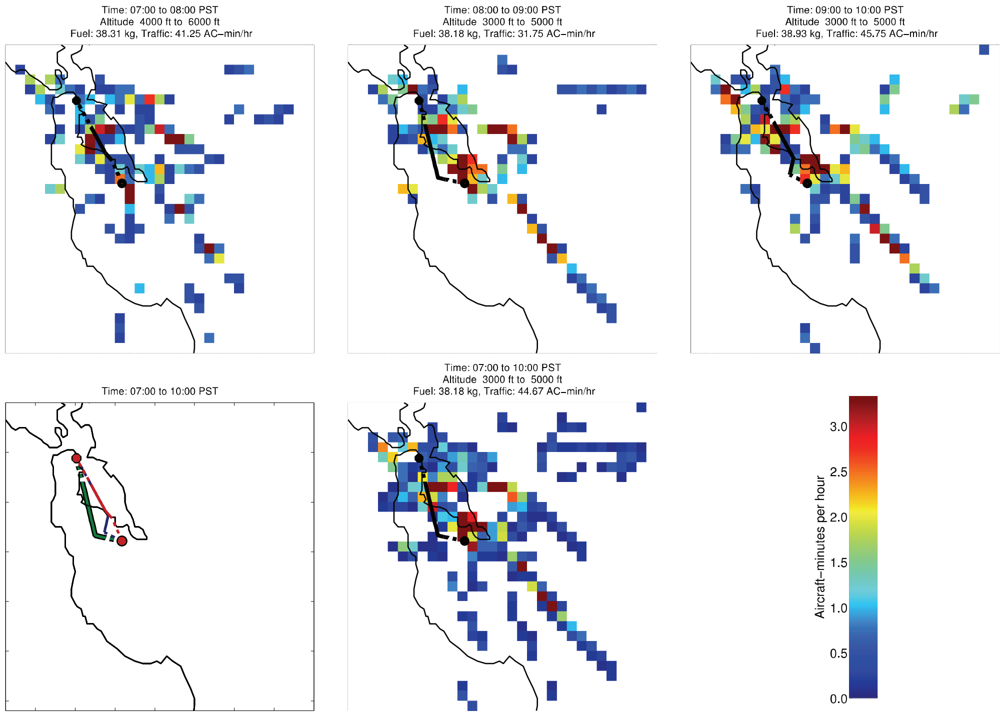


Figure 54. Paths planned between Palo Alto and San Francisco based on traffic density at different times of day (1-hour intervals from 7 AM to 10 AM and average traffic from 7 AM to 10 AM). Here, 15 percent extra fuel over the minimum fuel path for this particular station pair was allowed.

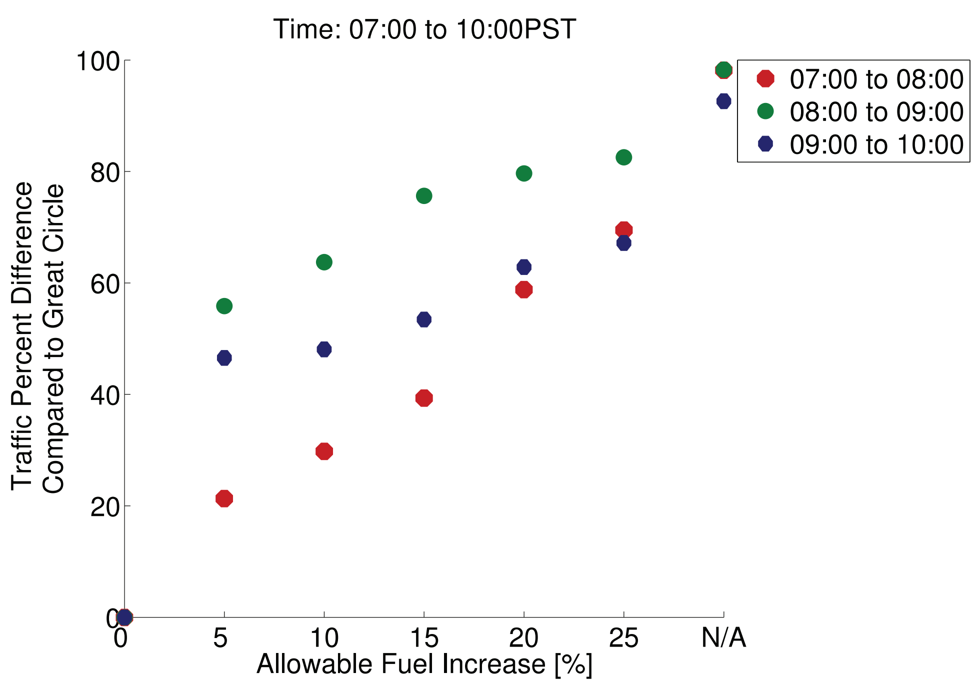


Figure 55. Percent reduction of traffic cost compared to minimum fuel paths for various allowable increases in fuel consumption above the minimum fuel path.

Enabling technologies

In order to facilitate the realization of the Hopper concept, some emerging technologies would have to be leveraged. Many technological and procedural advances and changes are currently being proposed under the Next Generation Air Transportation System (NextGen). Some of these technologies that are particularly relevant to Hopper operations are discussed below and summarized in Table 5.

Communication

Currently, voice over radio is used for communication between pilots and air traffic controllers during taxi, takeoff, and en route flight. Controller instructions to the pilot include departure route to be flown, speed and altitude changes, and adjustments to the planned route. This type of verbal communication is time consuming and error prone, requiring pilots to read back controller instructions. NextGen developments in this area include increased use of datalink (currently in limited use) with human-over-the-loop oversight.

The Hopper concept will be strongly dependent on some form of trajectory-based automation with datalink as an enabling technology. Operational tests involving the use of datalink for continuous descent approaches for transpacific flights have been conducted (ref. 39). However, the widespread use of trajectory-based automation to implement time- and fuel-efficient flight trajectories in today's airspace with today's datalink and fleet mix has not been demonstrated.

A test bed for evaluating high-level concepts that use trajectory-based automation as the basis for a next-generation air traffic control system has been developed at NASA Ames Research Center (ref. 40). These concepts employ trajectory-based automation, air/ground datalink, and higher levels of automation for separation assurance to increase airspace capacity. It is generally accepted that air/ground datalink, especially when integrated with trajectory automation, has the potential to improve controller productivity and enable better services for airspace users. This test bed has been used to evaluate a Trajectory-Based Operations (TBO) concept and its required automation system that uses currently available air/ground datalink communication capabilities and today's fleet mix in U.S. en route and transition airspace. The goal was to identify critical automation components as well as conduct a laboratory simulation to test integrated operation of selected (but not all) components. The following components were analyzed: minimum-delay conflict resolutions, wind-favorable routes, better conflict detections, uninterrupted climbs and fuel-efficient descents (without metering), and independent tactical detection and resolution as a safety net.

The automation element of the Hopper concept will rely on some form of datalink to communicate and resolve issues regarding the aforementioned operational components. Therefore, Hopper operations could leverage lessons learned from simulations focused on trajectory-based automation aided/enabled by air/ground datalink.

Ground operations

A notional Hopper station will have a vertiport for arrivals and departures, disembark and embark areas for passengers, and a charging/inventory area. After landing, a hopper flight will move through at least two, possibly three, of these areas before once again departing the station. The movement of each Hopper vehicle will need to be coordinated with other Hopper vehicles moving on the surface to minimize congestion and bottlenecks.

NASA’s Spot and Runway Departure Advisor (SARDA) is a tool that employs queuing model theory and time-based metering principles to optimize surface movement of aircraft in a way that minimizes delays and energy consumption (ref. 41). The Hopper concept can leverage surface optimization technologies found in SARDA to optimize its station surface operations.

Upon departure, Hopper will require departure clearance and release procedures to ensure that the Hopper vehicle can integrate safely and smoothly into overhead traffic. Precision Departure Release Capability (PDRC) technology evolves the NextGen vision of Integrated Arrival/Departure/Surface (IADS) operations as described in the JPDO Integrated Work Plan (ref. 42) and in the Concept of Operations for the Next Generation Air Transportation System (Joint Planning and Development Office). Operational concepts for a PDRC system are currently being developed (refs. 43, 44). To date, the focus has been on the integration of tactical departure scheduling and surface operations.

A capability similar to PDRC, implemented through an automated algorithm, could be employed by Hopper to integrate the tactical scheduling process with ground logistics in order to more efficiently release its Hopper flights into overhead streams of flights. This type of capability would be best implemented using datalink. The use of datalink will allow pilots to see departure routes and other procedures as text-based messages or graphical displays in the cockpit and cut down on error-prone voice communications. This will enable Hopper flights to depart frequently (perhaps one departure every minute during peak times) by cutting down on time spent giving and verifying departure procedures.

The Hopper concept could use an approach similar to that presented in reference 45, in order to create an integrated arrivals and departure scheduling algorithm capable of learning from, and improving on, past performance. This approach could provide optimized integrated arrivals and departures solutions that will have acceptable performance, even in the presence of uncertainty, and thus streamline the arrival and departure flows at Hopper stations.

Beyond NextGen, further developments in this area could lead to gate-to-gate 4D trajectory management, allowing for more precise flightpath specification and increased ability to fly such flightpaths with improved accuracy. Ubiquitous use of datalink with reduced or no human-in-the-loop interaction and minimal human-over-the-loop oversight will further streamline the departure process.

Terminal area operations

Spacing and separation of Hopper flights, both among other Hopper flights and background traffic, will be an important part of Hopper operations both near Hopper stations and in the terminal areas of major Bay Area airports. Traffic management initiatives such as miles-in-trail (MIT) are used to control flow rates to facilitate the merging of flows in congested areas (ref. 46). An MIT specifies the spatial separation of flights passing through a specific point in the airspace, for example, crossing a center boundary. MIT values are set by controllers in order to generate enough space between aircraft to merge two or more converging flows of aircraft. Controllers set these values based on experience and heuristics, and they tend to be conservative.

The Traffic Management Advisor (TMA) was introduced to address the problem of spacing flights to facilitate the merging of traffic flows (ref. 47). TMA is a real-time decision support tool designed to assist air traffic controllers in sequencing and spacing aircraft for landing. In contrast to MIT, which is a spatial-based separation of flights, TMA is a temporal separation tool. TMA generates efficient landing sequences and times for aircraft within roughly 200 nautical miles of touchdown.

TMA was implemented at Fort Worth Air Route Traffic Control Center (ARTCC) and evaluated in the summer of 1996. The operational evaluation found that the use of TMA allowed for a 5-percent increase in the average airport acceptance rate and reduced delay by an average of 70 seconds per aircraft, when compared to contemporary operations (ref. 48). Subsequent work in this area focused on implementing TMA at other ARTCCs and expanding the horizon of TMA to neighboring centers, known as multi-center TMA, or McTMA (refs. 49, 50). TMA is now used in all 20 centers in the continental United States.

Widespread use of Airborne Dependent Surveillance-Broadcast (ADS-B) will facilitate the use of planning tools such as TMA. ADS-B is an onboard surveillance technology used to broadcast and receive GPS-based positions between aircraft and ground-based systems (ref. 51). This system is intended to replace the current radar surveillance system. ADS-B provides more accurate position information than the current radar system and provides an opportunity to reduce separation standards. However, the process required to assess safety before procedures can be approved could be lengthy. For example, the process to approve the implementation of Reduced Vertical Separation Minima (RVSM) in the European Union required approximately 10 years.

NextGen will further evolve the concept of temporal control for separation by integrating, for example, a ground-based system such as TMA with airborne systems such as ADS-B and Flight Management System (FMS) so that aircraft can self-separate (requiring minimal human-in-the-loop interaction or human-over-the-loop oversight) based on a singular tactical/strategy plan (ref. 52). Here, an ATC will specify leading and trailing aircraft. The trailing aircraft will follow the leading aircraft at the specified distance, using ADS-B out from the leading aircraft to pinpoint its location. This is a change from current operations in which ATC uses ground-based radar information to get situational awareness (i.e. position and trajectory of each aircraft) and then specifies heading and speed changes to each flight in order to keep the proper separation.

The Hopper system could use TMA or a similar tool to manage Hopper-to-Hopper interactions to efficiently utilize arrival and departure capacity at Hopper stations. Additionally, the use of TMA to sequence and space flights arriving into the major Bay Area airports will facilitate the integration of Hopper with those streams, or crossing those streams, when necessary.

Weather mitigation

As a commuter transportation system, Hopper will be required to operate under a variety of weather conditions. While low visibility caused by marine stratus is the predominant weather factor in the Bay Area, considering a Hopper system in other metropolitan areas would require strategies to mitigate other weather factors, such as convective weather.

In order to avoid convective weather, flights may be rerouted around regions of bad weather. Historically, these reroute decisions have been made strategically before flights depart. Due to the complexity of managing traffic during weather events, controllers typically have little time to react to changes in weather. As a result, fuel and time-saving adjustments to reroutes are not typically implemented. The Dynamic Weather Routes (DWR) system was introduced to address this problem (ref. 53). The DWR concept includes a real-time algorithm for generating acceptable reroutes for in-flight aircraft that both route the flight around convective weather (with locations based on updated weather predictions) and can potentially decrease flight time or fuel costs. In addition to regions of convective weather, DWR also takes into account sector congestion when generating new reroutes. The resulting reroute options are displayed to airline air traffic control coordinators. Coordinators can then send reroute information to pilots who can request a reroute from the FAA air traffic controller through an already standard process. Thus, this tool allows airlines to actively seek more efficient reroutes around weather and request their use through the approved channels. Widespread use of datalink would facilitate the implementation of DWR, making the communication of new proposed routes between airline coordinators, pilots, and ATC faster, easier, and less error prone.

DWR technology promotes more efficient use of available airspace and provides a method of reroute generation that could be used by both airlines and the Hopper network to avoid convective weather or other conditions. For example, this type of technology could be used to generate and implement reroutes for Hopper flights that avoid congested regions of airspace for in-flight Hopper vehicles. Allowing Hopper flights to reroute to avoid congested areas in real time will make the problem of separating Hoppers and other aircraft easier, thus easing the burden on air traffic controllers.

Research is currently being conducted to investigate the use of synthetic vision systems to provide pilots with sufficient visual references to enable operations under visual flight rule–(VFR-) like procedures even in low visibility conditions (refs. 54, 55). This type of technology could be used by Hopper to safely adhere to a fast-paced arrival and departure schedule even under low visibility conditions.

4D trajectory planning

A combination of traffic-demand growth and increased use of regional airports has increased the occurrence and severity of coupling between operations at proximate airports. These metroplex phenomena constrain the efficiency and/or capacity of airport operations and have the potential to reduce safety and prevent environmental benefits. Reference 56 contains a study on the management of metroplex operations that includes metroplex design and management of shared resources, such as airspace, fixes, and controller time.

Given the similar nature of how Hopper flights will operate within a Metropolitan area with its stations in close proximity, it can be assumed that Hopper operations will have very similar traits. Therefore, such studies can aid and direct the Hopper project during its system development. By leveraging these types of lessons learned, a more efficient metropolitan network could be realized.

In order for Hopper to realize a fully integrated system comprised of both ground and airborne systems that employ automation, both sub-systems (i.e. air and ground) must be synchronized. Research seeking to developed methods for improved accuracy in ground-based predictions/simulations would greatly assist this goal.

A principal theme of future traffic management is the use of planned four-dimensional trajectories (4DTs) for airborne and surface operations at busy airports. In contrast to autopilots following airborne 4DTs, human pilots (at least with regard to future commercial flights) will continue to manually control the movement of aircraft on the ground. The resulting variability in compliance with planned surface trajectories will have a significant impact on optimal surface planning systems.

In reference 57 the relationship between surface trajectory compliance and elements of surface traffic management operational concepts are studied. Topics include how frequently aircraft trajectories may be re-planned and how far in advance plans must be frozen. Understanding this variability, and its impact on planning time-based/constrained trajectories, could influence how a future Hopper design team might proceed with respect to defining the design requirements for ground-based systems as well as the onboard surface technologies for Hopper aircraft.

Reduced crew operations

The cost of staffing pilots will be significant for Hopper operations. The ability to operate Hopper vehicles via a single pilot, remote pilot, or autonomously could significantly reduce the cost of Hopper operations.

A reduction from two-pilot operations down to single-pilot operations is a challenge. Several issues are of significant importance, including automation issues, operational issues, pilot incapacitation, communication/social issues, and certification and approval issues (ref. 58). With a greater number of tasks allocated to automation in a single-pilot-operation scenario, the pilot may lose situation awareness of different automation states. Further, with new technology and procedures being developed, more operations responsibilities may be centered in the cockpit and a single pilot may not be able to manage this workload. There is also a concern that the lack of social pressure from a second pilot will cause the single pilot to be less attentive to tasks.

The community is also looking beyond single-pilot operations to remote-piloted and autonomous air vehicles. Work is currently being done to plan for the integration of remote-piloted and autonomous aerial vehicles in the National Airspace System (NAS). In reference 59, the authors lay out current air traffic management requirements and procedures to which forthcoming automation tools must adhere.

ADS-B will likely be used to enable automated sense-and-avoid tools that will detect nearby aircraft and generate maneuvers that can be executed to ensure that proper separation between aircraft is maintained. The potential use of ADS-B for this application is discussed in reference 60, along with enhancements to the ADS-B system that would be required to deal with ADS-B signal loss and malicious spoofing.

Current research in remote-piloted and autonomous operations is driven by the integration of small remote-piloted aircraft into the NAS being used, for example, for road traffic surveillance or package delivery. Development of remote-piloted and autonomous operations beyond this type of application to passenger transport introduces the additional considerations of passenger safety and comfort.

General assessment

As technology and tools advance through NextGen and beyond, the integration of Hopper with background air traffic will become more viable. Several key issues must be addressed to bring about realization of technologies that would enable Hopper.

Assessment and approval of reduced separation requirements based on introduction of more accurate surveillance, such as ADS-B, will increase airspace capacity and allow Hopper to operate in dense traffic. Approval and implementation of automated sense-and-avoid technologies will reduce air traffic controller workload.

Research should be conducted in the area of 4D trajectory-based operations focused on finding solutions and developing technologies that will enable the real-time synchronous operations of airborne and ground systems.

Work is currently being done to create future NAS regulations that will permit the operation of remotely piloted unmanned aircraft systems (UAS) in commercial airspace. In order to realize a future Hopper-type concept, a similar effort must be made, leveraging UAS accomplishments where applicable, to create evolving NAS regulations that will ultimately permit the operation of autonomous passenger transportation vehicles in commercial airspace.

Ensuring the integrity and security of transmission of digital information (such as datalink communications and ADS-B) is imperative. Before autonomous operations of passenger aerial vehicles can be realized in commercial airspace, research in digital communications that improves the integrity, timely delivery, and security of digital information to such a confidence level that human-in-the-loop (HITL) oversight is no longer required for the gate-to-gate operations of aircraft would be required.

In order to adhere to a strict schedule and be a reliable transportation mode for commuters, Hopper must be able to operate under a variety of weather conditions. Technology and procedures minimizing the impact of weather conditions on Hopper operations will be necessary.

In summary, Hopper would benefit from the following advances: decreased separation requirements as a result of the adoption of more accurate surveillance technology such as ADS-B; development of NAS regulations permitting the operation of autonomous passenger transportation vehicles in commercial airspace; improved integrity, timely delivery, and security of digital information communication; and synthetic vision systems allowing Hopper to operate under VFR-like procedures even in low visibility conditions. While current trends in air traffic management and research address these topics, a potential application such as Hopper could provide a more concrete motivation for development in these areas. Finally, Table 5 summarizes the preceding discussion of how future air traffic technologies might influence Hopper operational procedures.

Table 5. Future Air Traffic Technologies and Their Influence on Hopper Operational Procedures

Flight Profile Segments	Services Required	Current Technologies/ Procedures	NextGen Technologies/Procedures	Beyond NextGen Technologies/ Procedures	UAS Technologies/ Procedures	Onboard Technologies
Strategic Planning		• Strategic Traffic Flow Management (TFM): GDP, GS, AFP, playbook reroutes, etc.	• Dynamic GOP (Wx Forecasting) (Dynamic Wx Forecasting) (Dynamic TMIs)	• Resource Management (TFM/AutoMax)		• ADS-B
Staging/Charge						• En Route Surveillance & Detection
Embark/Debark						• Wx Detection & Avoidance
Helo-Pad/ Departure	• Departure Clearance & Release Services	• Radio, RADAR & SOPs • PDRC (uncoupled) • Limited data Link w/HITL oversight	• PDRC (coupled) • Expanded Data Link w/HITL Oversight	• Gate-to-Gate 4D Trajectory Management • Dynamic Free Form Wx Rerouting (e.g., playbook segments, ad hoc) • Ubiquitous Data Link w/Reduced- to no-HITL Oversight		• 4D Trajectory Prediction w/Conflict Resolution and Wx Avoidance
Climb	• Sequencing Services • Spacing Services • Separation Services	• Radio, RADAR & SOPs • Traffic Management Advisor (TMA) • Traffic Flow Management (TFM): MITs, etc.	• TMA w/Extended Metering • TMA w/Semi-Autonomous Airborne Response Capability (Eri's Work) • Expanded Data Link w/HITL Oversight	• Gate-to-Gate 4D Trajectory Management • Dynamic Free Form Wx Rerouting (e.g., playbook segments, ad hoc) • Ubiquitous Data Link w/Reduced- to no-HITL Oversight		• Automated Emergency Landing Capability
En Route	• Sequencing Services • Spacing Services • Separation Services	• Radio, RADAR & SOPs • Traffic Management Advisor (TMA) • Traffic Flow Management (TFM): MITs, Airborne Holding, etc.	• Dynamic Structured Playbook Wx Rerouting • Traffic Flow Management (TFM): Direct 2 • Expanded Data Link w/HITL Oversight	• Gate-to-Gate 4D Trajectory Management • Dynamic Free Form Wx Rerouting (e.g., playbook segments, ad hoc) • Ubiquitous Data Link w/Reduced- to no-HITL Oversight		
Arrival/Descent	• Sequencing Services • Spacing Services • Separation Services	• Radio, RADAR & SOPs • Traffic Management Advisor (TMA) w/Efficient Descent Advisor (EDA) • TFM: MITs, Airborne Holding, etc.	• Traffic Management Advisor (TMA) w/Extended Metering • TMA w/Efficient Descent Advisor (EDA) • TMA w/Semi-Autonomous Airborne Response Capability (Eri's Work) • Expanded Data Link w/HITL Oversight	• Gate-to-Gate 4D Trajectory Management • Dynamic Free Form Wx Rerouting (e.g., playbook segments, ad hoc) • Ubiquitous Data Link w/Reduced- to no-HITL Oversight		
Landing/Helo-Pad	• Sequencing Services • Spacing Services • Separation Services	• Radio, RADAR & SOPs • Traffic Management Advisor (TMA) • Traffic Flow Management (TFM): MITs, Airborne Holding, etc.	• Traffic Management Advisor (TMA) w/Extended Metering • TMA w/Semi-Autonomous Airborne Response Capability (Eri's Work) • Expanded Data Link w/HITL Oversight	• Gate-to-Gate 4D Trajectory Management • Ubiquitous Data Link w/Reduced- to no-HITL Oversight		
Taxi		• Radio, Surface RADAR, SOPs, etc.	• SODA • Expanded Data Link w/HITL Oversight			
Airspace Impact/ Requirements		• Dedicated Corridors, Avoid Commercial Arrival/Departure Routes, Extend Class B Airspace to Surface		• Advances in technology will allow operation without dedicated corridors		

Potential Business Models

General Discussion Related to Hopper Business Cases

A metropolitan aerial transportation system requires a completely different type of business model compared to conventional commercial air travel, as well as emerging on-demand aerial mobility concepts, e.g., references 61 and 62. A number of primary, secondary, and tertiary businesses were identified for potential application to the Hopper aerial transportation system network. Figure 56 is a high-level overview of these potential business models. These business models, in turn, could have a significant influence on the design and operations of a Hopper fleet.

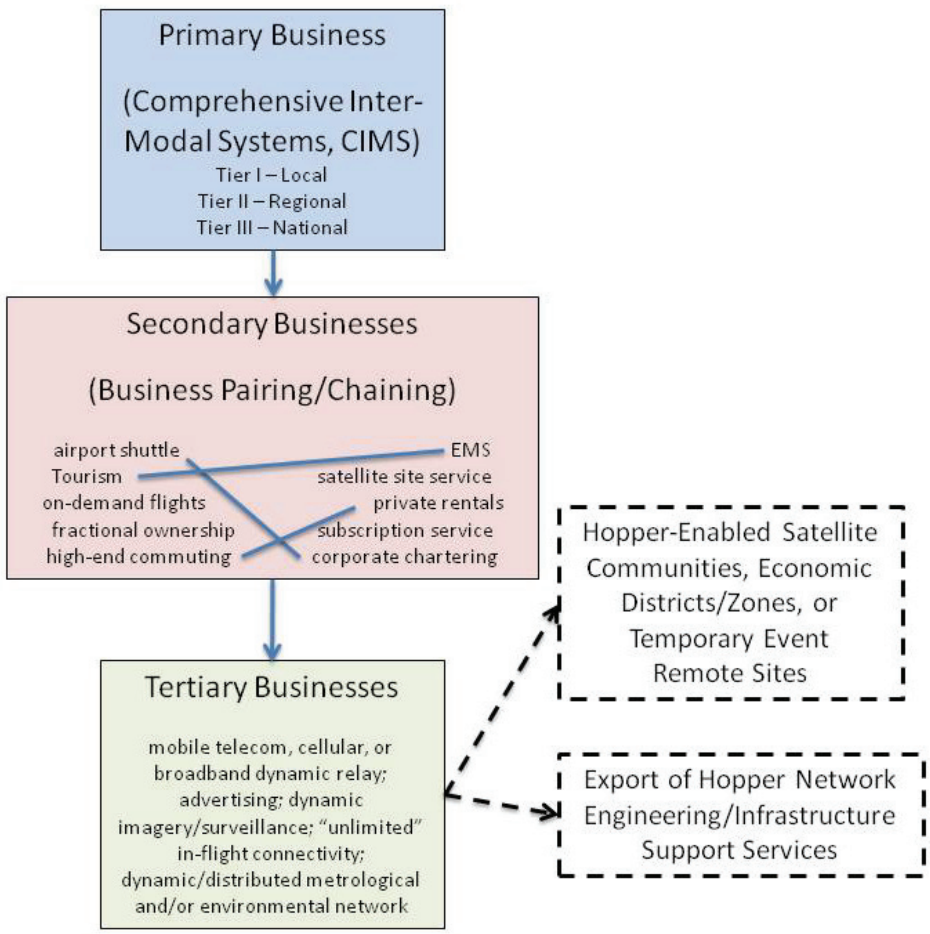


Figure 56. An overview of potential Hopper business models.

The primary business model for Hopper could be encapsulated into a three-tier transportation system labeled for the purposes of this study as Comprehensive Inter-Modal Systems (CIMS). This three-tiered CIMS is described as follows:

> Tier I (local)—"bundled" taxi or private limo pickup/drop-off to/from origin/destination and vertiport.
>
> Tier II (regional)—the above plus connections to/from regional mass transit options and/or commercial transport (e.g., scheduled flights from BART Fremont to San Jose Caltrain stations; connections to high-speed-rail stations; scheduled flights from coast communities to San Francisco or South Bay/Silicon Valley).
>
> Tier III (national)—Bay Area Hopper flights integrated into major airports with corresponding development of other Hopper networks in other metropolitan regions such that seamless transport from residence to final destination across the continental U.S. can be realized.

Secondary Hopper businesses were aggregated under the label of business pairing or chaining. Business pairing/chaining is defined in this study as concurrently conducting two or more complementary business to increase frequency of flights and/or ease transitioning from episodic to scheduled flights. Examples include: airport shuttle; emergency medical service (EMS); tourism; "satellite" or "remote" site limited scheduled service; on-demand flights; private rentals, fractional ownership, or subscription service; high-end commuting; and corporate/business chartering. Such business pairing/chaining is not that unusual for current-day helicopter operators. The unique aspect of such business pairing/chaining with the notional Hopper network is in the business model balance act required between opportunistic/episodic-type business activities versus scheduled public-transit-like service.

Tertiary Hopper-related businesses are labeled as supplemental business activity (supplemental business activity being defined as bringing in non-passenger revenue at no or little cost to primary business). Examples include: mobile telecom, cellular, or broadband dynamic relay; advertising; dynamic imagery/surveillance; "unlimited" in-flight connectivity; and dynamic/distributed metrological and/or environmental network.

Secondary and tertiary businesses are potential means by which revenue might be increased over that accrued through the primary business mode. It is readily recognized that it will be a major challenge to reduce costs and increase supplemental revenue such that Hopper fares could drop below typical commercial aviation fares to those levels approaching ground transportation (taxi and limo) rates, and even more ambitiously, to levels approaching public transit fare rates. The inherent higher energy costs alone of aerial transportation (whether fixed-wing or VTOL) would necessitate some sort of significant counteractive/counterbalancing cost reduction potentiality or unique revenue stream for the Hopper aerial transportation system.

In addition to these potential primary, secondary, and tertiary business cases for evolutionary development of a Hopper network there are several examples of societal/public-good rationale: public-transport/public-good infrastructure investment (such as rail/roadway subsidization); sponsored “incubator” networks for community economic competitiveness; lower-cost alternative to higher-cost infrastructure, i.e. high-speed rail; and public promotion of green aviation and green communities (underlying rationale for electric propulsion for Hopper aircraft).

Additionally, there are potential unique “first-to-market” opportunities for Hopper network developers in that the developers could also leverage their experience and capabilities to be engineering/infrastructure support service providers for other follow-on Hopper-like network development efforts in other metropolitan regions. Further, there could undoubtedly be synergism between potential commercial UAV/UAS operations and Hopper operations in that telecom/broadband Hopper-enabled connectivity could be applied not only to ground-based applications but to UAV operations as well. The Hopper fleet in flight carrying telecom/broadband wireless network and computer server hardware, as a tertiary business model, could literally be the ultimate “cloud” application for UAV operations to support low-altitude, urban-environment-logistics-type commercial UAV missions/applications such as small package delivery. Another UAV/Hopper synergy is the potential dual use of Hopper vertiport stations and infrastructure for UAV operations during off-peak, or nonoperating, Hopper operational hours (midnight to 4 AM, for example, for reasons of noise mitigation).

It is beyond the scope of this current study to perform any substantive analysis related to the potential revenue from the various business models noted in the preceding discussion. In many cases, the business models are too speculative in nature to attempt revenue estimation. In a very qualitative pursuit of such Hopper revenue estimation, one could first bound the problem by considering the revenue stream for small commercial aviation (regional) air carriers on one extreme and rail-based public transportation such as Caltrain and BART on the other extreme. Alternatively, the bounds could be derived from Amtrak rail regional fares/revenue, e.g., “The Capital Corridor” in California on one end and Bay Area taxi/limo rates/revenue on the other. Figure 57 illustrates such a simple qualitative assessment by considering the annual fare revenue, in $M, for the range of ridership levels considered in this study for various assumed averaged daily fares. Average daily fares on the order of $10–$25 are approximately representative of current-year Caltrain daily fares (full fare); fares on the order of $25–$50 are representative of local taxi fares; fares on the order of $50–$100 are representative of local limo rates and/or regional Amtrak fares. Another parallel approach to take for future studies in this area is to consider extension of BaySim, or a comparable agent-based discrete event simulation, to accommodate economic modeling in the simulation. A third approach would be to evaluate whether use of a demand modeling analysis such as TSAM (Transportation Systems Analysis Model) (refs. 63–65), might be extended for a Hopper-type metro/regional aerial transportation system concept.

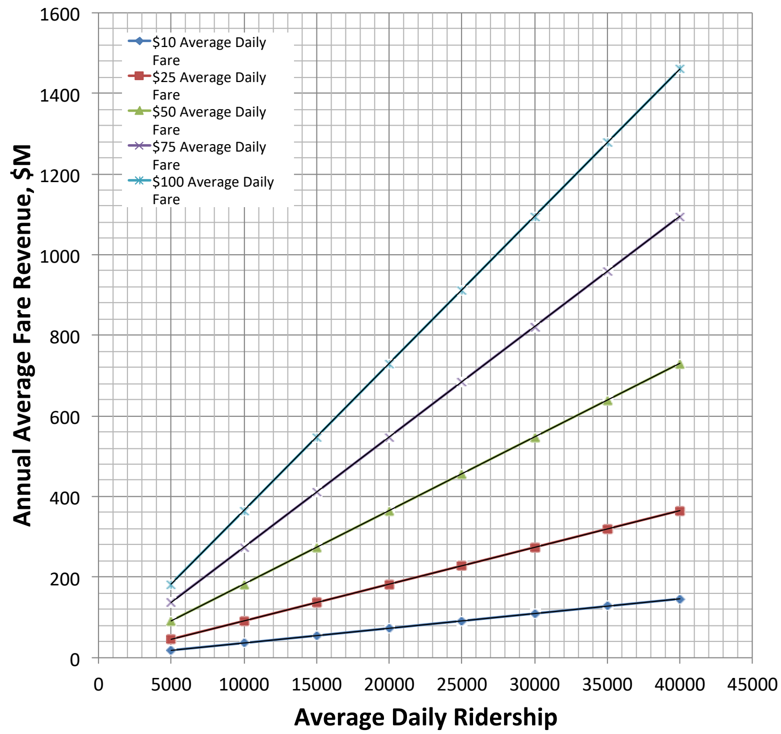


Figure 57. A simple qualitative estimate of annual average fare revenue at various assumed daily fares.

Finally, beyond the questions as to economically viable business models for a Hopper network, it is also crucial to consider how to bring down overall life cycle costs for a notional Hopper fleet. It is equally crucial to consider fleet/vehicle development cycles—and their underlying philosophies/strategies—as to the feasibility of whether airframe manufacturers could bring such a vehicle to market in the identified time frame.

Cost Considerations of Notional Hopper Aerial Transit System

Figure 58 illustrates the notional cradle-to-grave cost considerations of the Hopper network. Figure 59 illustrates the notional cradle-to-grave cost considerations of battery-based Hopper vehicles and Figure 60 illustrates the notional cradle-to-grave cost considerations of fuel-cell-based Hopper vehicles.

Electric-propulsion aviation has a generally positive environmental perception about it; however, although nominally environmentally benign from an emissions perspective, there are other environmental costs that need to be considered as these vehicles become available. Worrying about the solid/hazardous waste (battery) disposal considerations for a small number of technology demonstrator aircraft is one thing, but a large fleet of Hopper aircraft with multiple

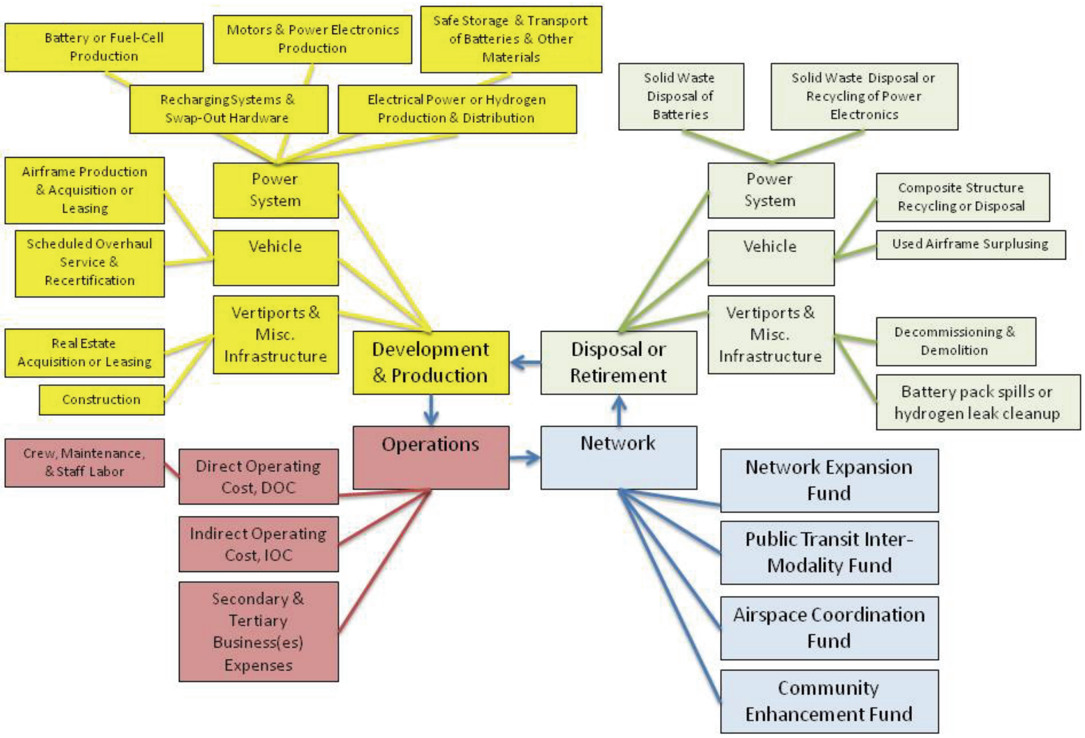


Figure 58. Hopper network cradle-to-grave costs.

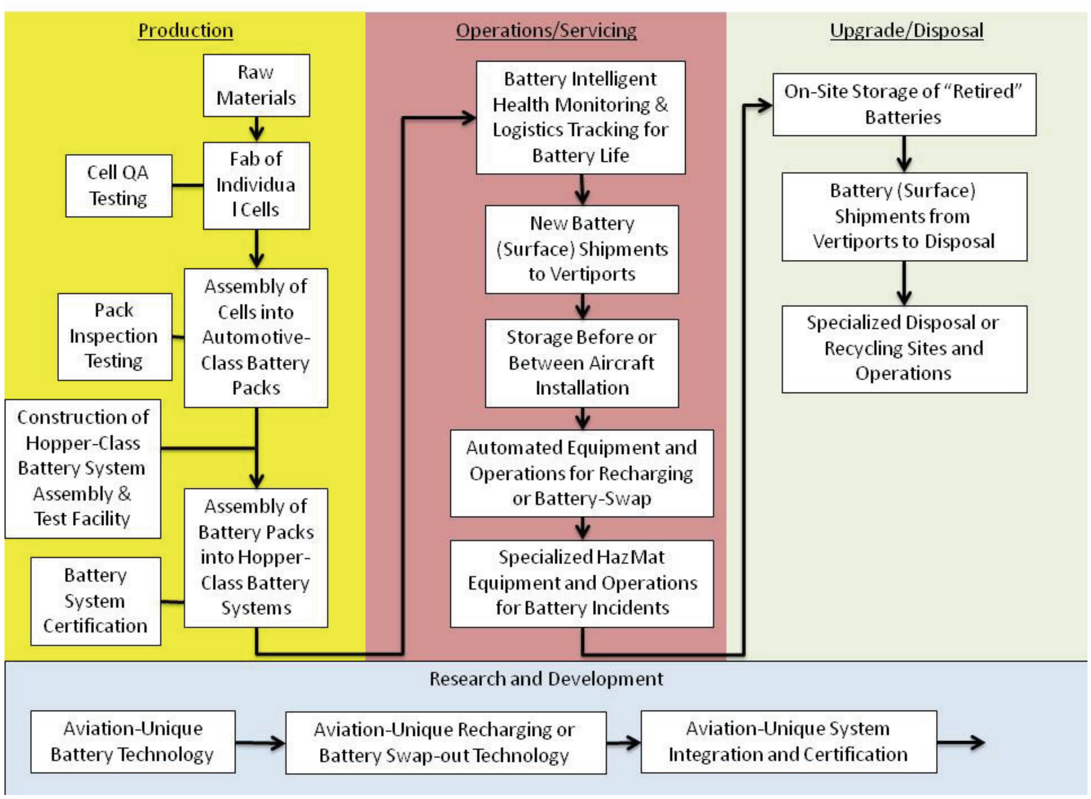


Figure 59. Battery-specific cradle-to-grave costs.

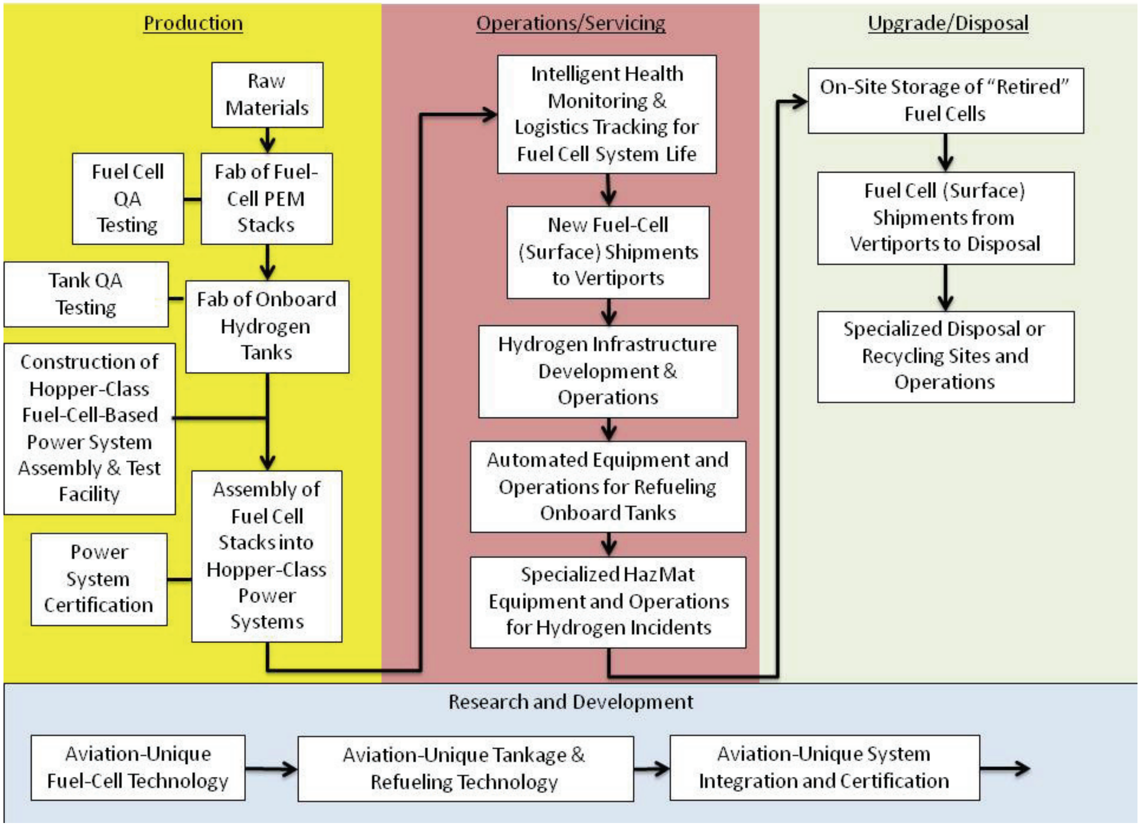


Figure 60. Fuel-cell-specific cradle-to-grave costs.

commuter flights per day is quite another matter altogether. Solid/hazardous waste disposal of expended Hopper battery packs will be a major environmental and cost consideration in the deployment of a fleet of Hopper vehicles (in fact, it will be a major consideration in any fleet of battery-enabled electric-propulsion aircraft). For example, many battery chemistries are highly flammable, even in a discharged state. Further, the cases and electrodes of the batteries could contain harmful metallic content (ref. 66). Increasing the energy storage efficiency of battery packs, and improving the maximum number of discharge cycles they can endure, will help mitigate this potential solid/hazardous waste problem. Additionally, the global socioeconomic cost considerations might be the ultimate deciding factor between battery- versus fuel-cell-based electric-propulsion systems, especially for the aviation sector. Batteries might cost less from a vehicle-centric perspective but might ultimately cost more that fuel-cell-based systems when the raw material, manufacturing, logistics (inventory control and warehousing, public safety and health protection assurance, transport/delivery, servicing, etc.), and disposal costs are fully considered.

Performing actual cost estimation of the cradle-to-grave costs for a Hopper aerial transportation system was beyond the scope of this study. Some cost elements would be relatively straightforward to estimate (with modest confidence) using current estimation methodologies, e.g., vehicle/airframe acquisition costs using the NDARC cost modeling analysis for a relatively conventional tandem helicopter design similar to existing production aircraft (i.e. the U.S. Army's CH-47 Chinook helicopter). Even direct and indirect operating costs might be modeled by incorporating elements of commercial airline operating cost models (ref. 67). Many other cost elements, though, would be very speculative in nature to estimate. For example, estimating the cost of Hopper-class advanced batteries and/or fuel-cell power systems would be problematic. A simple linear scaling of production/acquisition costs (dollars per KW-hr) from current automotive-class batteries and/or fuel cells would likely yield unreasonably high power system costs for the circa 2030–2040 time frame. Additionally, continuing the cost discussion with respect to power systems, it is also very unclear as to what the discharge cycle life of circa 2030–2040 power systems will be. The discharge cycle life—and associated periodic replacement cost—of the power system (whether battery or fuel cell) will have a profound effect on vehicle/fleet life cycle costs. Accordingly, most Hopper life cycle cost discussions will be deferred to future studies with the exception of a discussion to follow regarding the potential implications of advanced technologies on the Hopper concept.

Technology Development and Introduction to Potentially Reduce Hopper Network Cost

Given the relatively small niche market for metro-regional aerial transportation, it is highly unlikely that "clean-sheet" designs would be developed for Hopper vehicles. Instead it is far more probable, if such vehicles are to be developed beyond technology demonstrators, that they will be heavily modified electric-propulsion variants of existing civil/military rotary-wing vehicles (e.g., ref. 68); only in this manner would airframe development costs likely be kept to a minimum. This might be seen as contrary to the vehicle conceptual design emphasis of this report and its predecessors (refs. 1, 2), but it reflects a pragmatic perspective on how such vehicles might one day be developed. Electric-propulsion variants of light-, medium-, and heavy-lift versions of rotorcraft would have to be subject to compromises in performance and payload/passenger capacity in order to accommodate the design constraints associated with electric propulsion and the evolution towards an "electric rotorcraft." One compromise that should not be made though, from a spiral development perspective for the electric propulsion systems as a whole, is abandoning design-wise propulsion system modularity and upgradability. There is likely a certain inevitability that early versions of Hoppers might have to be hybrid hydrocarbon/electric-propulsion systems, followed perhaps by (initially limited performance) battery-based systems, vehicles with next generation improved battery systems, and then maybe fuel-cell-based electric-propulsion systems. (This sequence of introduction of specific energy-storage systems is purely speculative and merely offered as an illustration that aviation-compatible energy storage systems, and electric propulsion as a whole, may radically evolve over the next couple of decades. The only prudent way to deal with this uncertainty is, again, to emphasize propulsion system modularity and upgradability in the design and development process for these aerial vehicles.)

Automation and autonomous/intelligent systems technology could have a tremendous impact on the viability of Hopper network economics.

Notional Implementation Plan Scenarios and Future State Iterative "Forecasting" and "Backcasting"

As discussed earlier in this report, a Hopper network will not be designed and implemented as a whole; instead, it will evolve from a rather simple network to a more complex system over time. This poses several future challenges in terms of a system-of-systems analysis of the Hopper network. Both forecasting and backcasting tasks—for analyzing the notional evolution of a Hopper network—should be tightly integrated into one overall effort. It is proposed that the conceptualization/development of a new software tool (using "sneakerware" to interface with NDARC, FACET, and BaySim) be performed; e.g., Figures 61 and 62. For discussion purposes, the tool is designated IMPLEMENT: Investigating Mission-PLausible-Elements Mandating ENabling Technologies. Some limited precursor feasibility work was performed with this initial tool prototype being developed in the Mathcad™ general-purpose analysis application software package (ref. 69).

More of this precursor IMPLEMENT work is discussed in Appendix C. This initial work, in particular, drew in part from the BaySim simulation results discussed earlier. Figure 63 is an illustrative example of "backcasting" yearly revenue estimates based on an assumed target ridership level circa 2035 of 30,000 Hopper passengers per day.

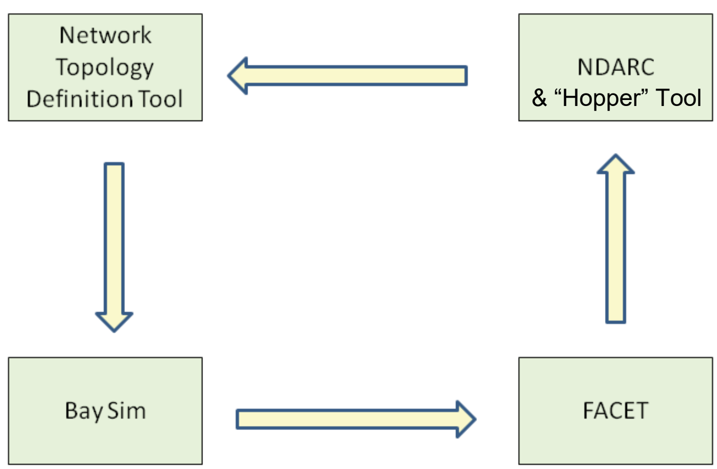


Figure 61. Phase I and II approach.

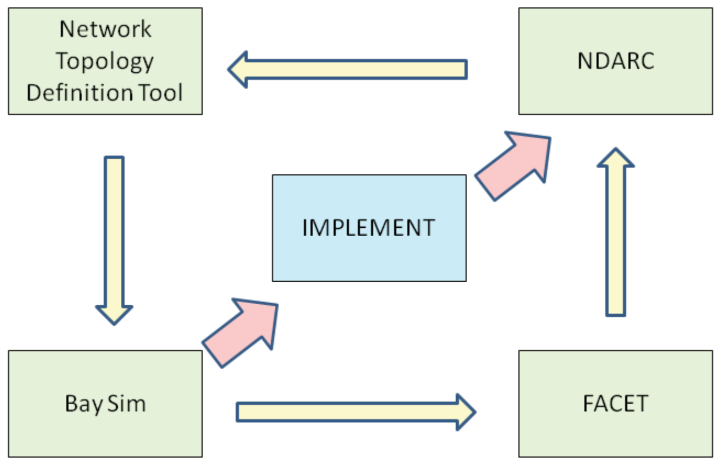


Figure 62. Proposed approach for future work.

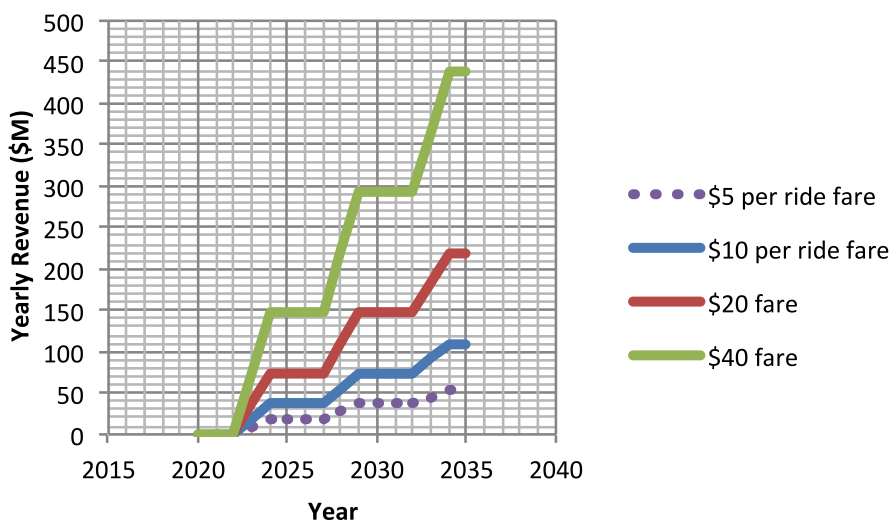


Figure 63. Projected yearly revenue for various assumed origin-destination fares.

Station Conceptual Design and Operations Considerations

The following discussion is a high-level perspective of the design/trade-space for Hopper stations and their systems; e.g., "oil rig type" platforms near the Bay Bridges, or elevated structures built over rail stations or expressways, or Japanese-style parking garage multi-story structures with elevators capable of raising/lowering hopper aircraft. This overall discussion provides an opportunity to think out-of-the-box prior to selecting the most feasible/plausible station concept. The discussion then includes speculative storyboard-type narratives of both the passenger experience and the vehicle operations—including pre- and post-flight—and overall station operations, with emphasis on the high degree of system-of-systems automation that will be required to fully realize the Hopper concept. Additionally, efficient and cost-effective operations of Hopper vehicles as "public transit," versus conventional fixed-wing commercial air transport, may require revisiting some of the accepted practices and procedures of current-day airport and commercial flight experience. For example, reducing Hopper door-to-door commute time, as compared to surface transportation options, may well require highly expedited security procedures/protocols for vertiport operations and Hopper flights. Having to check into a vertiport an hour or two in advance of a flight, or multiple flights/hops, will not yield an acceptable transportation alternative to surface transportation, even under highly congested street/rail conditions. Technological advances may be part of the solution to expediting the door-to-door transit time. Among those advances might be the use of autonomous (albeit passenger-carrying) Hopper vehicles versus crewed vehicles.

To aid in the following metro station operations discussion, three storyboards are outlined. The storyboard descriptions reflect an early- (circa 2020), mid- (circa 2030), and late-stage (circa 2040) implementation of the aerial metropolitan transportation systems.

Circa 2020 (small commercial on-demand and limited subscription services, primarily using turboshaft-powered vehicles):

> *Xavier has to make an extremely short turnaround business trip to San Francisco from the East Coast. Having little time to do anything more than download essential business notes onto his personal digital device and book online his flight to SFO, he travels to the airport and boards his flight. En route he uses the aircraft's onboard Wi-Fi network to charter helicopter air service from SFO to the closest city-center vertiport to his final business-meeting destination. Time is of the essence for Xavier; to be competitively successful distance cannot be seen as a barrier to providing time-critical services to the customer. These small (one to two aircraft on the pad at a given time) city-center vertiports, though few in number, were an outgrowth of a public/private partnership wherein the vertports not only support commercial services but, upon need, also support essential public emergency response and public safety services.*

Circa 2030 (small networks, based on both commercial on-demand/subscription services as well as small commercial and/or public-transit-like regularly scheduled services, primarily using turboshaft-powered vehicles):

> *Mid-day, at work, Jane gets a phone call from her boss instructing her to go to a face-to-face meeting called at the last minute to resolve a pre-fabrication programming issue. Her primary office/workspace is in San Francisco and the meeting is in Milpitas; going to such a meeting would require at least an hour traveling by automobile. Fortunately, Jane is a subscriber to a helicopter air shuttle subscription service. For a modest yearly fee she is afforded an allotment of air commute flight hours that she can draw upon with little or no advance booking. Normally, she uses this subscription service to take short flights to Santa Cruz for periodic weekend getaways. The service provider can offer affordable subscription fees to its clients by offsetting the costs of operation through a number of alternate revenue-generating measures to the subscription service such as air tourism bookings and limited scheduled ferry service across the San Francisco Bay. Quickly contacting her service provider online, she is able to arrange for a flight departure from a nearby vertiport near one of the centrally located downtown piers. A quick taxi ride to the vertiport and she is on way to her business meeting.*

Circa 2040 (large networks embodying comprehensive inter-modal systems and primarily using electric-propulsion vehicles):

> *John's typical morning commute begins with an autonomous taxicab (driverless, electric automobile) ride from his home to a local transit center. This transit center provides multi-modal transportation services including taxis, buses, light-rail, and Caltrain (or BART) support and, additionally, a full-service vertiport with regularly scheduled Hopper service throughout the Bay Area. John's job takes him on frequent excursions throughout the Bay Area; for this reason he enjoys the convenience and speed of the Hopper transportation network. The network has evolved over the past two decades from an initially small, to a now moderate-size, consortium of private and public transportation system entities that provide a modest but comprehensive metropolitan/regional inter-modal transportation system. Today, John's morning commute is straightforward: the taxicab ride from his residence to the Palo Alto transit center vertiport, a flight via Hopper to a downtown vertiport in San Francisco, and a short bus ride to his office building. The scheduling/ routing for his commute is all automated and has been enabled through his personal digital device. The routing has been optimized to minimize his transit time during the commute and maximize his overall convenience. Next week, John will have to take a commercial fixed-wing flight to Southern California; his inter-modal routing to/from the airport has*

already been optimally planned—including scheduling constraints related to predicted delays for the time of day of travel, reflecting commute ridership levels and airport security line lengths.

VTOL Metro Station Concept(s)

Hopper vehicle design characteristics will have a substantial influence on station design. The size and number of passengers onboard the vehicles will have a direct bearing on the total square footage required for the station. Among the key considerations in station design is the means by which the electric-propulsion Hopper vehicle batteries are recharged or replaced. Some of the battery characteristics of the baseline 30-PAX Hopper design are:

Range: 65 nm

Battery capacity: 1311 kW-h

Battery weight: 4916 lb (0.65 kW/kg specific energy)

Volume: 74.1 cubic-feet (554.3 gal.)

In terms of recharge rates and number of cycles, there is a lot of data out there with various answers, and the two factors are related. A goal of 150 cycles is probably reasonable with recharge rates of 1/5C to 1C (where C is the battery capacity), so 5- to 1-hour recharge rates. These relatively low discharge cycles highlight some significant implications for vehicle design; e.g., if batteries are kept in replaceable external sponson/wing-mounted fuel-tank-like streamlined pods, then vehicle sizing will have to model such a configuration arrangement and account for delta-drag and performance change; another possibility is modular separation of drive and cabin units (cabins would be swapped into "refreshed/recharged" drive units). The goal here is to show the wide ranging vehicle design implications of assumed station CONOPs and which concept is the "best" one.

Implications for station design/architecture, automated and manually operated facilities/ subsystems, and how to optimally integrate stations in a cost-effective and neighborhood friendly manner are highlighted next. Hopper stations should support the following functional requirements (assuming a battery-based electric-propulsion Hopper fleet):

1. Ability to charge (ideally onsite but optionally offsite) and replace (mandatory onsite) batteries.
2. Control tower/room with high-bandwidth networking on aircraft; more like network control than air traffic control.
3. If batteries are replaced rather than recharged while still onboard aircraft, then battery depots at, or nearby, the station need to be provided. If batteries are recharged onboard the aircraft, then a hanger/storage depot for the aircraft needs to be provided.
4. Automated/semi-automated equipment to replace batteries on aircraft (gantries, pallets, forklifts, etc.). For example, batteries could hang from aircraft sponsons like external fuel-tanks for conventionally fueled aircraft. Automated equipment would be

needed to remove and replace large battery assemblies on such sponsons in a safe and reliable manner. Such equipment would also need to surface transport charged/ discharged batteries to/from battery depots. Alternatively, if batteries are not removed but recharged onboard, then automated charging stations (with robotic arms to insert/withdraw charging plugs/cables or, maybe, employing wireless inductive charging) would need to be provided.

5. Automated tugs to surface transport Hopper vehicles to parking structures (hangers) and or loading/unloading zones (maybe jetways like conventional commercial aircraft, but probably not). Alternatively, maybe some sort of monorail/moving-sidewalk approach to moving aircraft from place to place within/about the station, or the vehicles themselves could self-tug to hangers and loading/unloading zones.
6. Freight/aircraft-rated elevators needed (if the station landing platform is significantly above ground level) to transport aircraft to tractor-trailer surface-transport of disabled vehicles.
7. Passenger loading/unloading zones. More efficient approaches to boarding/ disembarking to/from aircraft and terminal facilities.
8. Automobile parking structures and/or access infrastructure (passenger walkways, tunnels, escalators, elevators, bridges, etc.) to inter-modal transport. If the Hopper network is closely coupled to autonomous ground transport (e.g., driverless cars for hire) then both sets of infrastructure requirements need to be closely couple together. Ideally, one would want to exit an autonomous taxi at curbside, cross a short plaza, and then immediately board an aircraft through a convenient ground-level access.
9. Deployable (morphing) station ground infrastructure structures. For example, deployable jetblast deflectors to minimize rotor wake outwash hazards for aircraft landing or takeoff; loading/unloading zone structures may be deployable or morphing; deployable safety/crash barrier structures.
10. Curbside and ticketing amenities, and security cordon infrastructure. An interesting side question to consider is, if the Hopper aircraft are fully autonomous and are protected from direct seizing of control or indirect "hacking," then are today's commercial airport security provisions required? Or would Hopper security provisions be more like mass transit (rail, bus, and subway)? Further, personal digital devices, reservation software, and mass-transit-like business models might eliminate the necessity for such commercial air transport security protocols.
11. Could reinforced/covered roadways or expressways serve as "cleared" corridors for takeoff and landing glide paths into/out of stations? If so, then maybe auxiliary "covered roadway" structures could be used for the battery and aircraft depots noted above.

The current state-of-the-art in automated battery swapping and/or rapid recharging of automotive-class battery packs is arguably presented in references 70 and 71. Though Hopper/ aviation-class batteries will be an order of magnitude larger in terms of total energy-capacity as compared to current automotive-class battery packs, it is reasonably plausible to envision modular systems that could be serviced by automated equipment (Fig. 64). This technical goal/challenge of rapid recharging or, alternative energy-storage module swap-out, is not limited to battery-based electric-propulsion aviation assets. A similar argument could be made for fuel-cell-based aerial vehicles: i.e. automated swap-out of hydrogen tanks, or, perhaps, swapping out complete end-to-end hydrogen-tank and fuel-cell stack modules, or rapid refueling of non-removable, onboard tanks from ground-based hydrogen fueling stations, or finally, the incorporation of reclassifier systems into the fuel-cell modules to "recharge" the fuel cell by applying ground-based electrical charging to generate/pressurize hydrogen onboard the vehicle through hydrolysis. The success of the Hopper aerial transportation system concept, by nature of the number of flights per day per vehicle and the rapid turnaround required at individual vertiport stations for each vehicle, will largely be dependent on the feasibility of such notional automated refueling/recharging systems. (Hydrogen as the fuel cell's "fuel" is implicitly assumed throughout most of this report, from a nominally environmentally benign vehicle emissions perspective, although the production of hydrogen—particularly from fossil fuel feedstock—is not necessarily as benign as one might hope. Alternate fuels, especially methane as a fuel for solid oxide fuel cells (SOFC) is another design choice possibility, but it is one with an attendant increase in emissions.)

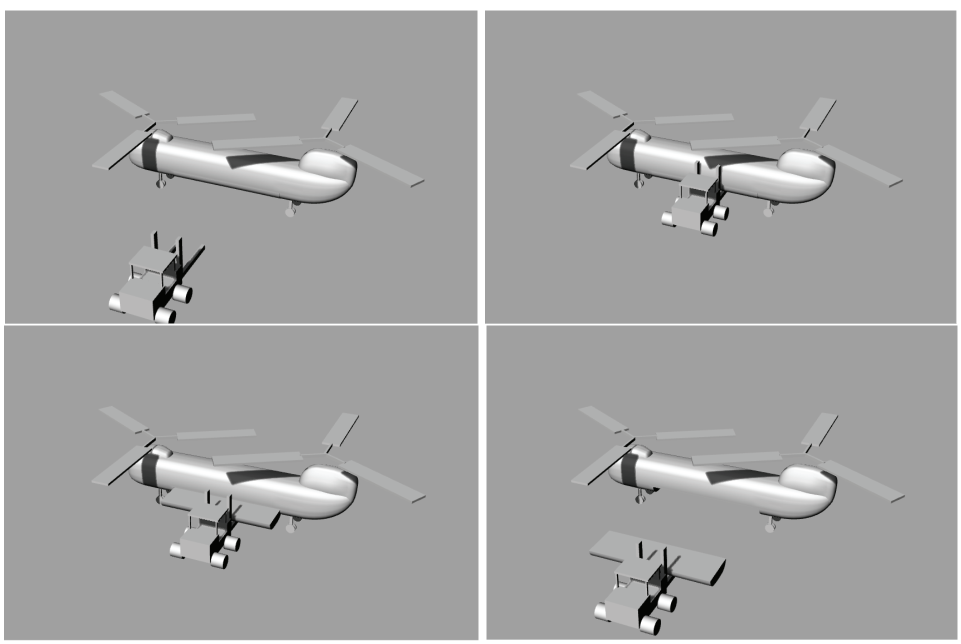


Figure 64. Automated battery swap-out (removal of battery: image time sequence left to right and top to bottom).

VTOL Metro Station Notional Operations

The following is a brief outline of the notional CONOPS for Hopper operations out of metropolitan stations, or rather vertiports. This CONOPS outline is intended to be fairly generic as to whatever station-to-station network topology is anticipated. Figure 65 illustrates some of the anticipated key attributes of a Hopper vertiport station.

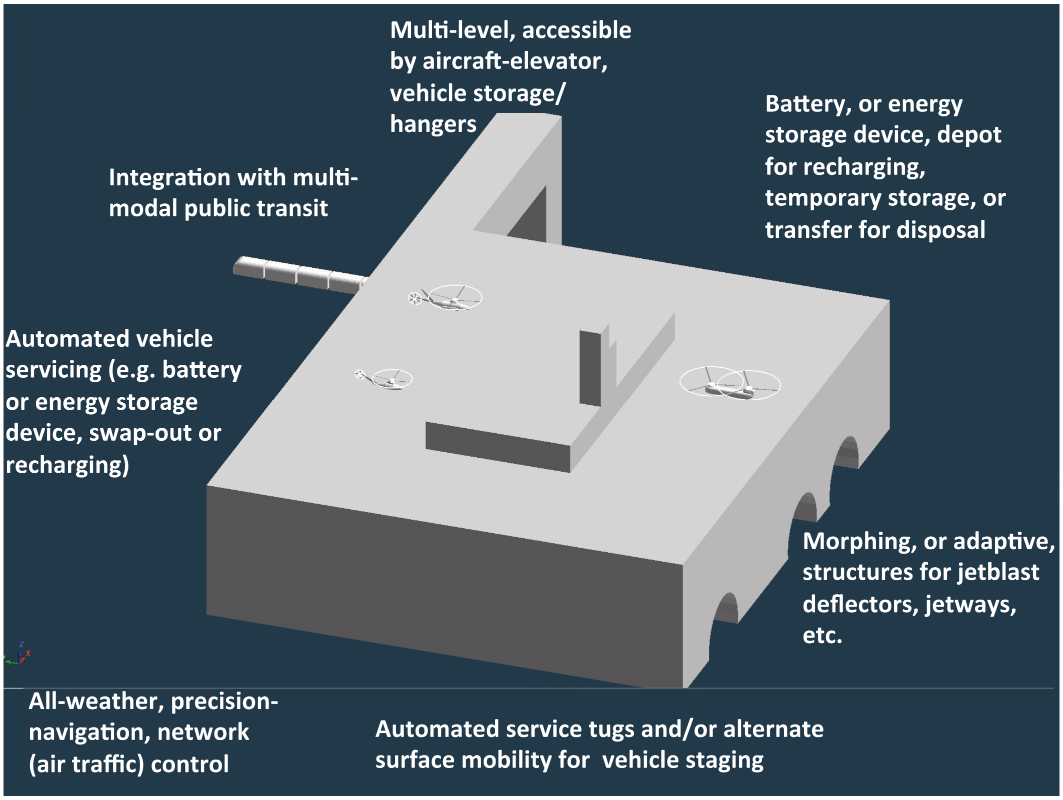


Figure 65. Notional station operations/capabilities.

Hopper Terminal Area Hazards Including Rotor Wake Interactions

The mid-fidelity CFD code RotCFD was used to make operational assessments as to notional VTOL metro station design and CONOPs as might be affected by rotor wake interactions (i.e. downwash/outwash); refer to Figure 66. RotCFD was developed under NASA Small Business Innovation Research (SBIR)-sponsorship and has been used previously for similar applications—large civil tiltrotor operations in the near vicinity of vertiport infrastructure (ref. 72)—as that examined in this study for the Hopper/aerial transit station problem.

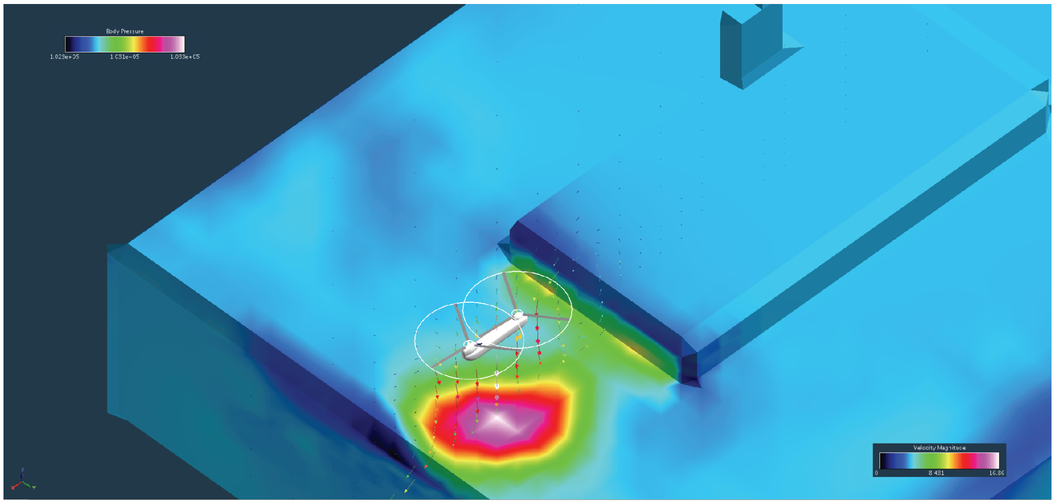


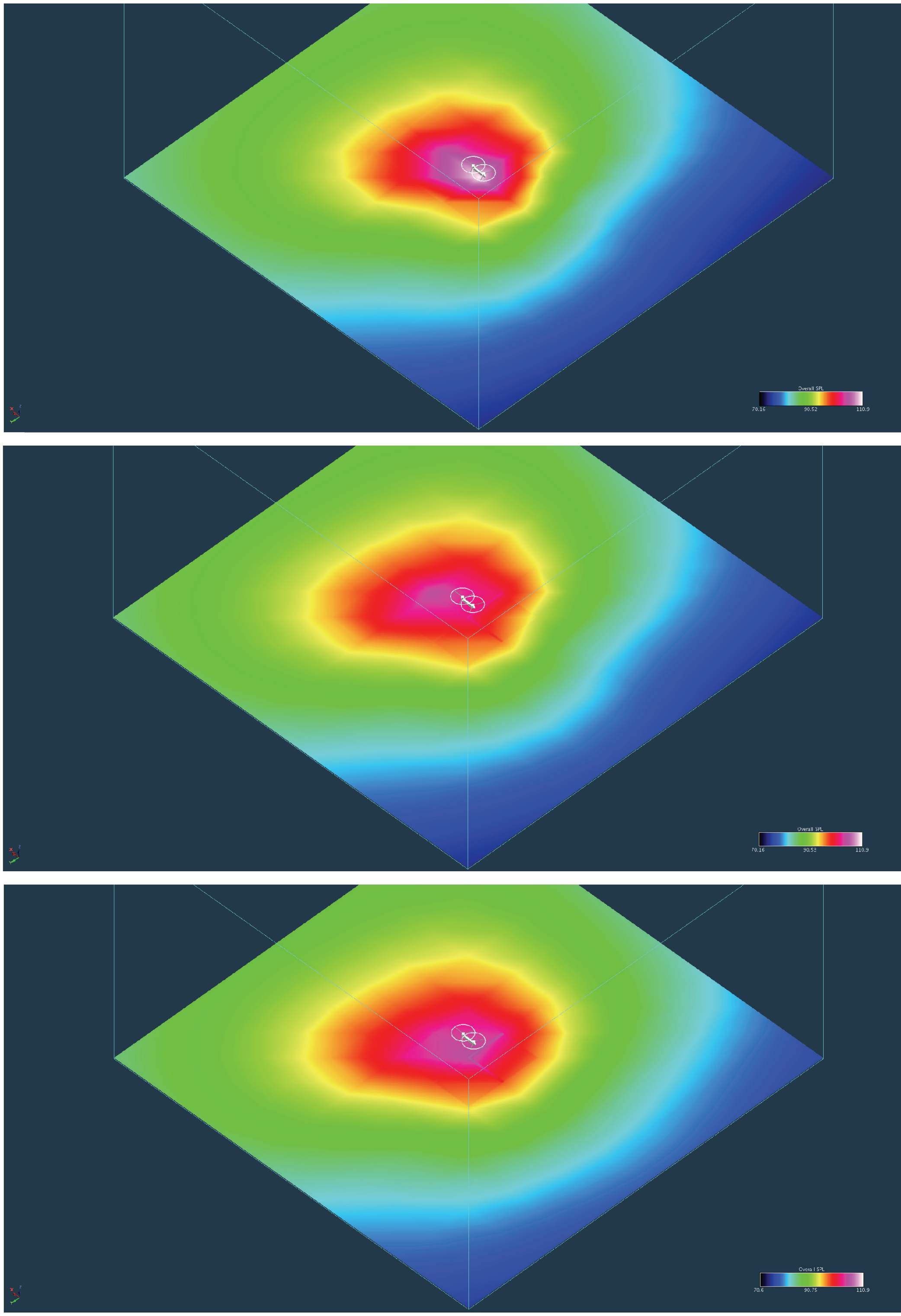
Figure 66. Representative rotor wake interaction prediction in the immediate environs of a VTOL metro station.

More RotCFD vehicle performance predictions and VTOL metro station rotor wake interaction predictions are provided in Appendix A.

Hopper Noise and Emission Concerns

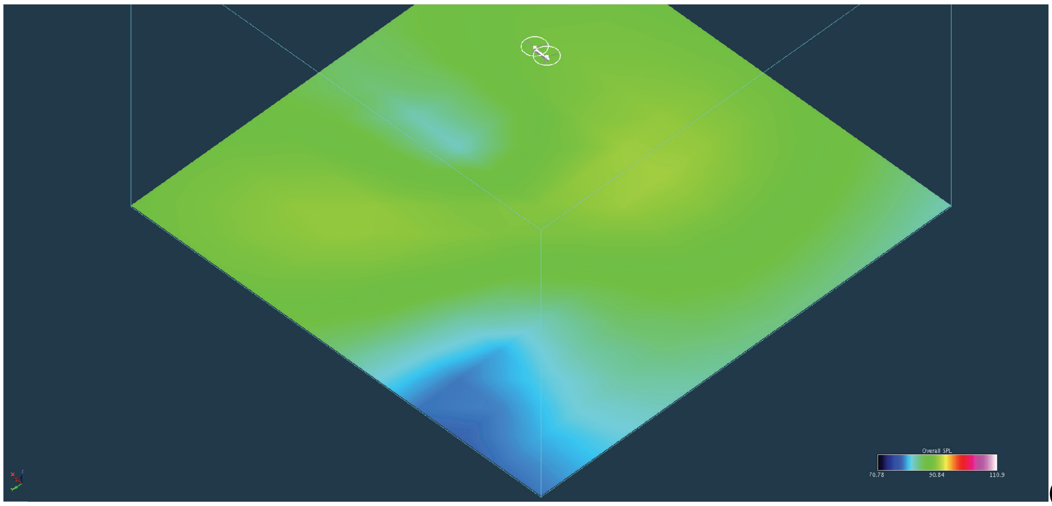
First-order acoustic predictions were performed, with an enhanced version of the RotCFD tool, for noise source estimates of the Hopper 30-PAX tandem electric helicopter conceptual design developed during Phase I of the study (ref. 2). These results are considered to be very preliminary in nature as RotCFD needs more extensive validation as an acoustic analysis tool than could be performed as a part of this study. There was a limited effort during this study to begin an initial validation effort of the tool in parallel with the Hopper noise source estimates; this limited acoustic validation work is documented in Appendix B for an existing vehicle (i.e. the Boeing Vertol BV-234) comparable to the 30-passenger Hopper vehicle. Future work might potentially use the Integrated Noise Model (INM; refs. 73, 74) or one of its successors such as the Aviation Environmental Design Tool (AEDT; ref. 75) to conduct a detailed noise emission assessment throughout the urban environment. Fortunately, the INM database includes a rotary-wing vehicle very similar to the 30-PAX tandem Hopper vehicle baseline reference design—the Boeing Vertol BV-234—more readily known by its military designation, the CH-47.

Figure 67a–d presents an illustrative sample of hover, or static operation, acoustic predictions for the 30-PAX electric tandem hopper baseline design. More results are presented in Appendix B.



(a) (b) (c)

Figure 67. Representative rotor/vehicle noise source predictions (hover/static operations): (a) h/R = 1; (b) h/R = 2; and (c) h/R = 3.



(d)

Figure 67. Representative rotor/vehicle noise source predictions (hover/static operations) (cont.): (d) h/R = 15.87 (150m AGL).

Alternative Vehicle Concepts

The Hopper vehicle conceptual designs examined in Phase I of the study (ref. 1) look outwardly like conventional rotary-wing aircraft (e.g., single-main-rotor and tandem rotor helicopters). This emphasis on conventional-type aircraft designs should not be interpreted as a definitive assessment of the optimal vehicle configurations for Hopper-type aerial transportation operations and overall suitability with respect to electric propulsion. From a vehicle development cost perspective, focusing on conventional vehicle configurations makes sense. Further, given the rather small market niche for Hopper-type metro/regional aerial transportation missions, variants of existing vehicle designs will likely be adapted for electric propulsion rather than developing clean-sheet designs. However, from a technology perspective, one of the key advantages of electric propulsion is that vehicle configurations can be developed that draw upon the distributed propulsion capability implicitly inherent in the use of electric motors. One of the early manned electric vertical lift vehicles (ref. 16) was a multi-rotor (16 rotors/propellers in this particular case) system versus a conventional one- or two-rotor system. Small all-electric RC-hobbyist quadcopters/quadrotors are now widely available, and their commercial success is inspiring larger, more capable, unmanned and, even potentially manned, vehicles. There are also advantages to electric propulsion, from a complexity and reliability perspective, even in the case of electric rotorcraft having only one or two rotors, in that drive systems could potentially be greatly simplified to allow for novel rotor configurations. Such is the case of early proof-of-concept work with an electric "tiltrotor" as noted in reference 17.[6] These vehicle configurations might well have been difficult, if not impossible, to develop using conventional internal combustion reciprocating engines or turboshaft engines. Accordingly, electric propulsion may be

[6] This vehicle is more of a hybrid fan-in-wing and tilting ducted-fan vehicle than strictly speaking a tiltrotor aircraft.

a key enabler to revisit exotic vehicle configurations abandoned in the past and enable the development of innovative new configurations. Table 6 summarizes some notional alternate, and in many cases exotic, vehicle configurations—as compared to the conventional single-main-rotor and tandem helicopter baseline configurations employed through most of this study—that might plausibly meet the Hopper mission. This list of vehicle conceptual design configurations is intentionally speculative in nature. It reflects, in part, the wide-ranging spectrum of vehicle conceptual design configurations that a growing community of electric VTOL innovators have been proposing. It is hardly an exhaustive list; some concepts are wholly new and some are refinements of past proposed vehicle configurations. Other, perhaps more conventional, VTOL configurations are not included in the list but could be readily suggested such as, for example, tiltrotor or tiltwing aircraft. These alternate (more exotic) Hopper configuration concepts are highlighted herein to provoke additional future thought as to the implications of rotary-wing electric propulsion and "electric rotorcraft," in a general sense, and potential new modes of operation and new aeromechanic issues and technologies presented by such vehicles. As they are not the focus of the current work, only a very limited discussion—for the above noted purposes—is presented for these vehicle concepts.

Table 6. Alternative Hopper Vehicle Configurations and Qualitative Assessment

Vehicle	Description	Advantages	Disadvantages
Autogyros	Autorotating rotor; electric propulsion for propeller; configuration can be with or without wing. (Fig. 68 shows a very specific example of an innovative oblique-wing "compound" autogyro.)	Can perform "jump" takeoff; tethered electric power could potentially be provided just prior to "jump." The lightest weight and lowest power configuration for low-speed rotary-wing flight.	Inability to hover. Limited to relatively low forward-flight speeds. May be adversely susceptible to wind gusts during takeoff and landing.
Quadcopter	Combined four-rotor and lifting (center) body configuration; rotor control would likely be a hybrid scheme between rotor speed-control and conventional collective and cyclic rotor blade pitch control (Fig. 69).	Symmetry of configuration could be used advantageously in terms of low-speed maneuvering and improved wind gust handling, as well as intentional slow-rotation of airframe to present passengers panoramic views of cityscape below.	High profile and parasite drag compared to conventional helicopter configurations. Exotic maneuvers enabled by vehicle symmetry might pose significant flight control challenges. Loading and unloading of passengers might present unique challenges.
Toroidal Aircraft	Could be thought of as a super-sized version of the Sikorsky Cypher UAV (ref. 76); passengers are seated in the interior of the fuselage toroid (Fig. 70).	Same general advantages as noted above for "quadcopter" configuration.	Same disadvantages as noted for quadcopter configuration, as well as additional rotor, duct, and airframe interactional aerodynamic challenges.
Quadrotor	Four-rotor system with a more conventional airframe as compared to quadcopter and toroidal aircraft configurations; inspired in part by Bell Helicopter Quad-tiltrotor (QTR) and a four-rotor version of the Mil Helicopter V-12 heavy-lift helicopter concepts. Nacelles/pylons don't tilt; aircraft flown in helicopter-mode only (Fig. 71).	Possibly lower profile and parasite drag than the quadcopter and toroidal aircraft configurations noted above.	Potentially significant rotor-on-rotor wake interactions in forward flight.

Table 6. Alternative Hopper Vehicle Configurations and Qualitative Assessment (cont.)

Vehicle	Description	Advantages	Disadvantages
Multi-rotors	Vehicle configuration with five or more rotor systems. Similar in concept to the initial vehicle configuration of ref. 16, though on a much larger scale. (Fig. 72 illustrates a very specific example of the multi-rotor concept, i.e. the vehicle airframe/fuselage is carried over/above the rotors instead of under the rotors as conventionally done by other rotorcraft.)	A high degree of redundancy from a system component and safety perspective. Such component redundancy or commonality could potentially drive down manufacturing costs. Vehicle could be readily scalable from small to large payloads.	Potentially very significant rotor-on-rotor wake interaction effects along with high profile and parasite drag. Passenger access to/from aircraft would be challenging and might require specialized “jetways” or other loading equipment.
Flying Platforms	Larger size version of the Hiller-type flying platform but augmented with ducted-fan propulsors for improved low-speed control above that afforded by center gravity shifting (ref. 77; Fig. 73).	Potentially mechanically simple systems. Additionally, loading and unloading passengers would be greatly simplified because of the lack of a conventional fuselage/cabin and landing gear. Could potentially be made very stowable between flights, and perhaps recharging, thereby reducing the vertiport (hanger) infrastructure/space required.	Probably restricted to very small number of passengers, maybe below that of utility for the Hopper-type mission. Certain configurations might lack a fuselage/cabin thus exposing passengers to elements and in-flight airstream; such configurations would be limited to significantly lower forward-flight speeds than conventional helicopters.
Flying Trucks or Jeeps	Rotors or fans shrouded or ducted on or within a structural frame that also supports a cabin (ref.77).	Potentially, though necessarily so, roadable.	Probably restricted to high-disk-load vehicles with large profile and parasite drag.
Twin-hull VTOL Aircraft	Two rotors, either tilting or fixed, supported by wings or struts between two fuselage hulls (ref. 78).	Potentially improved passenger loading and unloading over a single fuselage/cabin aircraft. Passengers and ground-assets would be protected on at least two of four sides, irrespective of rotors spin-up, while on the ground.	Potentially increased cabin noise/ vibration due to close proximity of rotating blade tips to the fuselage exterior. (Conversely, the community noise might be reduced as a consequence of noise being partially blocked by fuselage hulls.)
Modular Rotorcraft	An example of this configuration would, on demand, be for single rotor systems/vehicles to be combined into coaxial rotor systems/vehicles and such coaxial systems could, in turn, be combined into (four-rotor) tandem coaxial helicopters; finally quad systems could be combined to octo-rotor vehicles; subject to a different mission, the vehicles could be disassembled/reassembled into different configurations.	Increased safety and reduced maintenance costs through increased redundancy and/or commonality of system elements/ components.	Such vehicle configuration versatility may be unwarranted for the Hopper-type mission. Though notionally the Hopper fleet could have vehicles that range in size from 6 to 30 passengers, it is unclear whether a modular rotorcraft would be the best way in which to scale passenger load factor.
Amphibious Rotorcraft	Many urban centers in the United States are also home to seaports; combining amphibious-capability with rotary-wing flight could be a key enabler as to the vertiport siting (e.g., vertiports on piers or in the San Francisco Bay) (Fig. 74).	Increases the number of potentially viable vertiport sites for urban regions with significant waterways and ports. May also result in increased water over-flights to thereby increase overall community acceptance. Also might increase transportation system flexibility in that vertiport infrastructure might be reduced; including the possibility that temporary vertiports might be established under certain circumstances.	Taxiing-on-the-water transit time may unacceptably increase total trip time to make Hopper flights noncompetitive with surface transportation options.

Many of the vehicle configurations in Table 6 have been previously proposed; some, on the other hand, are novel and/or have been previously proposed from significantly different applications than that of the Hopper aerial transportation system. Reference 77, for example, provides a historical-perspective summary of the vehicle configurations similar to some of the alternate Hopper configurations noted in Table 6. Note that, intentionally, vertical lift vehicles such as tiltrotor, tiltwing, or powered-lift aircraft are not highlighted in Table 6 as being potential Hopper configurations. The reason for this is fourfold. First, it is unclear that with the Hopper's short "hops" vehicles such as tiltrotor and tiltwing aircraft, tailored for efficient long(er) range cruise, would be appropriate for the Hopper mission profile. Second, there was a fair amount of design similarity between the Hopper tandem helicopter and early commercial helicopter attempts such as the Boeing Vertol BV-234 (which, in turn, has common design heritage with the military CH-47 tandem helicopter still flying today). Such design similarity has knowledgebase benefits as shown in Appendix B. Third, it seemed to be a reasonable assumption, given the large passenger size of most of the Hopper fleet studied, that a clean-sheet design was probably impractical given the likely size of the public-transit-like market niche and the circa 2030–2035 fleet introduction; instead it was assumed that heavily modified variants of large military helicopters (Boeing CH-47, etc.) or modified versions of existing large commercial helicopters (Sikorsky S-92) might be developed to not only accommodate electric-propulsion systems but the operational requirements of the Hopper mission/application. Fourth, and finally, a considerable body of NASA rotorcraft research (most of which focuses on conventional rotor configurations) potentially awaits transitioning from the lab, wind tunnel, simulator, etc., to flight demonstration to production. Such research into active rotor control, active flow control, active structures, and many more technologies would transform a vertical lift vehicle, in its most represented form, the helicopter, from an aircraft with electric propulsion to an "electric rotorcraft"—a vehicle that is intrinsically "wired" to drive not only electric motors but a suite of electrically/actively controlled actuators and devices.

Figures 68–74 are notional illustrations of some of the Table 6 vehicle configurations. In some cases the illustrations might stretch the imagination as to their application to the Hopper mission. For example, Figure 73 showing a non-enclosed/no-cabin flying platform would not be viable for carrying 30 passengers for even short distances; such a vehicle might be feasible, though, for one or two passengers for short distances. Such vehicle configurations are shown in the spirit of provoking innovative thought as to the rather unique mission profile that Hopper aircraft nominally perform.

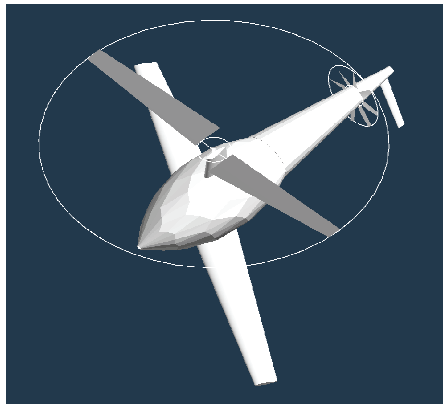


Figure 68. Autogyro.

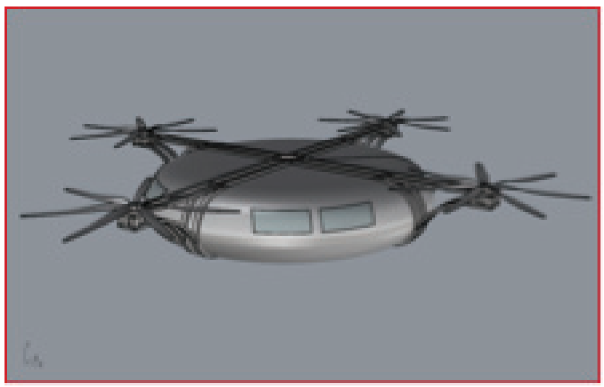


Figure 69. Quadcopter (image courtesy of ref. 79).

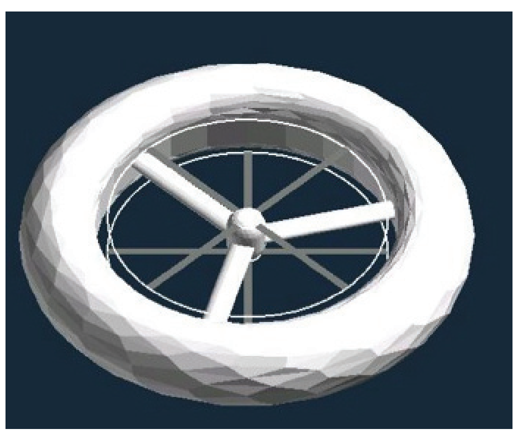


Figure 70. Toroidal aircraft.

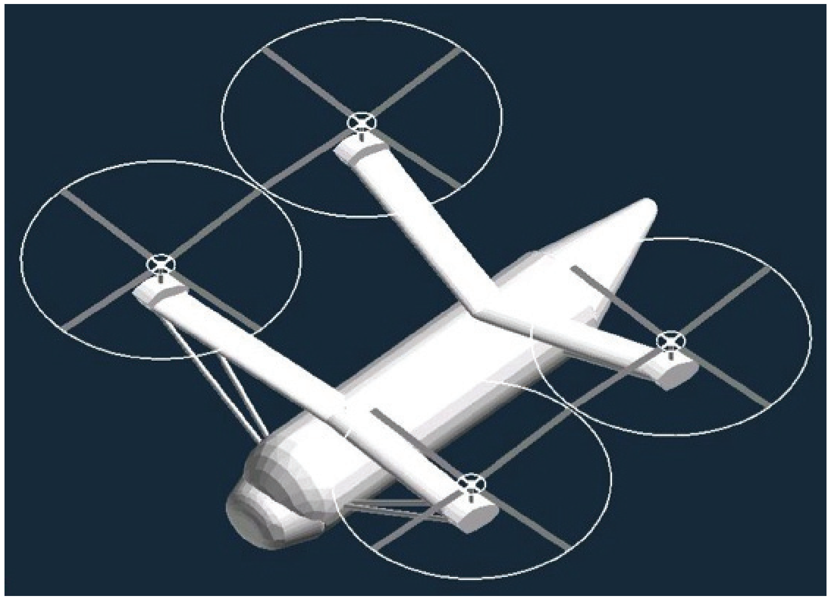


Figure 71. Quadrotor.

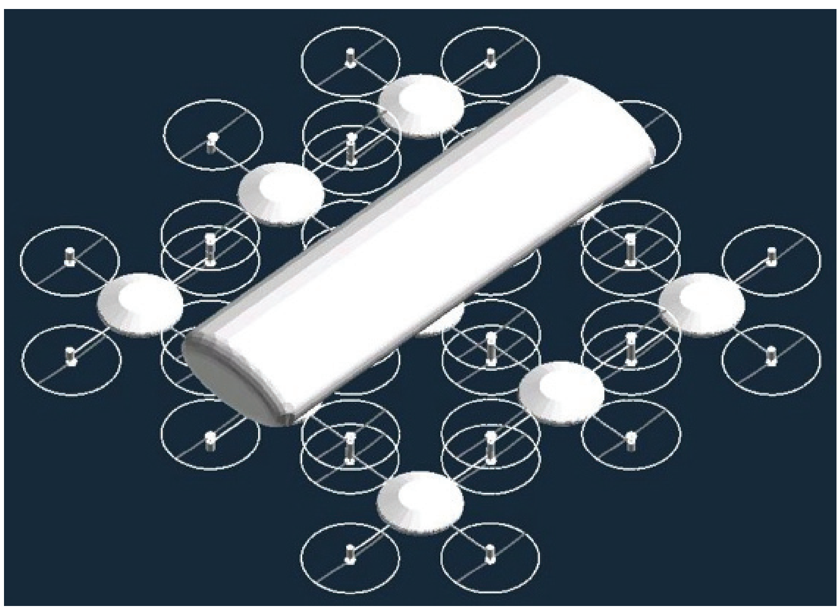


Figure 72. Multi-rotors.

Figure 73. Flying platform.

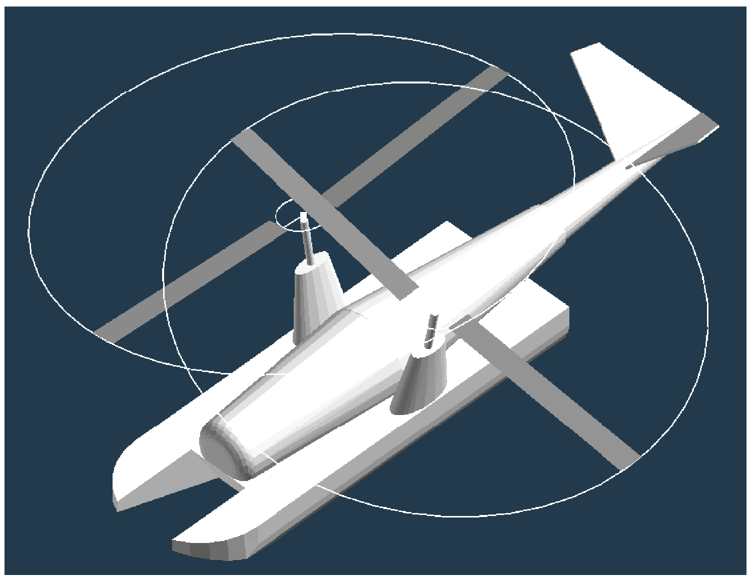
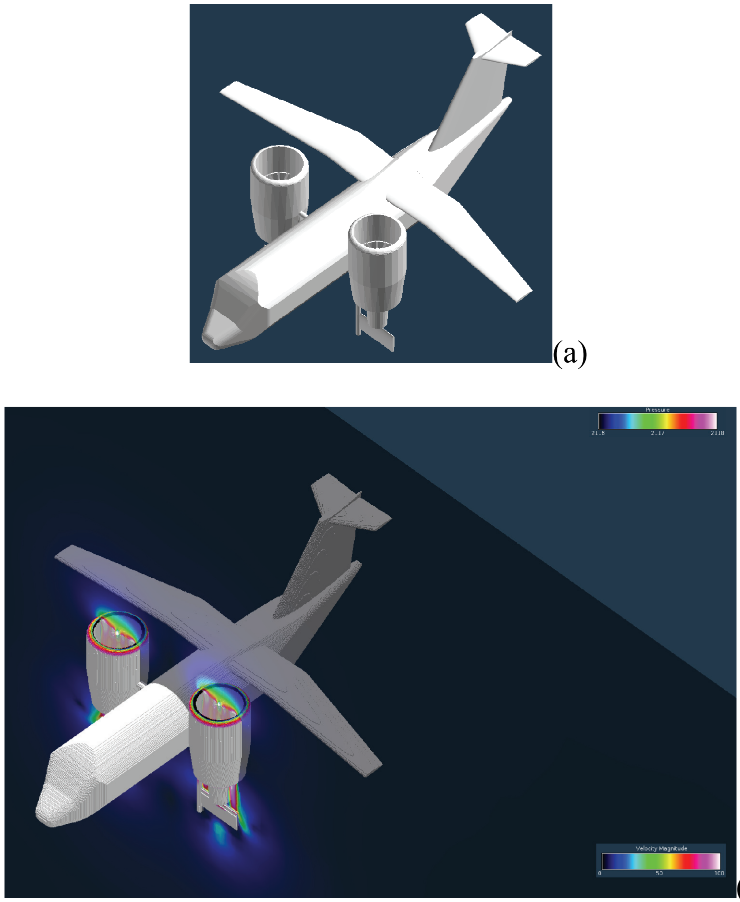


Figure 74. Amphibious Hopper configuration.

During the late 1980s and 1990s work was performed in the area of optimal trajectories for minimizing energy expenditure during flight, e.g., references 80 and 81. The unique extremely short haul mission application for Hopper vehicles raises interesting questions as to the optimal trajectories for such short range "hops." One of the fundamental questions raised early in this study was whether or not to continue to restrict the vehicle design space to conventional single-main-rotor helicopters and tandem helicopters. On one hand, there is considerable design heritage and an extensive knowledge base for these vehicle configurations. On the other hand, alternate, and perhaps more exotic, configurations might be more efficient and/or mission-compatible (to the public transit application) than these conventional helicopter configurations (excluding, of course, the electric-propulsion aspect of their design). Proven vehicle configurations such as tiltrotor, tiltwing, and/or powered-lift (e.g., Fig. 75) aircraft (not to mention the more exotic alternate configurations noted earlier) were excluded from this study, despite their superior cruise L/D because it was, and still is, unclear to the authors of this report,



(a)

(b)

Figure 75. Powered-lift aircraft as (alternative) Hopper vehicles (inspired by Grumman 698 aircraft, ref. 82): (a) general configuration and (b) hover CFD wake predictions.

at least, that the extremely short haul Hopper flights would be sufficiently long enough in duration and overall cruise range for conversion from helicopter-mode flight to higher-speed/higher-efficiency airplane-mode flight, to use the example of tiltrotor aircraft for the moment. In other words, the definition of optimal trajectories (and, where appropriate, transition/conversion corridors) for extremely short haul, Hopper-like flights or "hops" is an open question ripe for future investigation.

There is an important distinction to be made between modular and distributed-propulsion rotorcraft. Both distributed-propulsion and modular rotorcraft may employ multiple rotors for lift and propulsive force. However, the inherent attribute of modular rotorcraft, making them in part distinct from distributed-propulsion vehicles, is that modular rotorcraft should be capable of being assembled, disassembled, reconfigured, and reassembled on a mission-by-mission and even perhaps sortie-by-sortie basis. They should be considered the Tinkertoy- or Lego^{TM}-like collective system of the aircraft world. The multi-rotor "flying platform" in Figure 72 is conceptually a Lego^{TM}-like stacking of tractor- and pusher-propeller quadcopters (ones that could already now, in the small RC vehicle sense, be bought from hobbyist aircraft manufacturers and crafted into a notional assembly similar to Figure 72).

There are some very interesting flight control questions related to many of these alternative vehicle configurations. One of the more interesting set of questions has to do with flight control of quadcopters, quadrotors, and multi-rotor configurations in general. Conventional helicopters and tiltrotor aircraft have complex mechanical control systems to provide variable collective and variable cyclic pitch control (varying nominally on a once-per-revolution basis for primary flight control). For very small RC hobbyist-class quadcopters/quadrotors, etc., very simple flight control schemes are employed, the chief approach being speed control of fixed-pitch (constant collective and no cyclic) propellers. Though this simple speed control approach has led, in part, to the widespread success of these small vehicles, it is unlikely to scale well to larger vehicles. And yet, it may well be that a hybrid flight control—wherein individual rotor speed control could be matched/integrated with variable collective/cyclic control—might be the best solution for Hopper-class quad- or multi-rotor vehicles. Another interesting set of flight control issues arises when one considers structural flexibility of rotor support arms/braces (and/or "stacked" rotors and supports/braces) for multi-rotor and modular rotorcraft configurations. An extreme example of this would be if the flying multi-rotor platform in Figure 72 was allowed to have such a large degree of structural flexibility among its modular elements that it could be considered almost a "flying carpet" rather than a near-rigid structural assembly. Such flight control areas of investigation as hybrid rotor control for multi-rotors and structural flexibility implications of large modular rotorcraft assemblies are largely unexplored to date.

Whatever vehicle configuration that leads to the "best" Hopper design will undoubted have a common design aspect for all configurations considered: they will all have to incorporate some level of simple and efficient modularity/upgradability as to their energy-storage systems and electric-propulsion subsystems (power electronics, electric motors, etc.). For example, advanced batteries circa 2020 might very well be obsolete compared to batteries circa 2030; accordingly, it would be far from ideal to have to develop a new vehicle every few years to remain relevant with respect to energy-storage-device and electric-propulsion-system advances. Some vehicle configurations might be more amenable to such modularity/upgradability. For example, vehicles designed with sponson supports, where the battery packs can be mounted, or fuselage cabins that have "cutouts" (i.e. somewhat humorously, the Sikorsky "Skycrane" is an extreme example of this fuselage cabin "cutout" design attribute) to provide access/support underneath the vehicle cabin for the battery packs and/or other energy-storage modules.

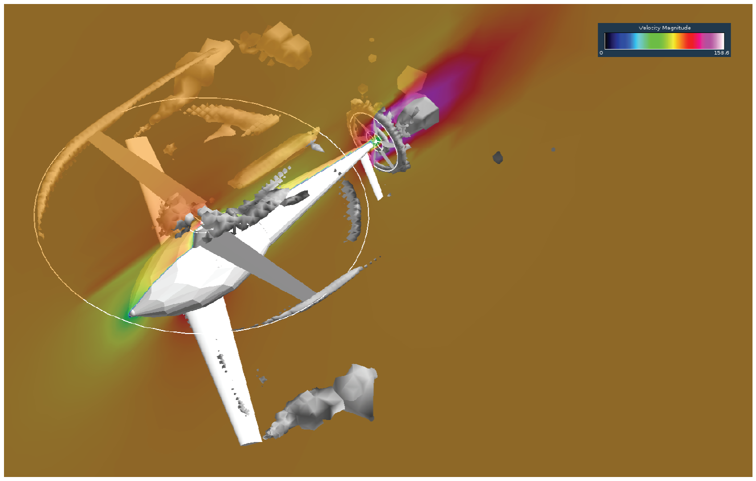
In a similar sense, all potential Hopper configuration design discussion will have to evolve/migrate from discussion regarding electric-propulsion issues alone to a broader and potentially richer discussion about the attributes and capabilities of "electric rotorcraft" as a whole. More thoughts on this topic are provided in the Technology Roadmap section of the report.

Finally, other than illustrating the potentially greater design space of Hopper-type vehicles as compared to the single-main-rotor and tandem helicopter conceptual designs developed and discussed in reference 1 and herein, it is beyond the scope of this study to engage in detailed vehicle sizing trade studies for these alternate configurations. However, to illustrate in a simple sense some of the aeromechanic challenges (rotor/vehicle interactional aerodynamics being key among them) of developing such alternate Hopper configurations, Figure 76a–f provides a sample set of low- to mid-fidelity preliminary CFD results (details as to the general CFD methodology and the NASA-SBIR-developed RotCFD software tool can be found in reference 83) for some of these alternate Hoppers. There was also a secondary purpose in performing these CFD test cases in that it allowed an opportunity to assess the utility of the RotCFD code as an effective aid in advanced rotary-wing vehicle conceptual design.

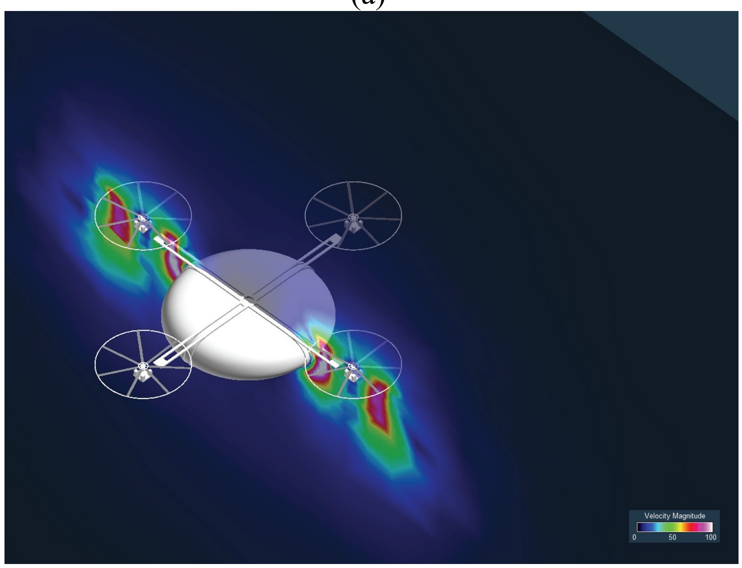
Figure 76a is a forward-flight CFD prediction of the electric autogyro configuration shown earlier. Vortices can be seen being trailed off of the tips of the oblique/pivoting wing incorporated in the vehicle design. The autorotating rotor is carrying only a fraction of the overall vehicle lift, as compared to the oblique wing, so very little lifting rotor-wake-induced velocities are being generated or "rotor disk" vorticity being trailed. On the other hand, the tail-mounted propeller is generating a considerable amount of thrust, so a strong propeller slipstream wake is shown in the CFD result.

The sample CFD results for other alternate Hopper configurations are all for hovering flight. Significant rotor-on-rotor and rotor-on-airframe interactions are shown in most of these CFD predictions. Therein lies the real value of bringing CFD early into the conceptual design process: computationally efficient and flexible low- to mid-fidelity CFD gives the aircraft/rotorcraft designer an opportunity to incorporate interactional aerodynamics effects earlier into the design process than otherwise feasible, thereby ensuring that more realistic/practical designs are identified in the conceptual design phase.

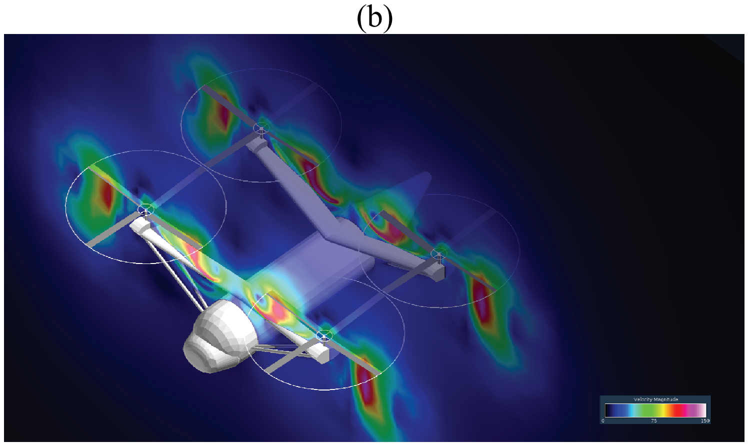
As an aside, the third "manned" electric rotary-wing vehicle capable of hovering known to the authors—and perhaps arguably the first remotely piloted vehicle to carry a passenger—can be found in reference 84; this vehicle was a hybrid multi-rotor/ducted-fan/flying-platform-type vehicle. To summarize the discussion in this section, there is plenty of room in the rotary-wing electric-propulsion design space for innovative vehicle configurations—both for Hopper-type applications and other emerging missions. Further, novel configurations such as those noted above will undoubtedly generate new technical challenges and new technologies. For the purposes of this study, though, there were several compelling reasons to adopt the 30-passenger tandem helicopter as the baseline for the study; chief among those reasons was retaining the advantages of design heritage with respect to the vehicle configuration for all but the electric-propulsion element. Additional details regarding the baseline 30-passenger tandem helicopter Hopper vehicle design are provided in references 1 and 2.



(a)

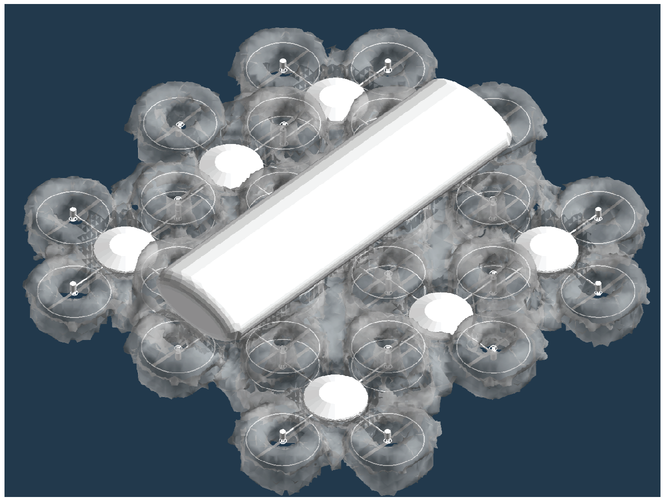


(b)

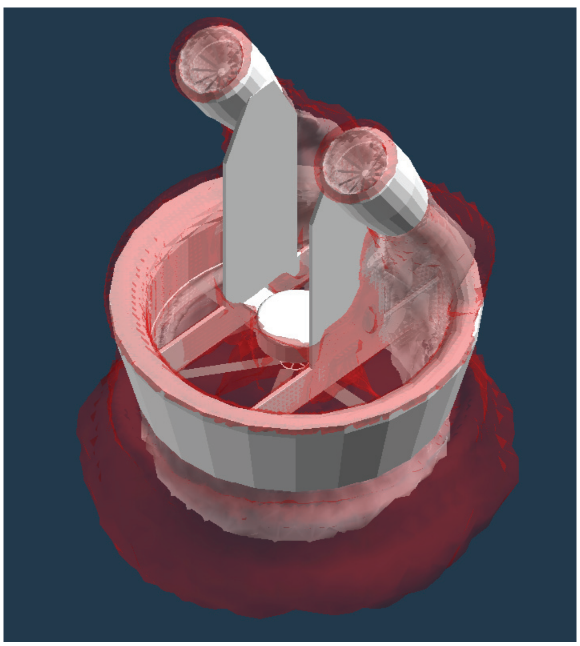


(c)

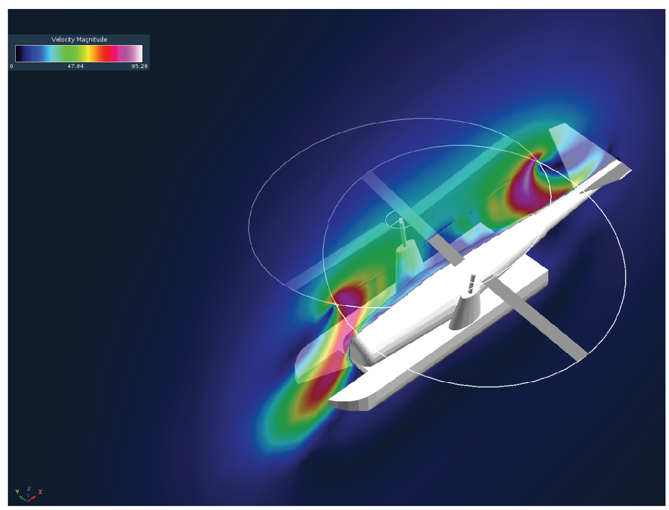
Figure 76. Limited aerodynamic analysis of some alternate Hopper configurations: (a) autogyro, (b) quadcopter; and (c) quadrotor.



(d)



(e)



(f)

Figure 76. Limited aerodynamic analysis of some alternate Hopper configurations (cont.): (d) multi-rotor, (e) flying platforms, and (f) amphibious (“synchropter” helicopter) rotorcraft.

Concept Applicability to Other Regional Transportation Networks

The San Francisco Bay Area has been the focus of both the Phase I (ref. 1) and Phase II efforts of this study. This regional focus should not be interpreted as implying that the aerial metropolitan/regional transportation networks in other regions of the country are not worthy of consideration.

A general analysis framework for applying this study's methodology to other metropolitan areas, beyond that of the San Francisco Bay Area, is shown in Figure 77. This general framework, aka "MetroSim," has yet to be implemented, but it would be relatively straightforward to generalize/extend the current BaySim tool (in conjunction with other analysis tools employed) to examine other metropolitan areas, other networks, and other aerial vehicle fleets.

Figure 77 is currently not an integrated, automated framework, as embodied by BaySim. It required a considerable amount of "sneakerware" between the study team's multidisciplinary subject matter experts and analysis tools in order to effectively perform the required tasks.

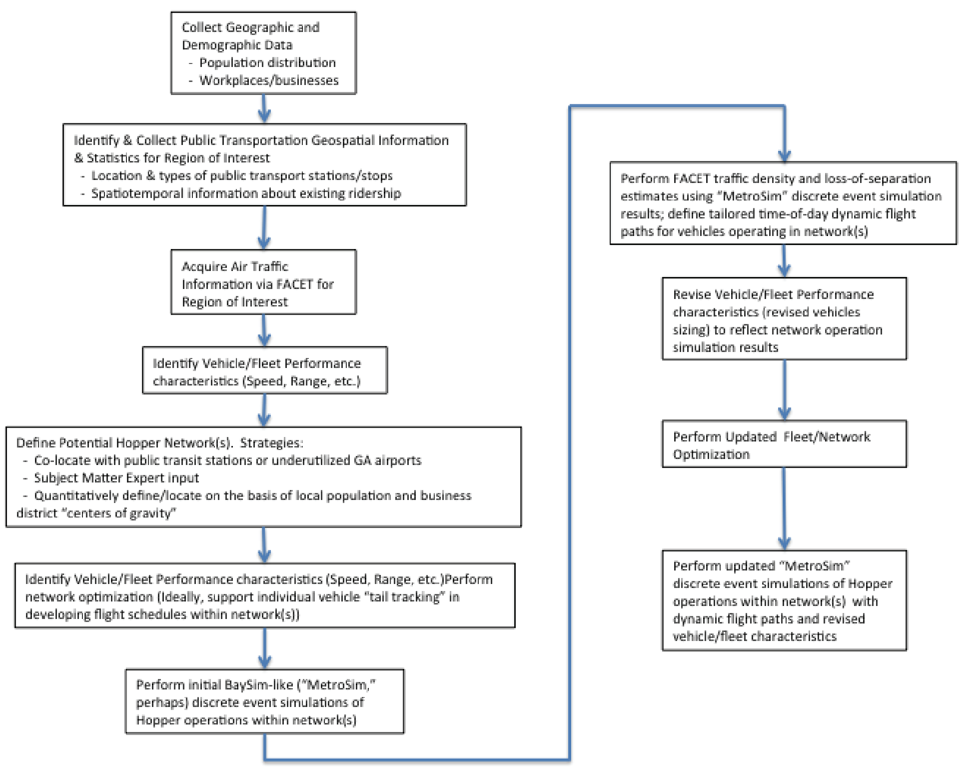


Figure 77. General analysis framework to consider other metropolitan areas for Hopper-like aerial transportation networks.

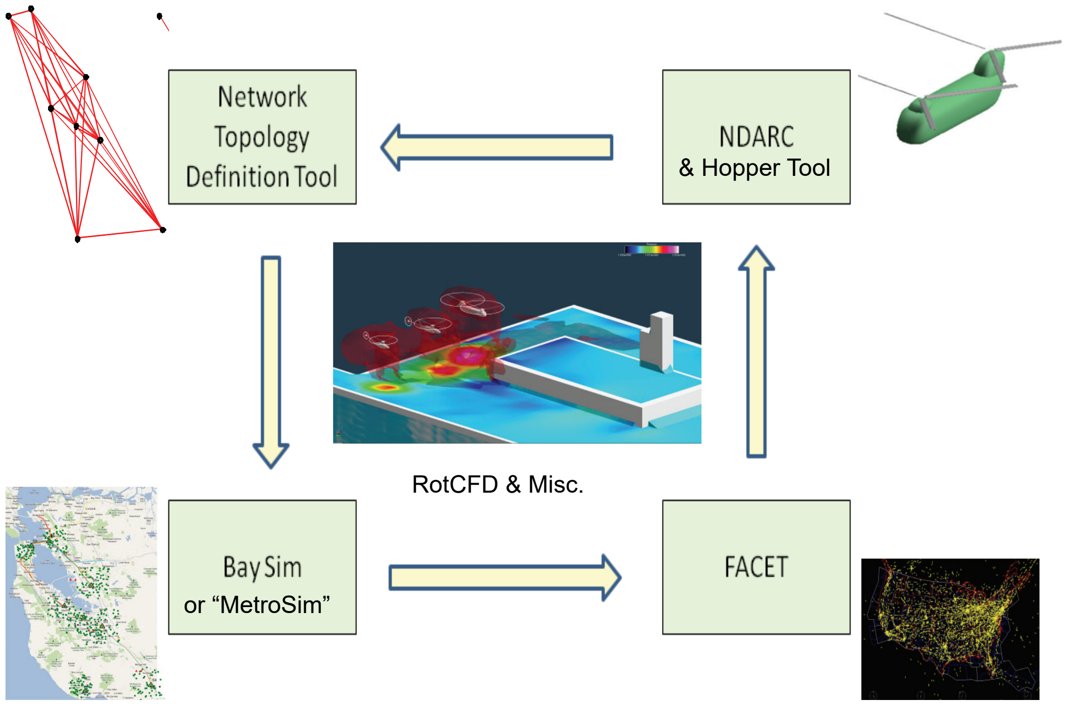


Figure 78. Iterative analysis process.

A high-level look at this process is captured in Figure 78 (which is a slightly more detailed version of Figure 61) for the tools used in the Phase II study. Again, it would be relatively straightforward to incorporate this iterative process, under the general framework of Figure 78, in future work to consider other metro/regional aerial transportation system networks.

This study reflects an ongoing shift away from vehicle-centric systems analysis studies to studies that encompass a system-of-systems perspective. Therefore the focus of this work was not solely or primarily on the conceptual design of Hopper vehicles, but instead the focus was on the study of the overall metro/regional aerial transportation system. The goal of this investigation was to perform the necessary system-of-systems analysis effort to consider the implications as to the identification of enabling technologies and reference designs—and missions—for extreme short haul VTOL vehicles with electric propulsion. This goal was effectively carried out using the San Francisco Bay Area as a benchmark test case. However, it would be an interesting future exercise to consider other metropolitan areas.

Rather than semi-randomly selecting alternate metropolitan areas for study for metro/regional flight, it would be desirable to arrive at criteria to underpin such a alternate test case selection. Such selection criteria might include: average commute time; average commute distance; number and variety of surface transportation options; current public transportation ridership and “load factor” levels; frequency of transportation disruptions (gridlock, freeway/bridge closures, weather incidents, etc.); number of small community airports and large commercial airports with the average commute distance/radius; the amount of circuitry for the average commute trip, i.e. the difference between ideal point-to-point trip distance and the actual distance traveled; and natural bodies of water/ports (for consideration of possible overwater and amphibious operations).

Technology Roadmap

It would take a suite of emerging technologies to realize a metro/regional aerial transportation system similar to the one detailed in this study. The required technologies are more than just those inherent in electric propulsion. This section of the report details a number of the technologies (and their technical challenges) anticipated to be needed to develop a practical, cost-effective, safe, and passenger/community-friendly Hopper vehicle(s) and network system. Some of these technologies will likely be developed outside of the aviation industry, but many of the technologies will be uniquely aviation-derived or derived with substantial aviation involvement. Where practical, the unique aviation aspects of the required technologies are highlighted in the following discussion. In particular, unique roles for NASA research are noted.

Figure 79 is a notional "swoosh" chart for Hopper vehicle/system development. The suggested approach detailed in the chart is a three-phase process by which technology demonstrator vehicles/platforms might be developed and used to demonstrate key technical capabilities. These capabilities include, in addition to electric-propulsion demonstrations, vehicle and (vertiport) station system automation and autonomy, electric-actuator-enabled active rotor and active flow control, and new airspace management and vehicle operation methods. The suggested demonstrated approach highlighted in Figure 79 is to start small (with regards to vehicle size) with limited demands on performance (flight endurance, etc.) and incrementally develop more capability with time.

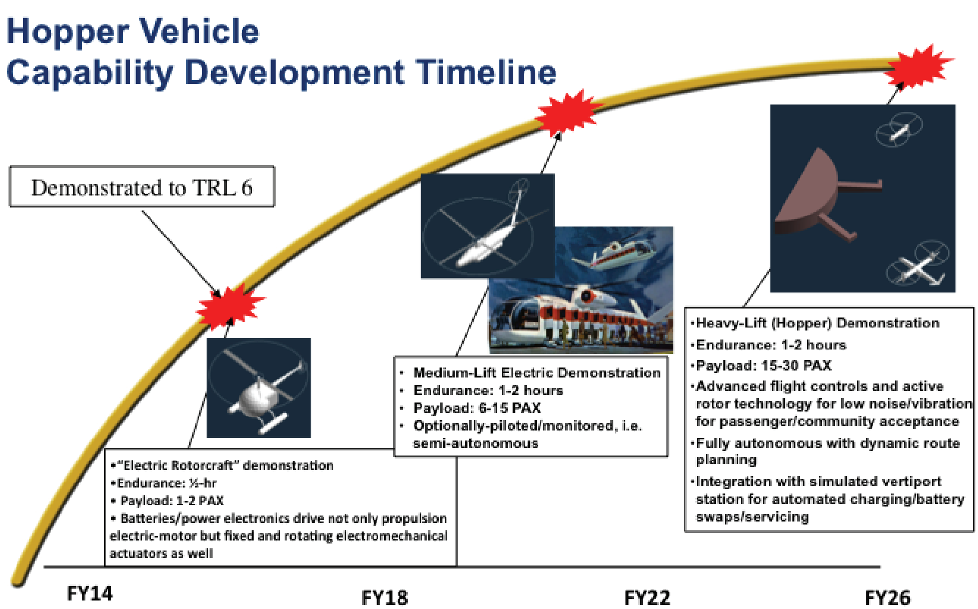


Figure 79. "Swoosh" chart for Hopper capabilities (background artwork/image of Hughes Helibus courtesy of AHS International).

Figure 80 presents a notional roadmap of Hopper-unique technologies. Most of these technologies and/or technical/operational issues are not currently being explored within the NASA aeronautics research portfolio. Some crosscutting technologies can be leveraged from the automotive and energy-storage-device industries, as well as leveraging research investigations into fixed-wing aircraft with electric propulsion, but in order to realize vertical lift aerial vehicles within a reasonable time frame (10–15 years), it will be necessary to make a concerted effort to address a large fraction of the technical/operational issues in Figure 80 from a rotary-wing perspective.

Along the way to one day potentially realizing a Hopper-like network, it is anticipated that a number of new technologies will be enabled by efforts to address the technological challenges identified in this, and perhaps other follow-on, studies. In turn, these challenges are consistent with long-held NASA strategic goals: environmentally responsible aviation, economic competitiveness, and aviation safety. Attempts to show this connectivity between the vision of a Hopper network, NASA strategic goals, and intermediate technological spinoffs or demonstration exit points, is presented in Figure 81.

To better understand Figure 82 some terminology needs to be first introduced. In the context of the GOTChA chart methodology, the following terms/definitions ideally hold. Goals: quantified, measurable system parameters that define what is to be achieved; system-level technology goals that will enable mission system concept capabilities. Objectives: constituents of the goals; quantified, measurable constituent component characteristics of the goals, whose collective achievement will enable the goals. (Goals and objectives are sometimes confused. One way to differentiate is to think of the technical objective as the item whose collective achievement will prove the feasibility of the goal.) Technical Challenges: the basis for the technology effort; basic technology hurdles (physical limitations) that need to be overcome to achieve the objectives, i.e. what technology development and demonstration activities are needed to achieve the objectives and demonstrate the goals. Approach: the technology projects to be conducted; i.e. the approach to be taken (the plan) to overcome each technical challenge.

Figure 80. Hopper technology roadmap chart.

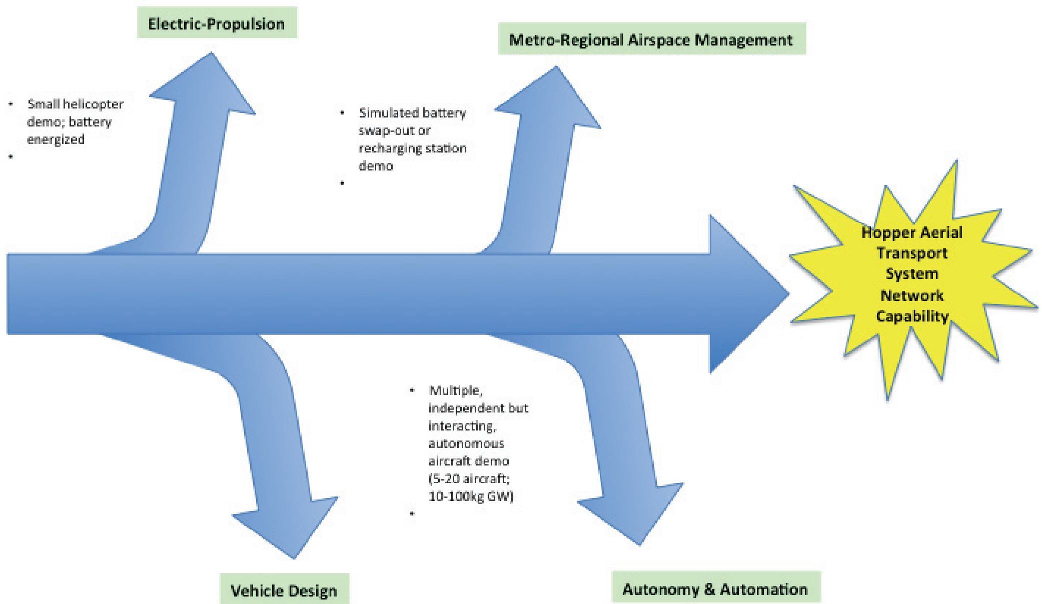


Figure 81. Hopper technology exit strategy and spinoffs.

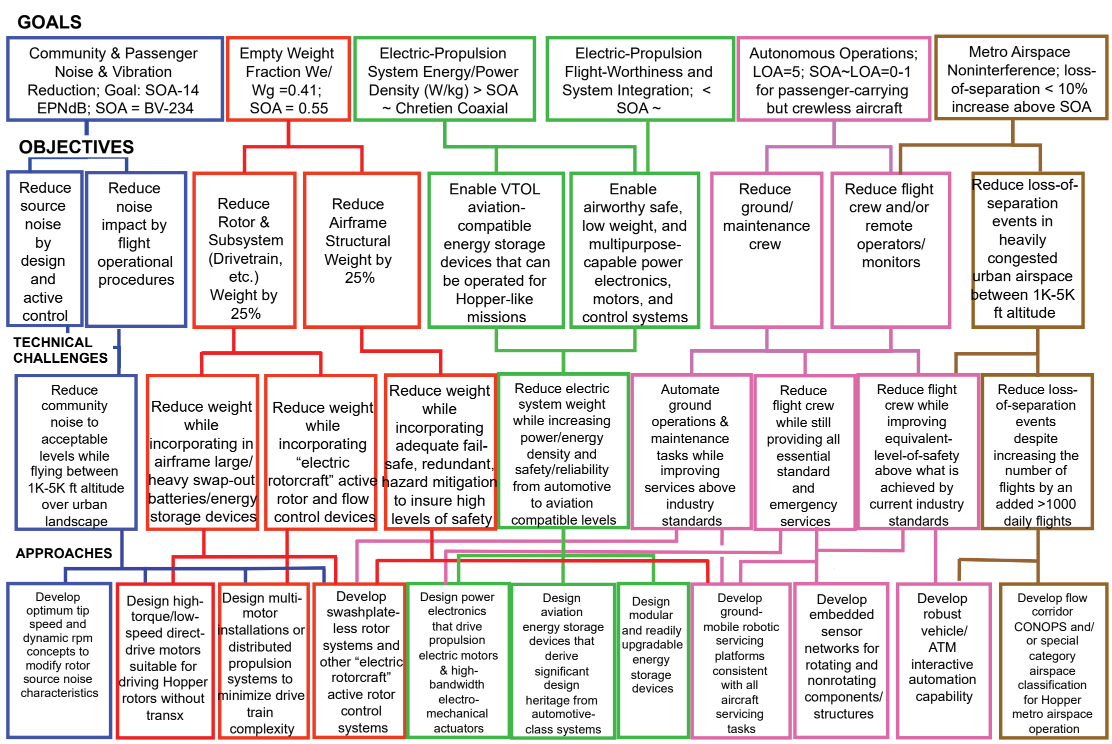


Figure 82. Hopper GOTChA chart.

Electric Propulsion

Figure 83 is a notional wheel of electric propulsion (WEP) for VTOL vehicles. This WEP is partly inspired, in terms of its graphical presentation of information, by the well-known "V/STOL wheel" of aircraft (ref. 85). The WEP represents an attempt to capture in a high-level sense the broad scope of possible rotary-wing electric-propulsion design space. The WEP is broken into four major groupings: all electric power, partial power, modular power, and remote power concepts. These four major groupings can be further subdivided into specific vehicle/electric-propulsion concepts/configurations. A representative sampling of specific concepts/configurations is illustrated in the inner sectors of the WEP. The discussion in this report is predicated on the assumption that Hoppers are all-electric powered vehicles.

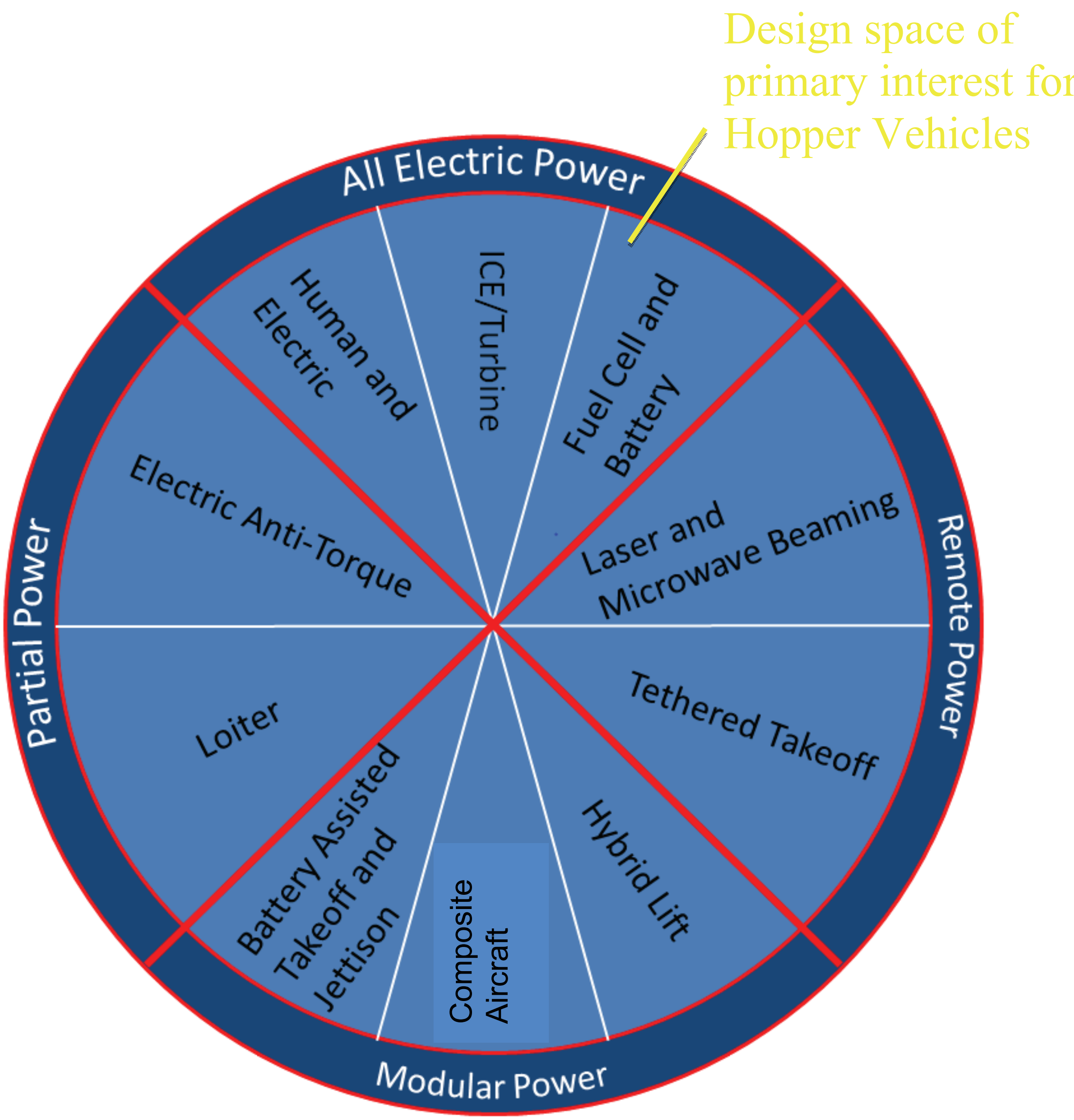


Figure 83. WEP for rotary-wing vehicles.

Note in Figure 83 that the term “composite aircraft” refers to a set of specific vehicle concepts in which a hydrocarbon-based mother ship transports, releases, and recovers electric-based daughter ship(s). Further, the term “hybrid lift” refers to a set of vehicle concepts wherein semi-buoyant vehicles are augmented with electrically driven lifting rotors.

Comprehensive System Integration Into the “Electric Rotorcraft”

If it is taken as a given that rotary-wing vehicles with some level of electric-propulsion capability are developed and fielded one day, then the inevitable technological follow-up question is: What other mission/vehicle capability could also be potentially enabled by having large-capability electrical power systems onboard such vehicles? Figure 84 summarizes a few of the possible options for future rotorcraft.

A new approach for reducing main rotor noise could be to develop an electric drive system to dynamically vary the main rotor speed, introducing high frequency perturbations on top of a steady-state baseline rotor RPM, forcing an aperiodic flow environment for each rotor blade that can drastically affect noise sources such as blade-vortex interaction.

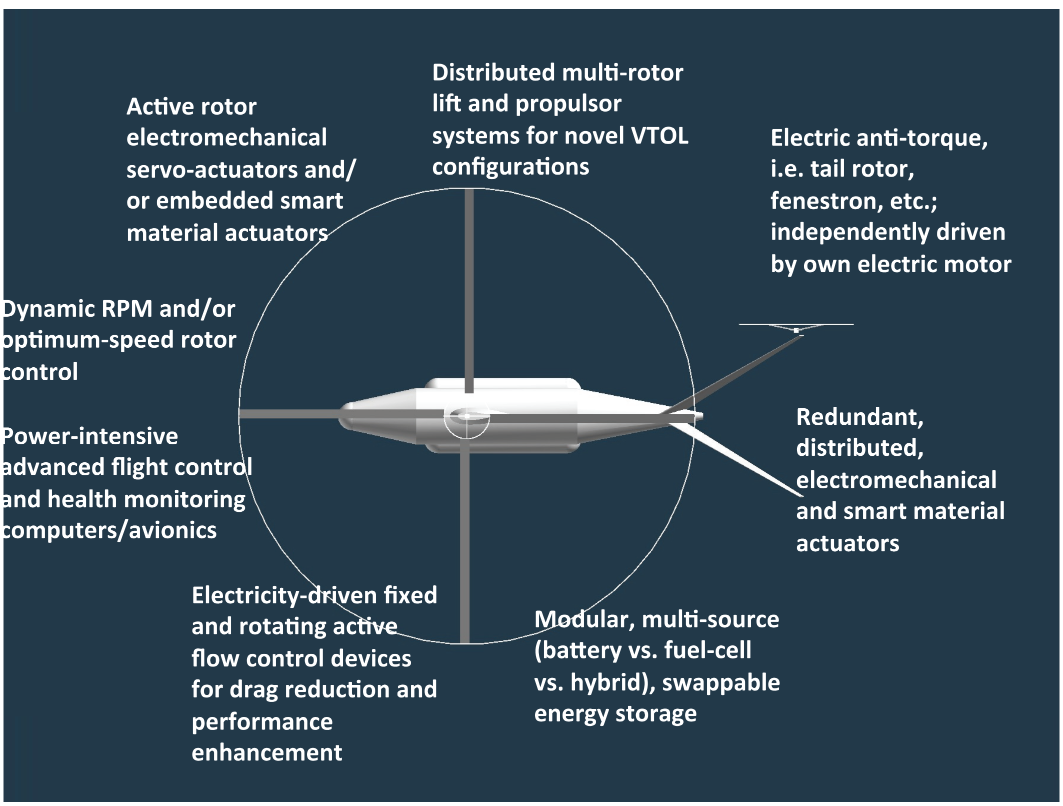


Figure 84. Electric rotorcraft notional systems/capabilities.

Despite the demonstrated utility of rotorcraft in many aspects of public service, noise continues to be a primary deterrent to increased use of rotorcraft in urban areas. Low-noise blade designs, active rotor control, modest reductions in rotor rotational speed, and tailored flightpaths are currently proven methods for reducing noise. The reductions, however, are still not significant enough to enable more widespread use of rotary-wing vehicles—the public remains annoyed by the sound of helicopters. In order of annoyance to the public, the major sources of helicopter noise are impulsive noise (including blade vortex interaction (BVI) and high-speed-impulsive (HSI) noise), then broadband noise (vortex noise, as in blade wake interaction (BWI)), and then rotational noise. The approach here is to attack the three primary sources directly. The basis is to change the fundamental nature of BVI, HSI, and BWI, by changing the interaction angles, phasing, and dynamic blade response on the advancing side of the rotor from where these noises arise. The design space for a low-noise rotorcraft is greatly expanded with the prospect of an electric propulsion system capable of powering a full-scale helicopter. For example, electric motors can drive the main rotor directly, eliminating the transmission and drive shaft. The main rotor and tail rotor can be driven separately so that the speed of each rotor is optimized for a given flight condition. A more radical concept may be to use the electric motor to dynamically vary the main rotor speed at frequencies of once per revolution or greater to create large changes in rotor noise by changing the rotor loads and the geometry of the rotor wake. This type of high-frequency speed variation is impossible with current engines, so the concept has never been explored. The use of an electric propulsion system is key to enabling such a dynamic RPM concept. Dynamic RPM will also potentially dictate novel mechanisms and hub structures/configurations that tailor the pitch-lag coupling of rotors to maximize the pitching response of the rotor to dynamic RPM-induced blade lag motion, to further mitigate rotor source noise.

Finally, Table 7 summarizes some preliminary thoughts on future airworthiness issues/considerations that might surface as electric rotorcraft are developed.

Table 7. Some Hopper/Electric-Rotorcraft-Unique Future Airworthiness Considerations

Issue	Consideration
One-Engine-Inoperative (OEI) contingency power	Electric motor speed/power curves are fundamentally different from reciprocating engines and turboshaft engines. This, therefore, will require a future re-examination of OEI requirements for electric aircraft, particularly VTOL platforms.
Certification of intelligent health monitoring systems to account for electric propulsion	Health monitoring systems currently rely on time history and frequency spectra regression analysis models to predicate drive system components problems. Such models depend on component behavior databases; in the case of electric-propulsion system components, such data might be quite limited.
Off-nominal operation and/or failure of “electric rotorcraft” active rotor control and/or active flow control devices	Hopper would have to be demonstrated to be capable of safe flight in the eventuality that the failure of key active rotor and/or active flow control devices has degraded the nominal performance of the aircraft.
Environmental degradation of electric-propulsion electrical systems/components	Rain, fog, and general moisture in the air might degrade inadequately weatherproofed systems. Similarly, lightning strikes might also pose unique problems for electric aircraft. Finally, the relatively high onboard vibration environment of rotary-wing platforms might pose unique challenges for potentially sensitive electric system components.

Table 7. Some Hopper/Electric-Rotorcraft-Unique Future Airworthiness Considerations (cont.)

Issue	Consideration
Electric-propulsion system-redundancy requirements	There is a critical design trade space that needs to be explored between building-in system-redundancy for safety considerations while at the same time recognizing that there will be severe weight constraints on any successful electric aircraft, including Hopper.
New standards will need to be developed for vehicle recharging and/or energy-storage device swapping.	Fail-safe securing mechanisms and status indicators will need to be developed for batteries or other energy-storage devices that are swapped out between flights. Similarly, battery charge status and overall health will have to be closely and accurately monitored.
Certification of firewalls and aircraft structural components for unique electrical and fire hazards for aircraft with electric propulsion	Kilowatt-class or higher electrical power systems will potentially require innovation in aircraft structural design.
Battery or fuel-cell system crashworthiness criteria (ballistic tolerance, as well, for illegal gunfire)	The potentially hazardous nature of these power/energy-storage devices will require careful consideration of their unique characteristics, and mitigation requirements during crashes and hard emergency landings.
Special airspace classification for Hopper vehicles	Given the frequency of flight of Hopper vehicles over well-prescribed, low-altitude routes/flow corridors, would this justify the consideration and adoption of special airspaces for these vehicles?
Twenty-minute reserve	Given the extremely short haul nature of Hopper flights, the VTOL capability of the vehicles, and the sizable fraction of total energy storage onboard the vehicle to preserve the 20-minute-reserve requirement, whether this reserve requirement can be reduced is worthy of future discussion.
Certification of autonomous aircraft	A hierarchy of autonomous system capabilities would have to be considered to certify Hopper vehicles and automated support/maintenance systems.
Water ditching procedures and mitigation steps	Water and high-power electrical systems obviously do not mix well together, particularly when it comes to passenger safety during emergency egress during water ditching. Both procedural and fail-safe engineering solutions would have to be pursued to adequately mitigate the safety concerns of electric aircraft flying over significant bodies of open water.
Ensuring adherence/compliance of passengers with respect to onboard standard and emergency operating procedures on “crewless aircraft”	How to keep smokers from smoking? Safety belts properly secured? Proper attention to and understanding of preflight safety briefing, etc.? How to ensure all these and more regulatory requirements on an autonomous aircraft carrying passengers but potentially no crew?
Harmonization of FAA- versus state-mandated public transportation rules	State-mandated public transportation rules are dominated by surface vehicle or railway considerations. For example, will Hopper have to provide space for and carry bicycles? Will Hopper have to have lifts, removable/stowable seats, and tie-in restraints for mobility devices such as electric wheelchairs?
Novel operating procedures and flight dynamics considerations for a multi-rotor aircraft configuration may need to be developed.	Flight control of multi-rotor vehicles (four or more rotors) might be significantly different from more conventional rotary-wing/VTOL aircraft. Additionally, flight control of such vehicles (and passenger in-flight experience) could become further complicated by the use of more symmetrical airframes (and, therefore, potentially more omnidirectional maneuvering capability).

Automation and Autonomy

For the purposes of discussion, this report adopts the levels of autonomy (LOA) noted in Table 8 as originally defined in reference 86. Important in the definition of this LOA is the concept of "hands-on time." Hands-on time is defined as the percentage of a pilot's time (direct attention paid to the Hopper operation) that would be required to safely operate the Hopper during a given mission. Hands-on time is limited to the pilot/operator and does not include other mission personnel (e.g., sensor/payload operator). Nominal values are presented in the table; actual hands-on time will vary with the mission.

What are the primary autonomy enablers? To be able to fly in civil airspace you need an autonomous aircraft system, in this particular case a Hopper, with a demonstrated Equivalent Level of Safety (ELOS) as an onboard-piloted system. It cannot cost any more to operate than an onboard-piloted system; in fact, automation should result in a cost reduction. The primary challenges (hurdles) to achieving these fundamental desired features are: system safety and reliability (addressing airworthiness, sense and avoid, and validation and verification); fault tolerant system architectures (providing robustness, situational awareness, automated operations); contingency management (fault detection, prognostics, emergency procedures); and other miscellaneous factors such as software certification, ELOS certification, and Air Traffic Management (ATM) interfaces with onboard-piloted and remote-piloted or autonomous assets.

Table 8. Levels of Autonomy (LOA) for Hopper Discussion

LOA	Level	Description (Features)	Sample Characteristics
0	Remote Controlled	Remotely piloted aircraft with a human-in-the-loop making all the decisions. Operator is in constant control. (100% hands-on time.)	> RC airplane
1	Simple Automation	Remotely piloted with some automation techniques to reduce pilot workload. Human monitoring to start/stop tasks. (80% hands-on time.)	> Basic autopilot
2	Remotely Operated	Human operator allows aircraft onboard systems to do the piloting. As part of the outer control loop, the human makes decisions as to where to go, when, and what to do once there. Remotely supervised, with health monitoring and limited diagnostics. Operator allows Hopper to execute preprogrammed tasks, only taking over if the aircraft is unable or fails to properly execute them. (50% hands-on time.)	> Integrated Vehicle Health Management (IVHM) > Onboard contingency management capabilities > Waypoint navigation
3	Highly-Automated or Semi-Autonomous	Aircraft (Hopper) automatically performs complex tasks. System understands its environment (situational awareness) and makes routine decisions and mission refinements to dynamically adjust to flight and mission variables. Limited human supervision, managed by exception. Adaptive to failures and evolving flight conditions. (20% hands-on time.)	> Loss-link mission continuation > Automatic takeoff/land > Adaptive control techniques > Reactive "search and find" terrain recognition
4	Fully Autonomous	Hopper receives high-level mission objective (e.g., location, time), and translates it into tasks that are executed without further human intervention. Hopper has the ability and authority to make all decisions. Extensive situational awareness (internal and external), prognostics, and onboard flight re-planning capability. Single vehicle operations. (Less than 5% hands-on time.)	> Automated in-flight re-planning > Mission sensor-directed operations

Table 8. Levels of Autonomy (LOA) for Hopper Discussion (cont.)

LOA	Level	Description (Features)	Sample Characteristics
5	Collaborative Operations	Brings in aspects of multiple Hoppers working autonomously together as a collective intelligent system. Group coordination. Individual vehicles/ systems in a collaborative group will have a least semi-autonomous LOA (3) to keep the operator workload of the collaborative operation at a manageable level. (Total hands-on time for sum of all air vehicles would not exceed a single operator's hands-on time of 100%.)	> Cooperative and collaborative flight > Mother- and daughter-ship collaborative operations > Team leader concept for cooperative systems > Robotic swarms

The problem is easy to describe but difficult to solve:

- First, what is the optimum level of vehicle autonomy and intelligence required for a particular Hopper mission/application, so as to ensure acceptable levels of success and safety while at the same time keeping development and implementation costs to a minimum?
- Second, what are the specific attributes of an autonomous system implementation essential for a given mission/application and aerial vehicle in order to maximize mission success?

The engineering community must be careful not to imbue systems with unnecessary, or otherwise inappropriate, levels of autonomy and intelligence for the particular purposes to which they are applied. However, from an operating cost perspective alone, vehicle and station systems should be either fully autonomous and/or highly automated. Crew and maintenance labor costs are perhaps the single largest set of Hopper costs that could conceivably be addressed by technology investments. The Hopper mission application may well be a key test case for the utility and/or essential implementation of autonomous aircraft technologies. However, it goes almost without saying, that public/passenger acceptance of flying in an aircraft without pilots onboard—or even remotely operating the flight controls—may be a difficult challenge to overcome. Nonetheless, perhaps as the automotive industry has to-date led the way for manned vehicle electric propulsion, so too may it lead the way for autonomous system technologies in the form of the embryonic "driverless car" effort.

A consideration about automation is the time that it takes to handle an emergency—from recognizing the issue to dealing with the emergency. This recognition time could be on the order of seconds. So, if a human is a key element of an automated system, then that person/operator needs to be kept engaged with respect to overall task management. Metrorail drivers are a good example.

One item that is missing in this system-of-systems automation/autonomous system discussion is conformance monitoring. What system looks over all of this and then makes corrections to the automated vehicle or tells the human to do something? This is obviously a major area of future research investigation for semi-autonomous and autonomous mobility systems.

Other Considerations as to the Success/Failure of the Hopper Concept

There has been considerable previous discussion as to some of the more obvious issues/considerations in the possible realization of a Hopper-like metro/regional aerial transportation system—i.e. economics, community acceptance, operational safety, and vertiport station siting. Less obvious, though, are other important Hopper-unique issues that will also have a direct bearing on whether or not such a transportation system might ever be developed. Among these additional issues are: privacy/intrusiveness concerns about frequent low-flying aircraft; all-weather operation concerns; streamlined or expedited security access to vertiport stations and Hopper aircraft; safety and e-waste disposal concerns for retired aircraft components and "consumable" (finite number of charge/discharge cycles) large battery packs for battery-powered aircraft; safety and infrastructure development concerns for hydrogen-cell-powered aircraft; intermodal connectivity between public transit systems and other emerging transportation systems such as driverless cars/taxis; and passenger/community acceptance of large autonomously-piloted aircraft. A few of these issues are discussed further, below.

There are likely to be unique privacy/intrusiveness concerns about frequent low-flying aircraft consistently following well-prescribed routes over the same communities and the same residences. These privacy/intrusiveness concerns are likely more than just the generally to-be-expected noise and safety concerns of the public. Those members of the public directly underneath the day-in/day-out, multiple times a day flightpaths of these aircraft may feel more than a little put upon than, say, neighbors a couple of blocks away. Taking great care to try to reduce the noise of these vehicles will help, but even so it is to be expected that many people directly underneath Hopper routes will still feel unease, in large part because of privacy and intrusiveness concerns, unless precautions are taken to minimize these concerns.

All-weather capability will be an essential requirement for Hopper vehicle operations. Commuters cannot be delayed, and/or worse, stranded, as a consequence of adverse weather conditions; Hopper commuters would expect equal, or better, continuity of operations than might be had with ground-based public transportation systems. The magnitude of providing this all-weather-capability is, of course, somewhat contingent on the metropolitan region being considered for Hopper operations. The San Francisco Bay Area has a relatively benign, temperate local climate. Likely the greatest weather challenge for the Bay Area is the occasional low-lying fog condition that occurs during the winter months (Fig. 85). Irrespective of the local climate under which a notional Hopper network might have to operate, the fact remains that a significant technological and infrastructure investment will need to be made to ensure that continuity of operations is not disrupted by weather.

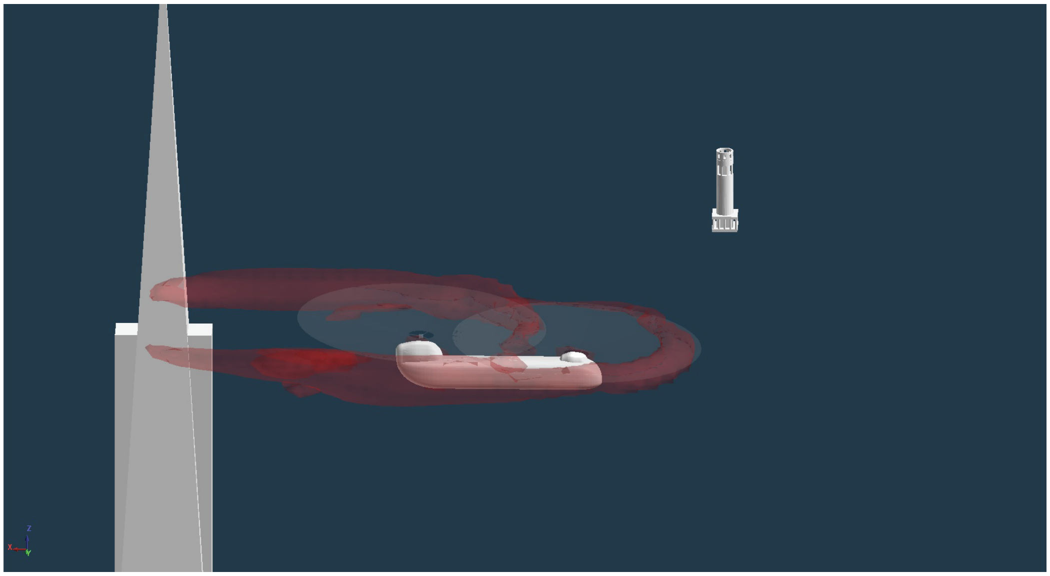


Figure 85. Hopper operations in the San Francisco Bay Area.

Autonomously piloted aircraft capability is not an essential requirement for Hopper vehicles; conceivably Hopper aircraft could be piloted much the same as current rotary-wing aircraft. Further, with modest advances in vehicle and support system automation, the skill set and experience required for safe and efficient piloting of Hopper vehicles could be made a fraction of what is currently required for commercial aviation pilots, to the point of being something akin to the skill levels of bus drivers or rail operators. However, from a direct operating cost perspective, it is somewhat inevitable to consider the technological and operational implications of autonomous passenger-carrying aircraft, particularly for the extremely short haul flights over well-defined flightpaths consistent with the Hopper mission profile. An analogous situation might be to consider the automated trams/subways used at airports across the world; after an initial introductory period very few passengers nowadays are disconcerted by the lack of a human operator physically onboard the tram/subway. This passenger acceptance is partly due to the fact that the trams/subways operate within well-defined routes, are through various means kept visibly clear of obstacles, traffic, and people, and travel for the individual passenger is of relatively short duration.

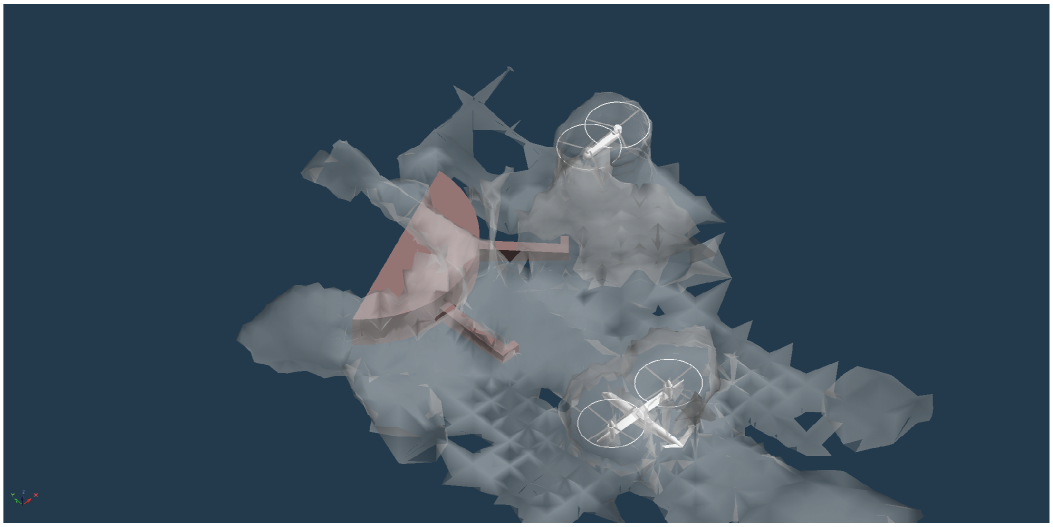
Integration With Current NASA Rotorcraft Research Efforts

Ideally the work from this study can be ultimately integrated with the ongoing research portfolio of the Revolutionary Vertical Lift Technology (RVLT) project, which is a part of the NASA Fundamental Aeronautics Program (FAP) within the Aeronautics Research Mission Directorate (ARMD).

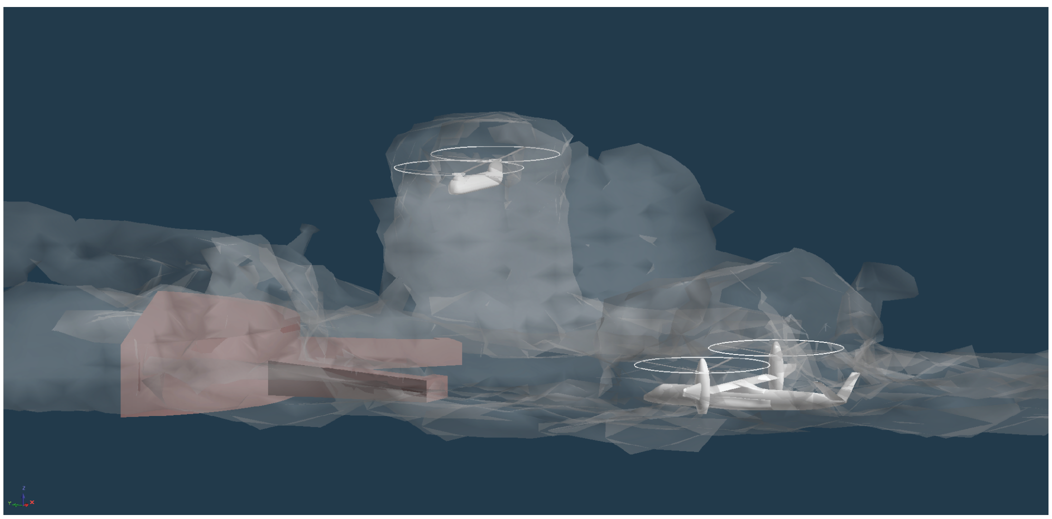
Technical challenges, as identified by the NASA rotorcraft research community, are as follows. Technical challenges: 1. demonstrate variable-speed power-turbine with 50 percent reduction in efficiency-delta associated with required shaft-speed change of advanced (rotorcraft) configurations; 2. demonstrate two-speed drive system with less than 2 percent power loss while maintaining current power-to-weight ratios; 3. quantify performance, noise, and vibration benefits of three active rotor concepts by test and analysis; 4. demonstrate 35 percent improvement in accuracy of predictions for rotor loads and performance for both hover and forward flight. Also, an additional area of emphasis is identified beyond the four technical challenges: demonstrate technologies required for community and passenger acceptance of large rotorcraft operating in the National Airspace System (NAS).

Finally, the key area in which the Hopper concept might have the greatest impact may be on the demonstration of technologies required for community and passenger acceptance of large rotorcraft operating in the NAS. Systems analysis were performed in references 8 and 9 investigating the potential of large civil tiltrotors to reduce NAS delays and throughput. The primary market for the early short-lived days of helicopter airlines, the 1950s to the 1970s, was, in fact, to act as a city-center-to-airport feeder for the commercial airlines. Hopper vehicles acting as feeder aircraft for civil tiltrotor and conventional fixed-wing aircraft operating out of urban airports is a natural area for future investigation. Refer to Figure 86a–b for a representative rotor wake interaction CFD result for a Hopper-like vehicle (the tandem helicopter) at a vertiport co-located at an urban airport operating in close proximity to a building structure and a regional (400- to 1000-nautical-mile-range) large civil tiltrotor aircraft.

Hopper integration with conventional fixed-wing air traffic and facilities will be an important technical issue. These integration challenges will only be exacerbated by emerging UAV civilian/commercial missions/applications (e.g., ref 19). Hopper vehicles would likely need to coexist with such UAV assets, which will also no doubt be performing low-altitude missions in the congested urban airspace environment. Future simulations, such as the currently reported BaySim work, will need to look at not only Hopper vehicles operating in metro-regional airspace but UAVs, general aviation (GA), and/or personal air vehicles of various different types, sizes, and capabilities.



(a)



(b)

Figure 86. Notional integration of a Hopper metro-regional aerial transportation system with civil tiltrotor short haul regional aircraft operating in and out of an urban commercial transport airport.

Some of the more immediate implications of this study as to future work and technology transition to NASA's Fundamental Aeronautics Program (FAP) are the electric-propulsion models that were developed as a part of this study; these models are already finding their way into Stanford's SUAVE vehicle conceptual design tool (ref. 87) and NASA's NDARC rotorcraft sizing tool (ref. 7). This study has also played an important role in internal electric-propulsion discussions within NASA's rotorcraft research community. There will likely be additional aircraft design investigations within NASA on a number of the alternate Hopper configurations. Finally, the Hopper concept potentially makes a great test case/application for NASA vehicle/systems autonomy research.

Concluding Remarks

This report documents the second phase of a study investigating the challenges and opportunities of a novel metropolitan aerial transportation system employing extreme short haul (with ranges less than 100 nautical miles) VTOL vehicles. Such "Hopper" vehicles could employ electric propulsion and incorporate high levels of autonomous system technology.

Altogether, the design space investigation revealed that a mid-term (next 15–20 years) solution for electric vertical lift vehicles supporting the Hopper metro/regional aerial transportation system mission could be feasible. Specifically, relatively near-term all-electric or hybrid-electric propulsion system technologies can make these short-range vehicles realizable perhaps within the next 10 years. Near-term battery technology (500–600 W-h/kg at reasonable power densities) will satisfy power and energy requirements for these short-range vehicles; more advanced Li-air batteries are unlikely to lead to further weight reductions as the technology trends for these batteries are driven by the consumer market and not the aviation sector. Clearly, when considering in part that Hopper battery packs will be an order-of-magnitude greater in size/capacity compared to current-production automotive electric vehicle batteries, there are aviation-unique aspects to electric-propulsion system development. To successfully develop rotorcraft with electric-propulsion capability (or any other type of aircraft) it is not simply a question of waiting until industry produces a sufficiently advanced battery (or fuel-cell or hybrid system) in terms of specific power and specific energy capability. Instead, results from this study support a role for NASA, and other Government agencies, to help enable/develop aviation-unique electric-propulsion technologies.

From an emissions standpoint, rotorcraft with electric propulsion are more environmentally benign than turboshaft-engine rotorcraft. However, though the vehicle concepts in this study were required to operate at much lower tip speeds and disk loading than conventional helicopters, rotorcraft noise reduction is still an important technological challenge. Acoustics and other over-flight issues will require extensive neighborhood outreach. A very preliminary set of acoustic predictions was made during this study. Other important operational considerations include rotor wake interaction in the proximity of vertiports (aka Hopper network stations), as well as airspace management issues inherent in attempting to interject a large fleet of aircraft into an already complex, congested airspace. One approach to addressing these airspace congestion issues may be to define airspace management concepts so as to operate the Hopper network independently of other air transport, instead of seeking to actively intermesh both sets of aircraft. Further, it was found that the challenges in integrating Hopper flights and Bay Area commercial traffic can be partially addressed with Hopper aircraft time-of-day dynamic routing as well as Next Generation Air Transportation System (NextGen) technologies. It seems that emerging technological and procedural advances, currently being proposed under NextGen, could be leveraged to facilitate the realization of the Hopper concept. The development/refinement of the BaySim Discrete Event Simulation (DES) has value not only in producing quantitative design tradeoff information, but also in 1) uncovering and examining detailed operational policies surrounding transportation networks, and 2) understanding behavioral and demographic issues for urban aerial transportation system ridership populations. More than anything, though, this study reflects a unique opportunity to merge several disparate aeronautics disciplines into a novel fusion of conceptual design, systems analysis, and simulation methodologies.

Appendix A—CFD Predictions of Hoppers and Rotor Wake Interactions

30-PAX Hopper Vehicle In- and Out-of-Ground-Effect

This work builds off of, in part, earlier work presented in reference 72 for a similar rotor wake interaction study for large civil tiltrotor aircraft operating from vertiports based at congested urban airports. This work uses a NASA-SBIR-sponsored computational fluid dynamics (CFD) tool especially tailored for rotorcraft conceptual design studies (ref. 83). One of the 30-PAX electric tandem helicopter designs from Phase I was modeled in RotCFD; initial CFD predictions were performed during the course of the Phase II effort. RotCFD is fairly good at rotor wake interactional aerodynamics studies. The RotCFD acoustic solver, though, has only seen limited development/validation to-date; one has to consider current acoustic results (refer to Appendix B) as "first-order" estimates. The following discussion is an attempt to determine if the RotCFD acoustic results can be validated against publically available FAA data from Boeing Vertol 234 civil tandem helicopter acoustic results.

Some of the modeling details that support the rotor wake predictions of Figures A1–A4 include: setting rotor collective equal to 10 degrees for both the fore and aft rotors; hover OGE; h/R = 6.66; NACA0012 airfoils; zero twist for rotor; "laminar" unsteady Navier–Stokes wake modeling (future work will use a turbulence model); and velocities and all computed properties in SI units.

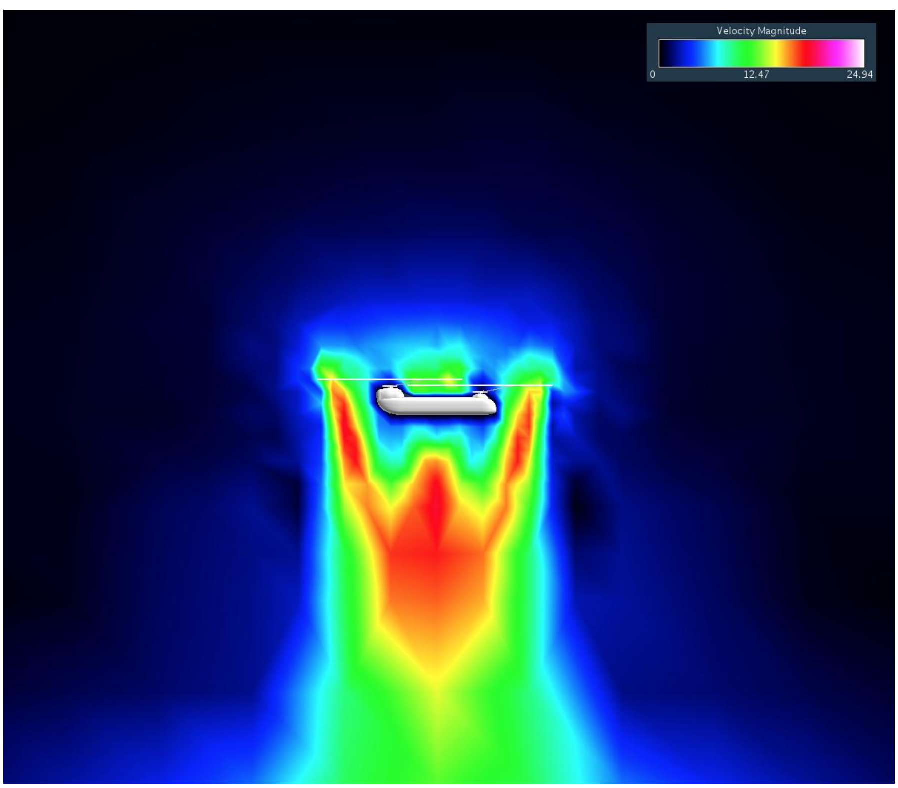


Figure A1. RotCFD rotor wake prediction; hover out-of-ground-effect (HOGE).

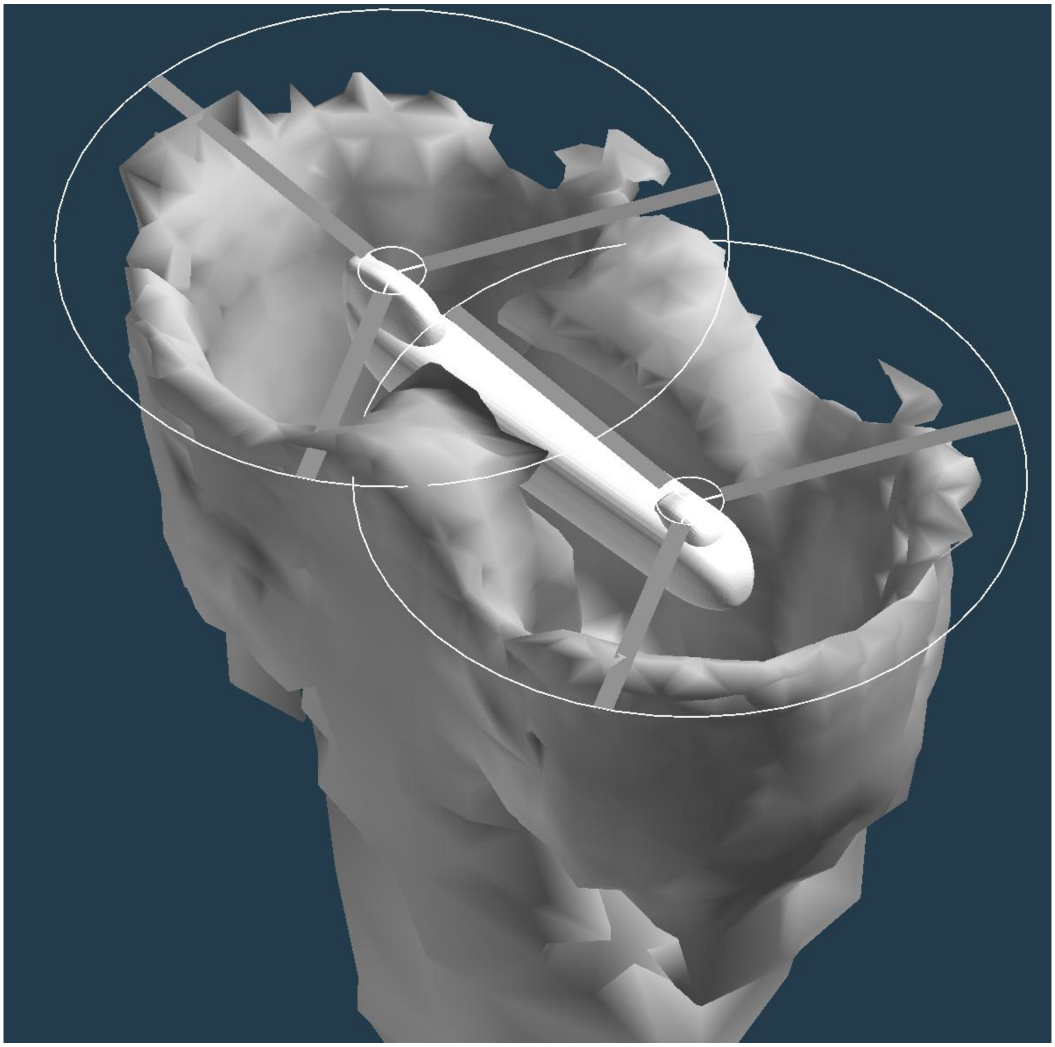
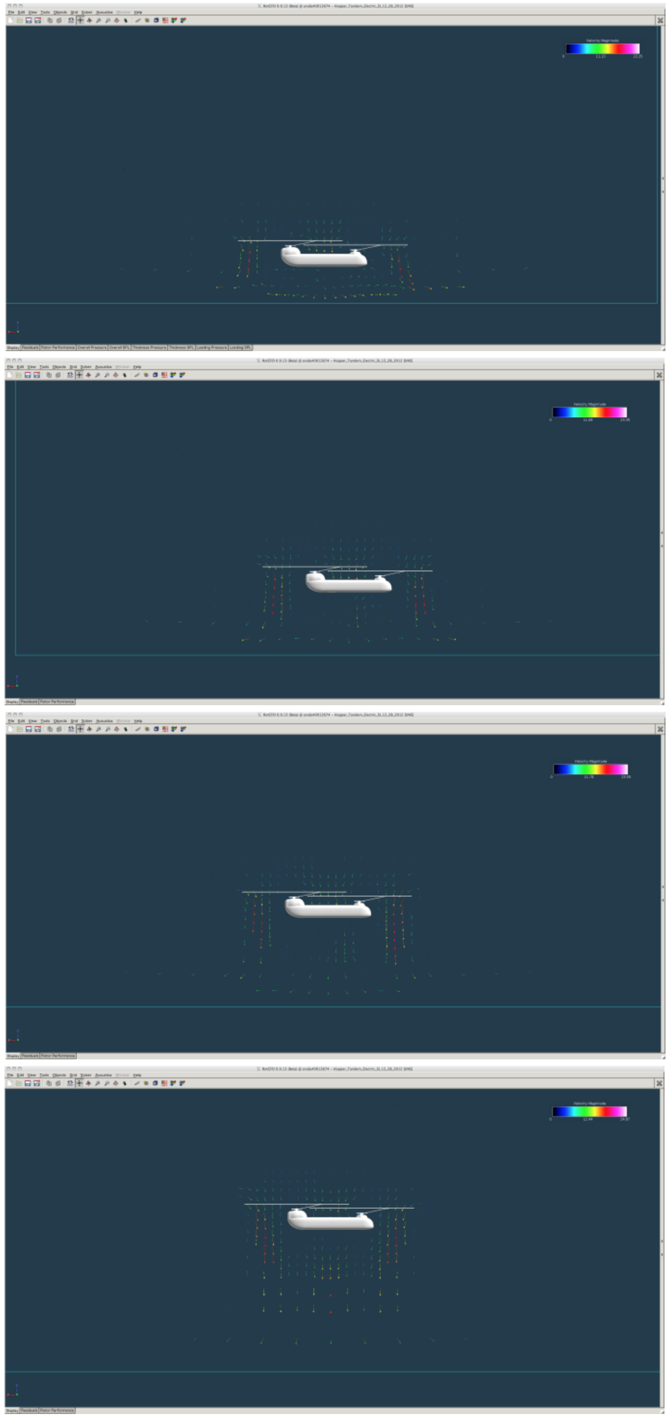


Figure A2. RotCFD rotor wake prediction; hover out-of-ground-effect (HOGE); velocity magnitude isosurface.



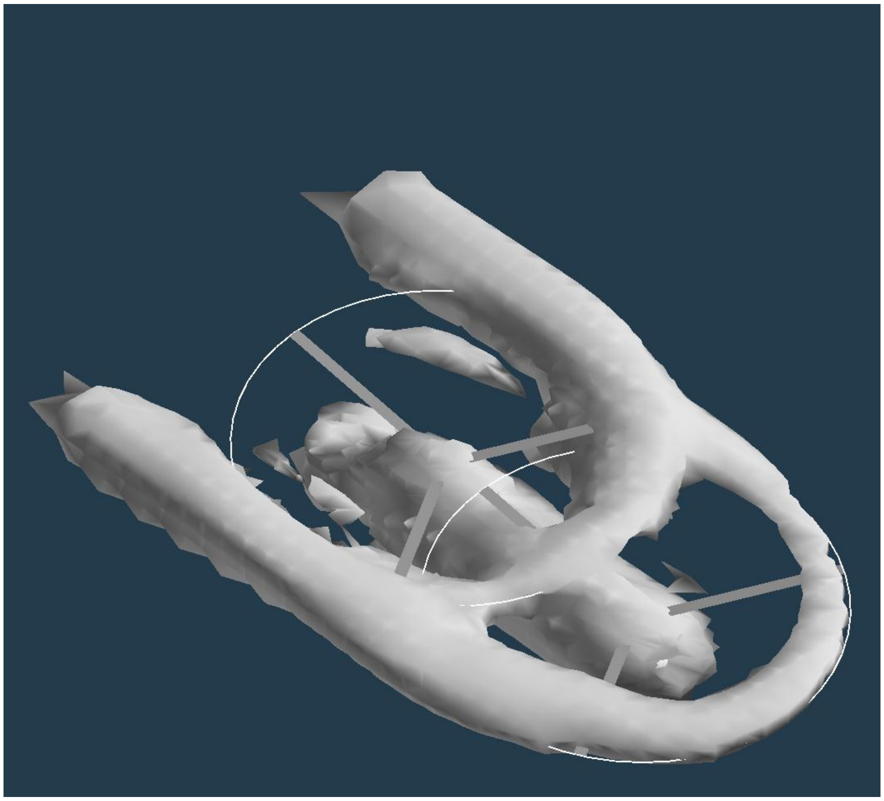
(a)

(b)

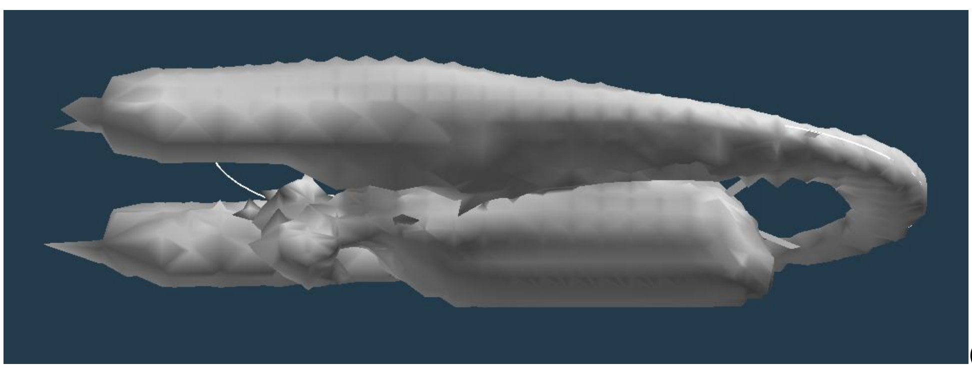
(c)

(d)

Figure A3. RotCFD rotor wake prediction; hover in-ground-effect (HIGE): (a) h/R = 1, (b) h/R = 1.5, (c) h/R = 2, and (d) h/R = 3.



(a)



(b)

Figure A4. RotCFD rotor wake prediction; forward flight (advance ratio of 0.15; V = 30 m/sec); out-of-ground-effect; vorticity magnitude isosurface: (a) top oblique view and (b) side oblique view.

Hopper Multiple Aircraft Wake Interactions

Figure A5 illustrates some of the rotor wake outwash challenges of closely spaced rotorcraft typical of a vertiport site with high utilization. In this particular figure, RotCFD predictions of the rotor wakes of two side-by-side tandem Hopper aircraft are shown; one Hopper vehicle is on the ground with rotors idling at low thrust, the other is hovering above and to the side in-ground-effect. It is conditions such as these that adverse loads and rotor flapping motion might be induced on the vehicle on the ground.

Figure A6 further illustrates how this wake interaction from one Hopper vehicle can influence the aerodynamic loads on another. It should be noted that the results are preliminary; a considerable amount of additional work needs to be performed in this area. Similar issues such as this require considerable analysis, experiment, and flight test effort to assess and establish procedures for naval aviation shipboard operations (reference 88 used a precursor version of RotCFD called Rot3DC for just such an exercise).

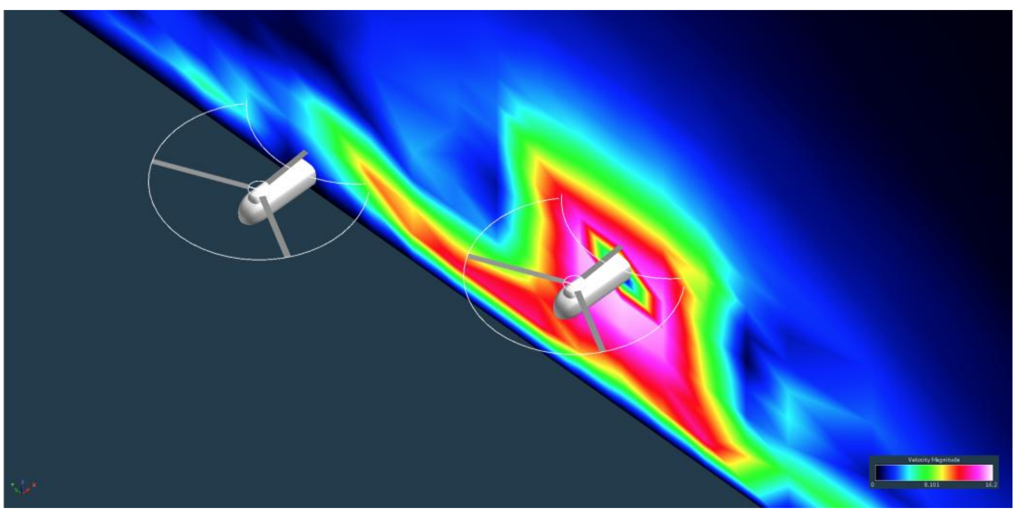


Figure A5. RotCFD rotor wake prediction showing the potential adverse effect of a hovering Hopper in close proximity to another Hopper on the ground at low thrust.

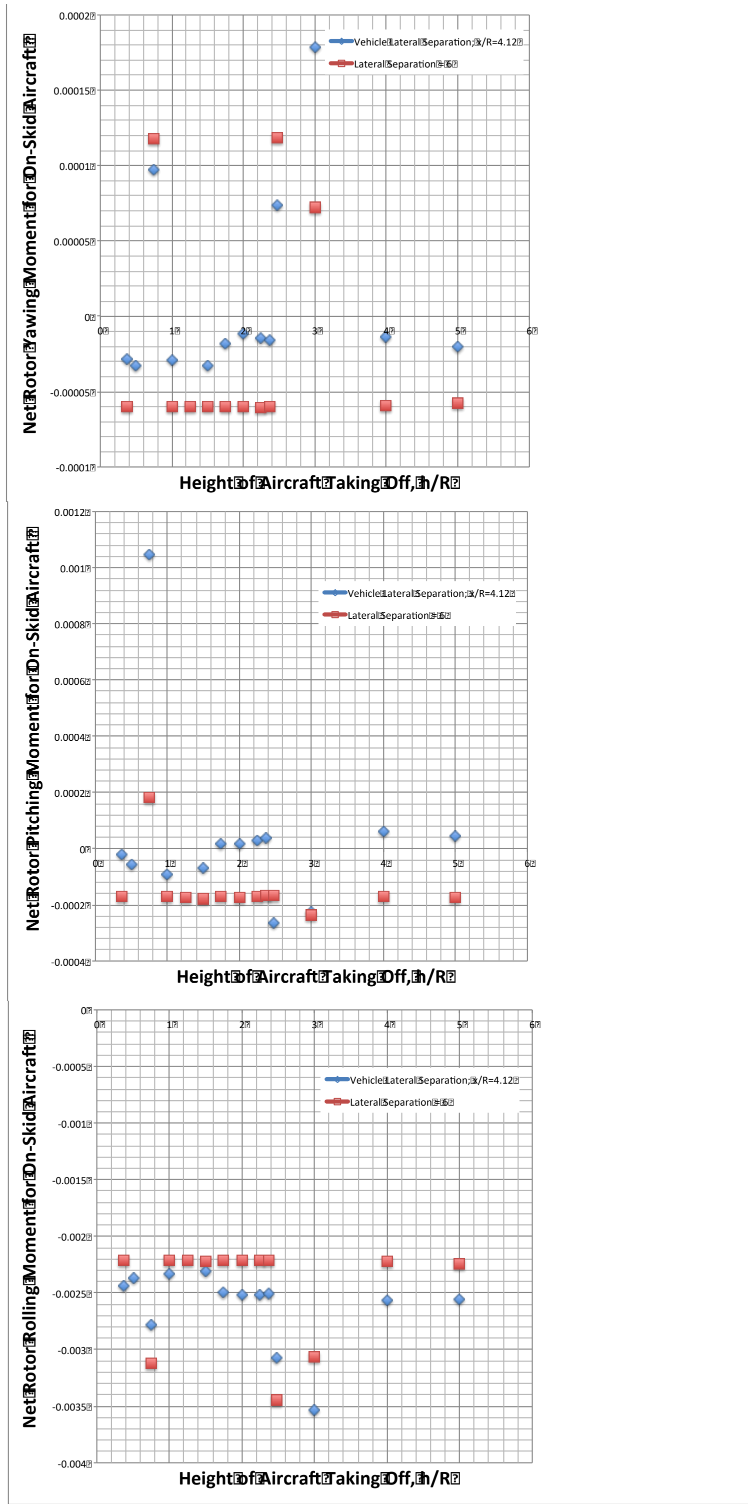


Figure A6. Representative RotCFD rotor wake predictions showing the potential adverse effect of a hovering Hopper in close proximity to another Hopper on the ground at low thrust: (a) net yawing moment coefficient (rotor contributions only), (b) net pitching moment coefficient, and (c) net rolling moment coefficient.

Hopper Wake Interactions With Station Infrastructure

The cost of real estate in heavily populated metroplex regions such as the San Francisco Bay Area is extremely expensive. The modeled Hopper station draws inspiration from the notional vertiport design illustrated on the report cover of reference 10. The vertiport siting from reference 10 accounted for many of the same considerations that will need to go into possible implementation of a Hopper network: siting in a highly urbanized area; collocation with a major nexus of complementary public transit (Fig. A7); and siting near a major tourism and or business center.

Figure A8 illustrates rotor wake predictions of a Hopper vehicle hovering near a notional vertiport station. Figure A9 shows the influence of crosswinds with respect to the station and Hopper vehicle.

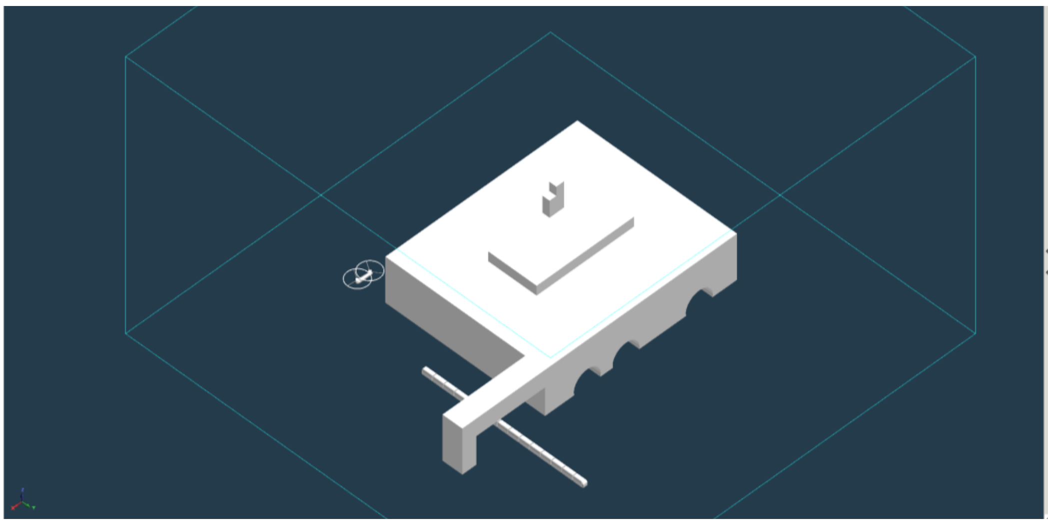


Figure A7. Hopper vehicle near an aerial transit station

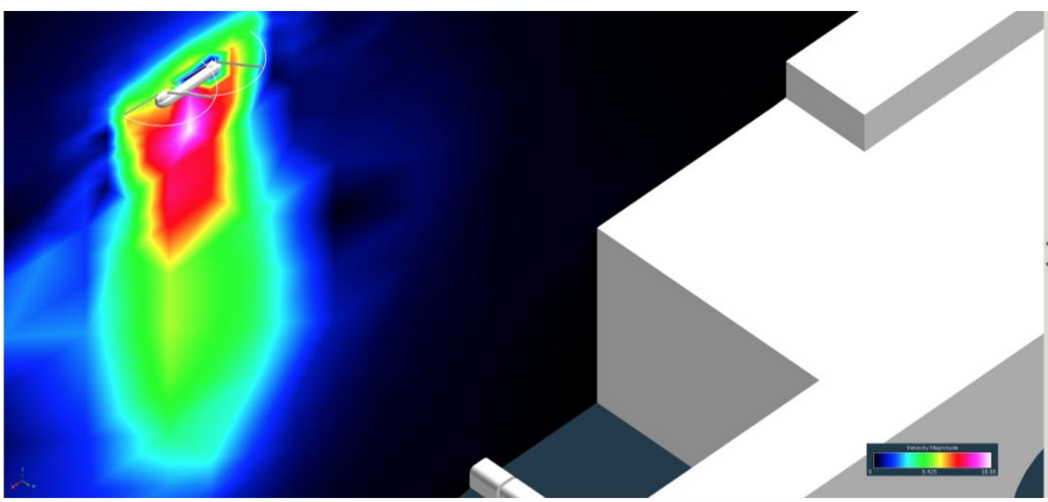


Figure A8. RotCFD rotor wake prediction showing the potential wake interactions with Hopper station ground infrastructure (Hopper HOGE near station).

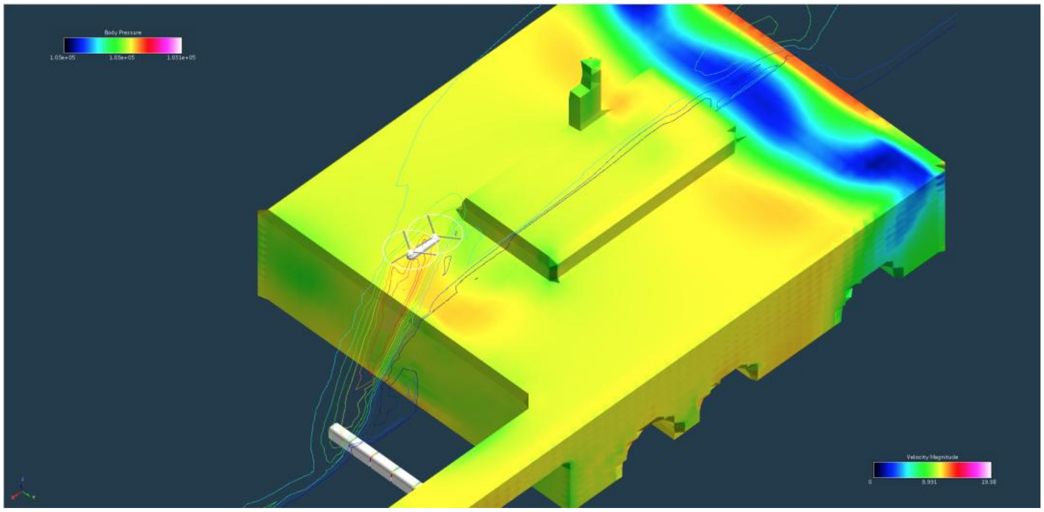


Figure A9. RotCFD rotor wake prediction showing the potential wake interactions with Hopper station ground infrastructure (Hopper HIGE over station with 5m/sec head-on wind).

Minimizing the Effects of Hopper Outwash Through Deployable “Jetblast Deflectors”

Figure A10 illustrates a notional set of deployable jetblast deflectors that would surround the takeoff and landing zone of a Hopper vehicle. The deflectors would raise and lower, on hinges, from being flush with the tarmac when not deployed, to deflector angles between 30–60 degrees from horizontal when deployed.

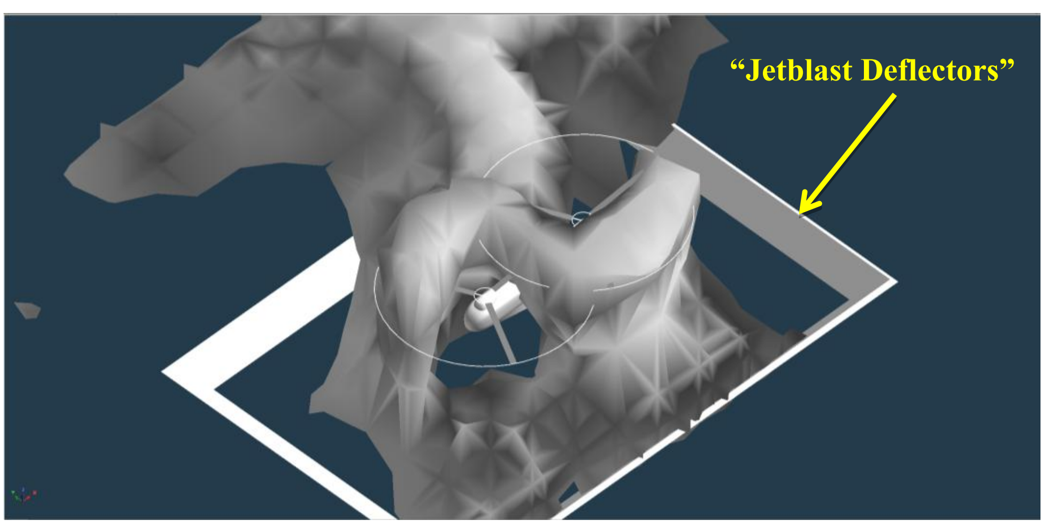


Figure A10. RotCFD rotor wake prediction showing the effect of notional deployable “jetblast deflectors” for minimizing outwash hazards at Hopper stations.

It is unclear whether such deflectors would be required for Hopper VTOL operations from an aerial transit station. However, it will be assumed crucial to minimize the total site area required for a Hopper station in order to minimize land purchase and station construction costs. Such cost considerations will undoubtedly require a close examination of wake hazard mitigation technologies such as the deployable deflector concept. Figure A11 presents some preliminary CFD predictions of the effect (or, more correctly, the minimal effect) of jetblast deflectors on the tandem helicopter mean thrust coefficient in-ground-effect.

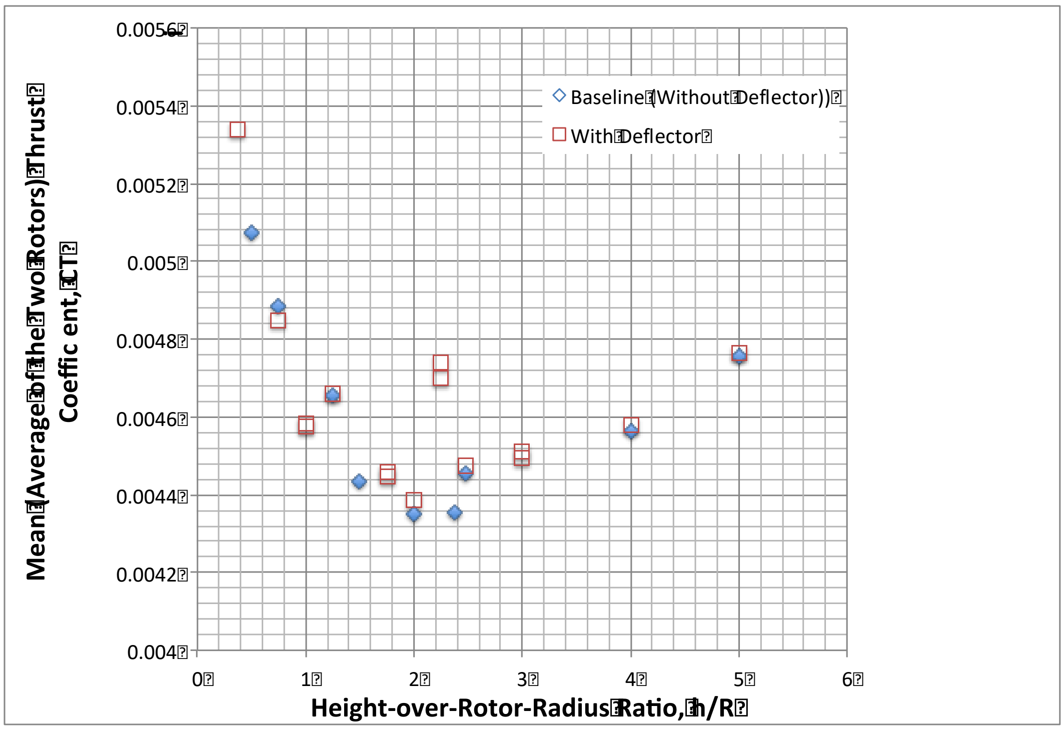


Figure A11. Predicted effect of jetblast deflectors on the mean thrust coefficient of 30-PAX tandem Hopper vehicle.

Appendix B—Acoustic Noise Source Estimates

Hopper noise will be a crucial factor as to whether or not the vehicle and the metro-regional aerial transportation system network concepts will ever be accepted by the public. Rotary-wing acoustics prediction is currently an area of intensive study within NASA and other organizations. At best, what might be expected to be contributed from this study is only a first-order acoustic assessment of the Hopper vehicles and network. Accordingly, this work uses a NASA-SBIR-sponsored computational fluid dynamics tool especially tailored for rotorcraft conceptual design studies (ref. 83). This tool has been recently extended, again through concurrent NASA-SBIR-sponsored efforts, to include a first-order acoustic solver module. The Hopper acoustic analysis also draws heavily from experimental flight test noise measurement work presented in reference 89 for the Boeing Vertol 234 commercial tandem helicopter.

Representative samples of the RotCFD acoustic solver output are illustrated in Figures B1and B2. Rotor-only source noise acoustics are predicted; no estimates were made for engine/drivetrain noise. A consideration in follow-on work is whether there is any electric motor acoustic data in the literature to compare to turboshaft engine noise in order to assess the impact of switching to electric propulsion. The RotCFD "steady" rotor option is used in the acoustic estimates, not the "unsteady" (or, rather, discrete blade simulation) option. The fore and aft rotors have a thrust coefficient between $0.004 < C_T < 0.0045$ in the hover OGE results presented.

The frequency spectrum and the predicted sound pressure time history can also be provided as output from RotCFD. Figure 3B shows an observer point just forward and to the right of the 30-PAX electric tandem helicopter reference design for this study; representative sample plots are provided in Figures B4 and B5.

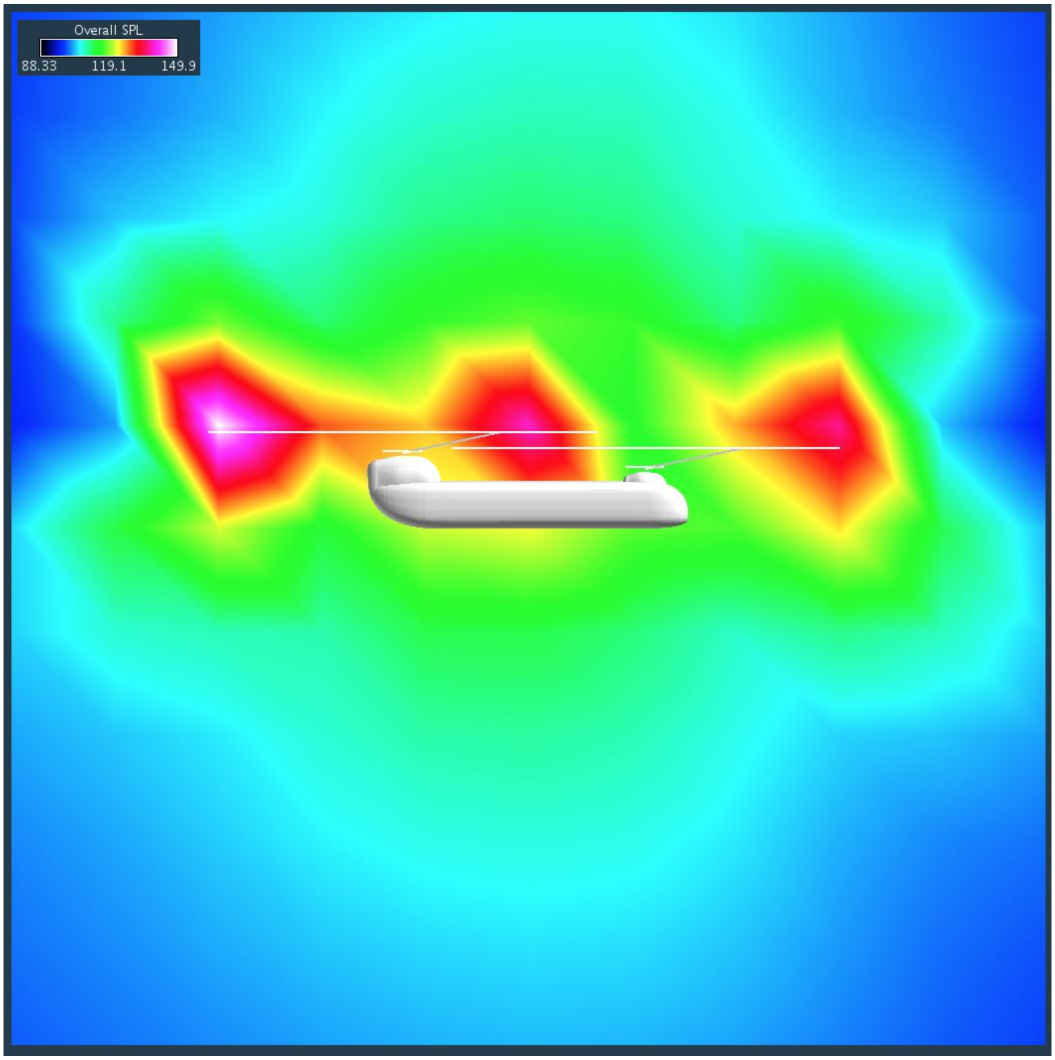


Figure B1. Tandem Hopper overall sound pressure level (OASPL) prediction from RotCFD (y-z plane).

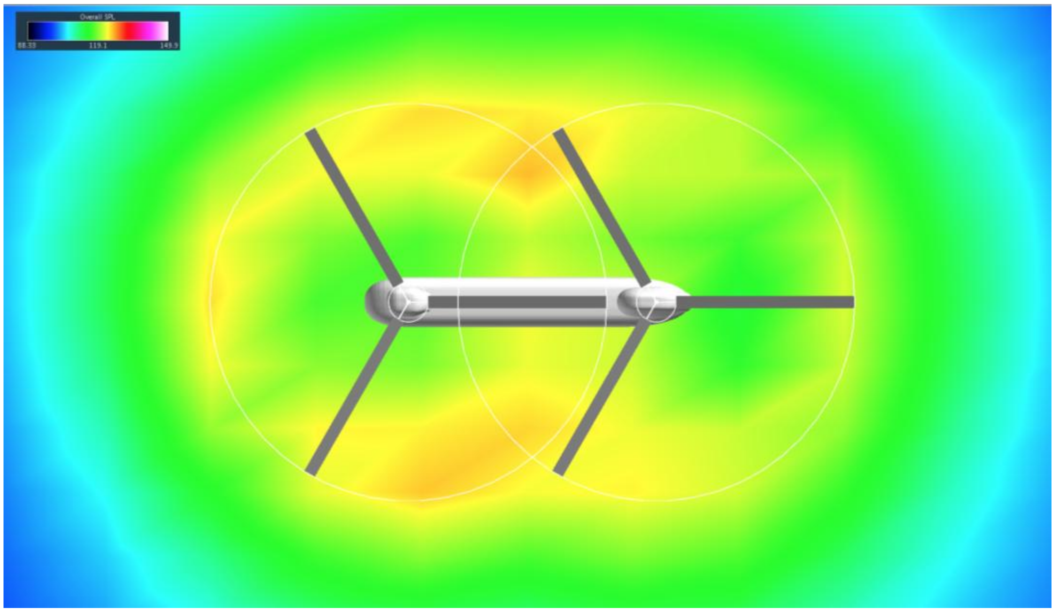


Figure B2. Tandem Hopper OASPL prediction from RotCFD (x-y plane; just below fuselage).

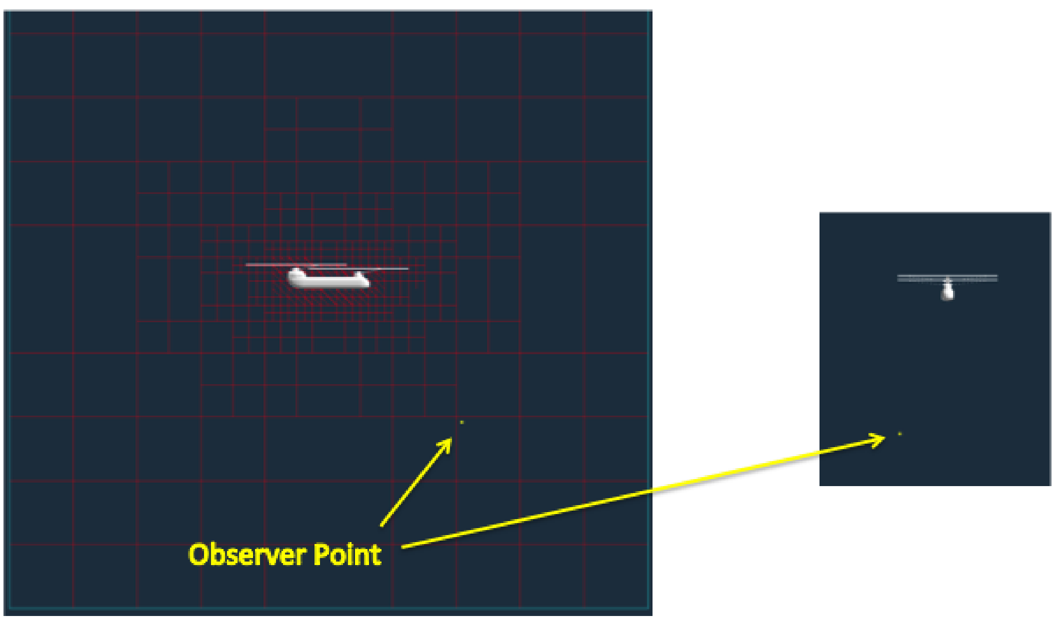


Figure B3. Representative tandem Hopper acoustic solver observer point.

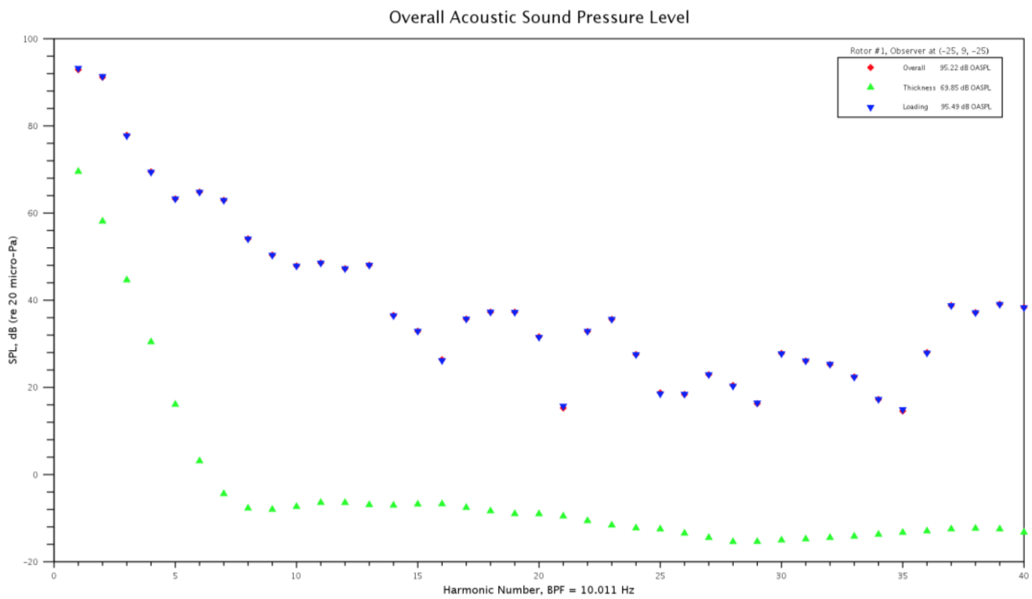


Figure B4. Representative tandem Hopper (single rotor) OASPL frequency spectrum at selected observer point.

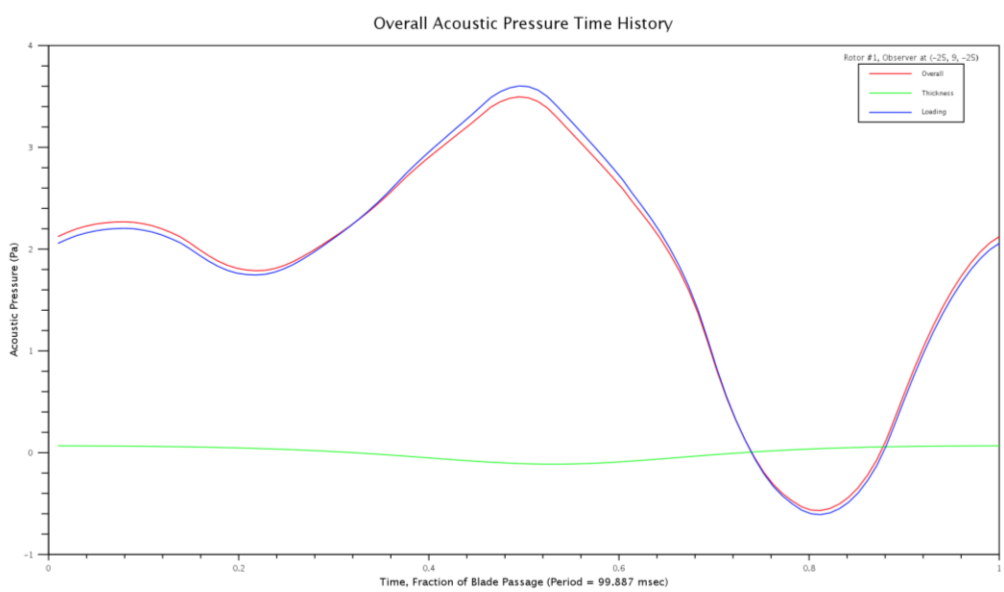


Figure B5. Representative tandem Hopper (single rotor) sound pressure time history at selected observer point.

An important consideration in these first-order RotCFD acoustic predictions is how representative are they with respect to actual rotary-wing vehicles. Figure B6 is a plot of overall acoustic sound pressure levels (OASPLs) in dB, as a function of emission directivity angle. Figure B7a–b is a set of OASPL contour plots for a hovering (static operation) Hopper vehicle.

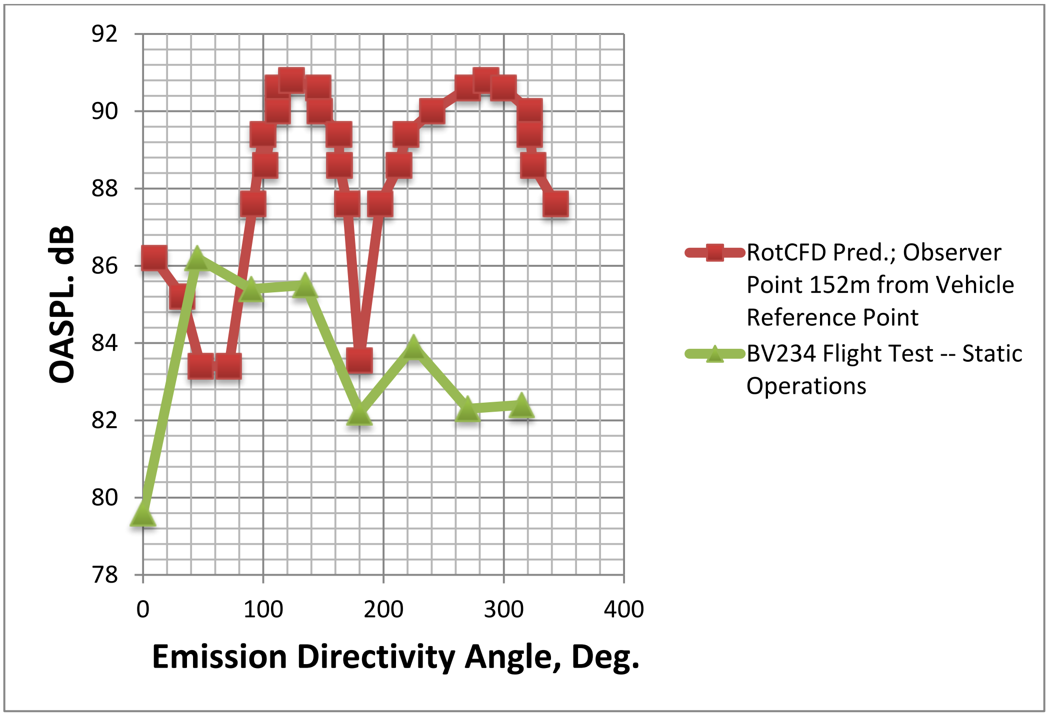
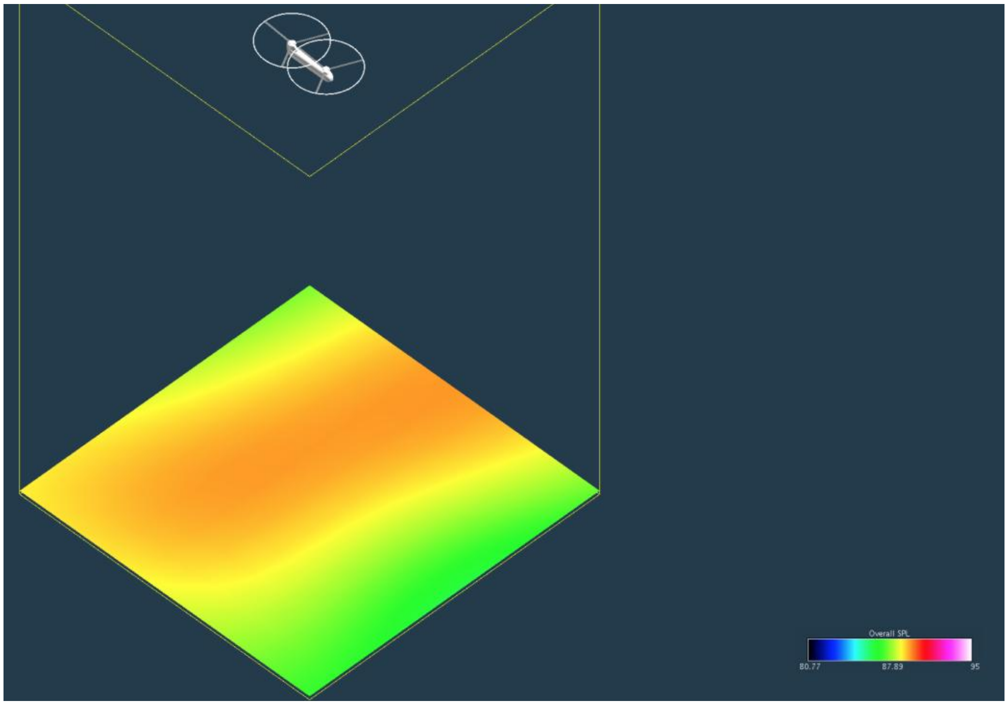
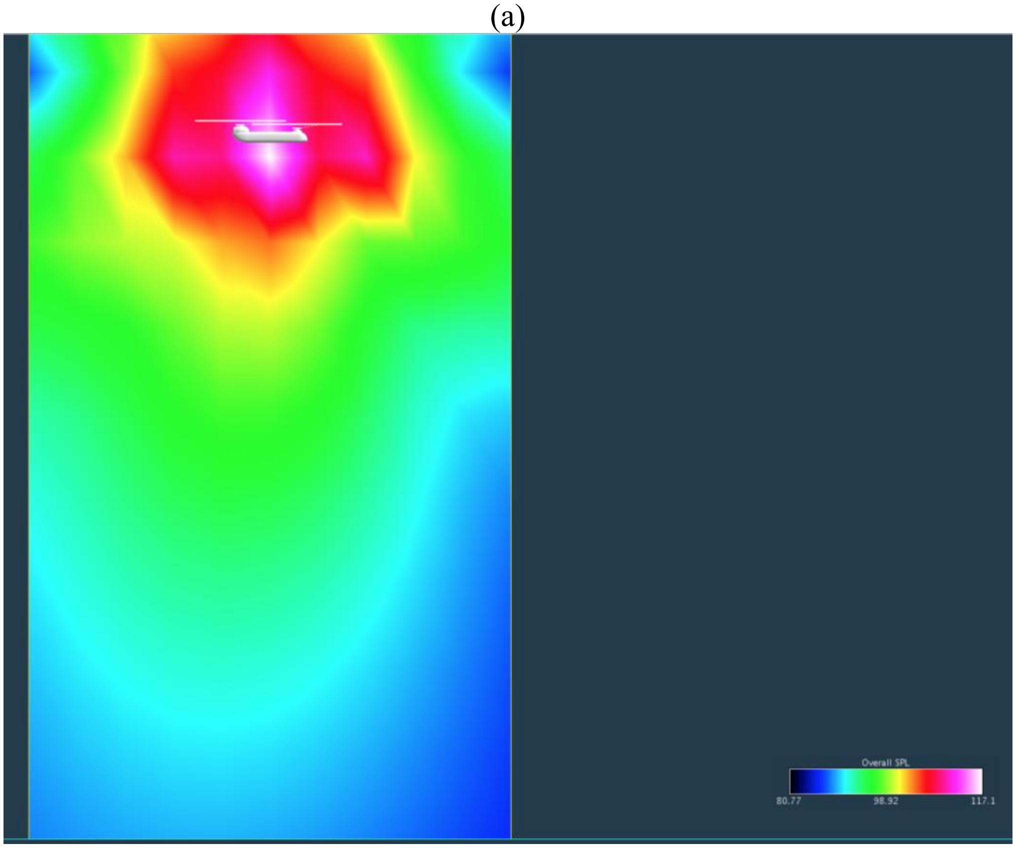


Figure B6. RotCFD prediction for 30-PAX electric tandem helicopter reference design and comparable flight test data (static operations) for the Boeing Vertol 234 commercial tandem helicopter (ref. 89).



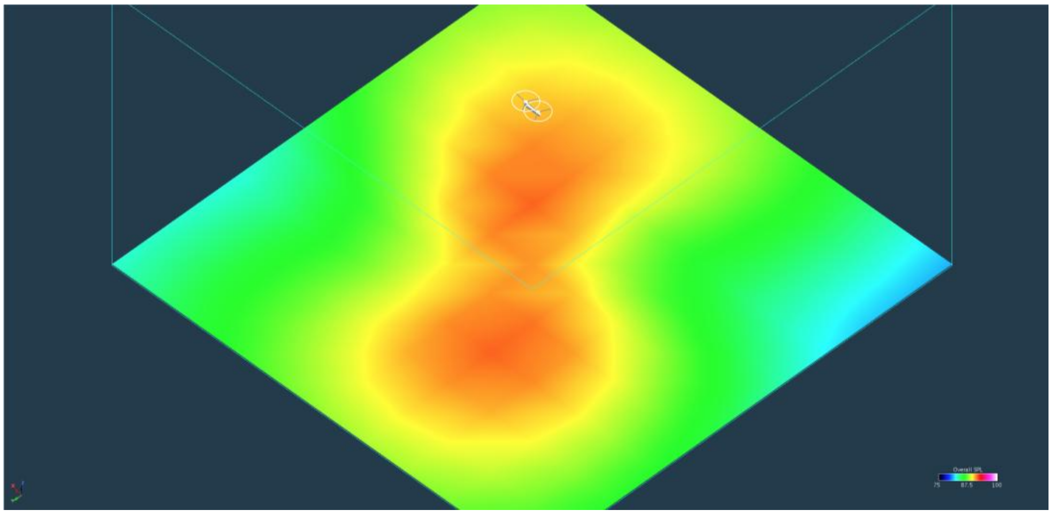
(a)



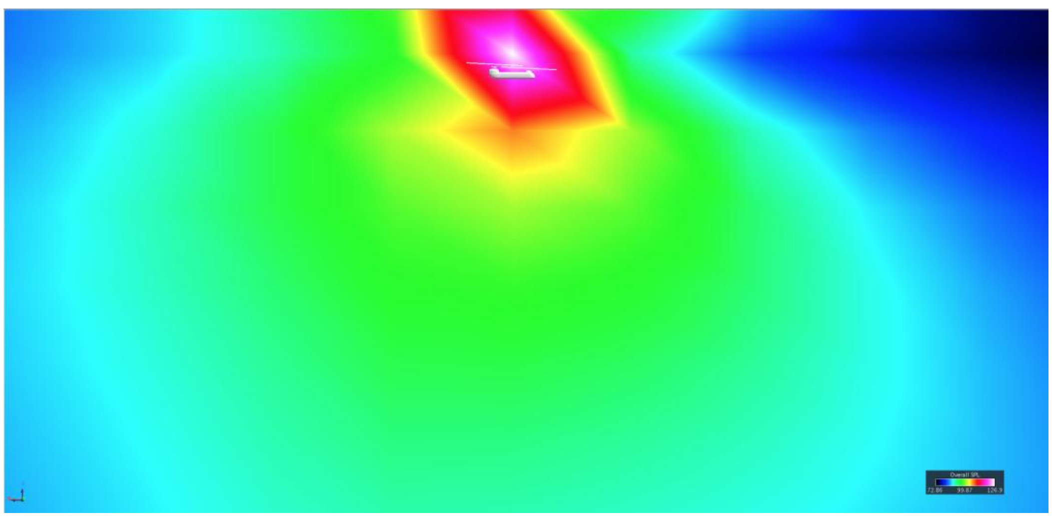
(b)

Figure B7. RotCFD OASPL prediction for 30-PAX electric tandem helicopter reference design for 150m AGL static (HOGE) operation: (a) orthogonal view and (b) side view.

Level forward-flight RotCFD acoustic predictions for the 30-PAX tandem helicopter Hopper vehicle are shown in Figure B8a–b.



(a)



(b)

Figure B8a–b. RotCFD OASPL prediction for 30-PAX electric tandem helicopter reference design for 150m AGL forward-flight operation: (a) orthogonal view and (b) side view.

A limited acoustic comparison was made between the BV-234 (a comparably sized tandem helicopter) and the 30-PAX Hopper vehicle; refer to Figure B9. Given the results from Figure B6 (static operation) and Figure B9 (flyover), the Hopper vehicle is predicted to be somewhat noisier in hover than the BV-234 but quieter during a forward-flight flyover. The Hopper vehicle was conceptually designed to have reduced tip speeds compared to conventional tandem helicopters such as the BV-234, so it is not completely surprising that lower noise levels are predicted for a portion of the notional flight envelope of this vehicle. However, this is only a qualitative comparison with a software tool that is still in early development; much more work will be required before a reasonably definitive acoustic assessment of Hopper vehicles can be made.

Future work will also need to develop a first-order methodology to estimate sound exposure level (SEL) from OASPL results from RotCFD (or, alternatively, acoustic predictions will need to be made with the FAA INM and AEDT tools). In turn, future work will need to estimate day-night average sound level (DNL) from SEL; this may entail adding feature(s) to BaySim to make cumulative acoustic footprint predictions for Hopper urban flyovers.

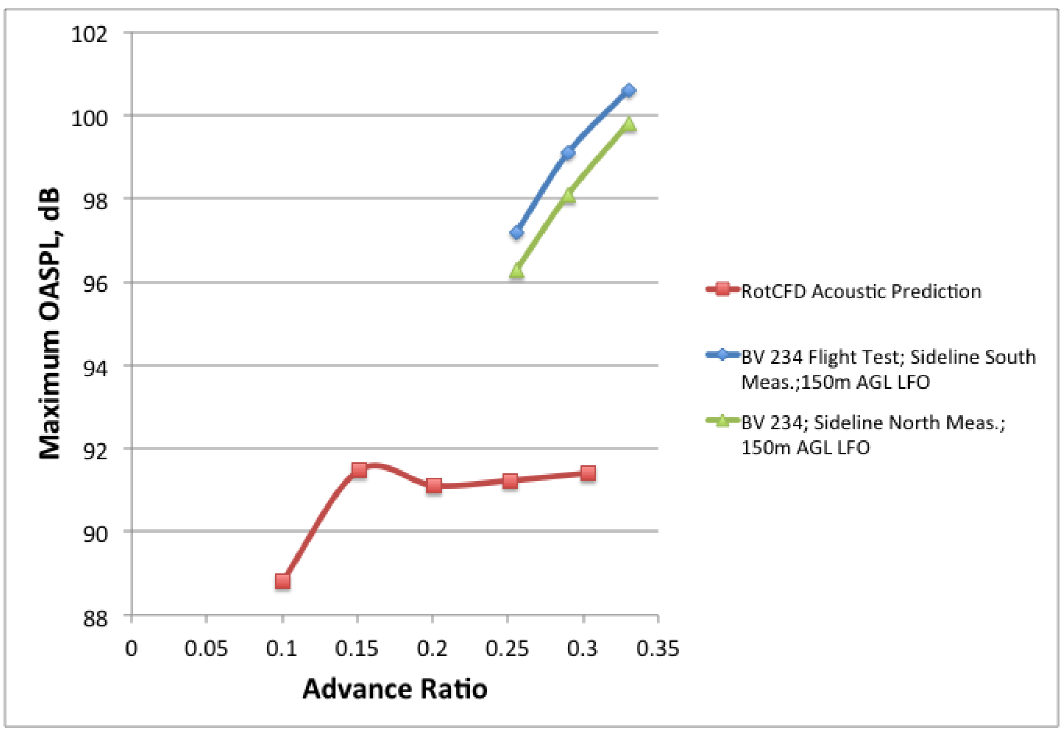


Figure B9. RotCFD maximum sideline OASPL prediction for 30-PAX electric tandem helicopter reference design and comparison to BV-234 flight test data for 150m AGL level flyover (LFO).

Appendix C—IMPLEMENT Analysis

Phase I of this study (ref. 1) only considered an eight-node, any-node-to-any-node (n x n) topology for the Hopper network, particularly as applied to influencing the early BaySim simulations. A more pragmatic ring-spoke topology and associated Hopper CONOPS was devised for the Phase II study. Additionally, it is anticipated that a metro/regional aerial transportation system like the Hopper network would be less designed as, and instead evolved from earlier, smaller networks, or point-to-point origins and destinations. Figure C1 illustrates a notional network evolution of a Hopper network (proceeding with time from left to right in the figure) from simple three-node networks to larger, more complex networks (14 nodes).

Successful implementation and operation (from an economic or societal/public good perspective) of the simple networks would nominally lead to the development of new nodes and new networks over time. As a part of the overall simulation and analysis effort, BaySim simulations were run at various ridership levels for each of the networks in Figure C1. The BaySim results for the complete set of networks are, in turn, ultimately intended be used in the proposed IMPLEMENT analysis.

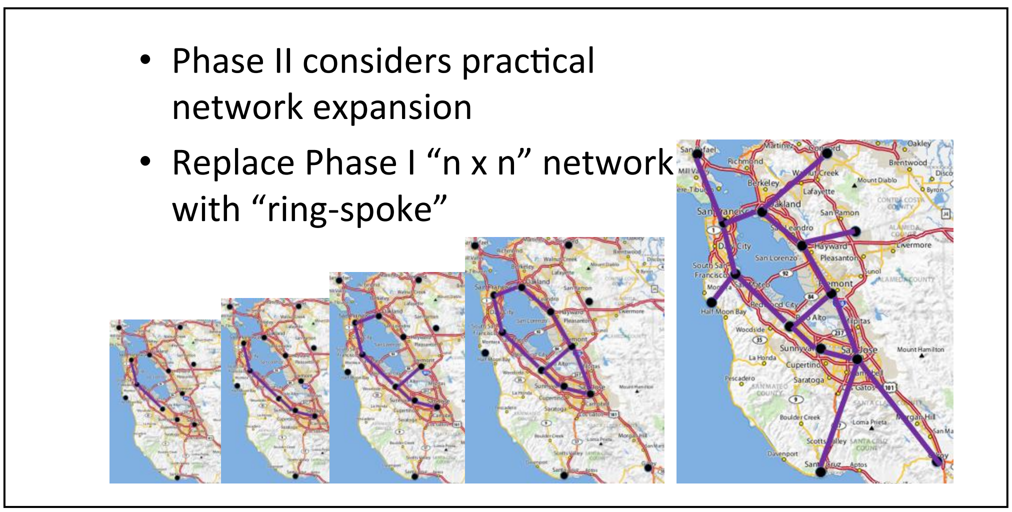


Figure C1. Notional evolution of the Hopper network.

Backcasting

1. Initial backcasting analysis starts with assumed linear ridership trend lines from Initial Operating Capability (IOC) to target (end) date of study (Fig. C2). IOC is assumed to be a simple two- to three-node network implementation.

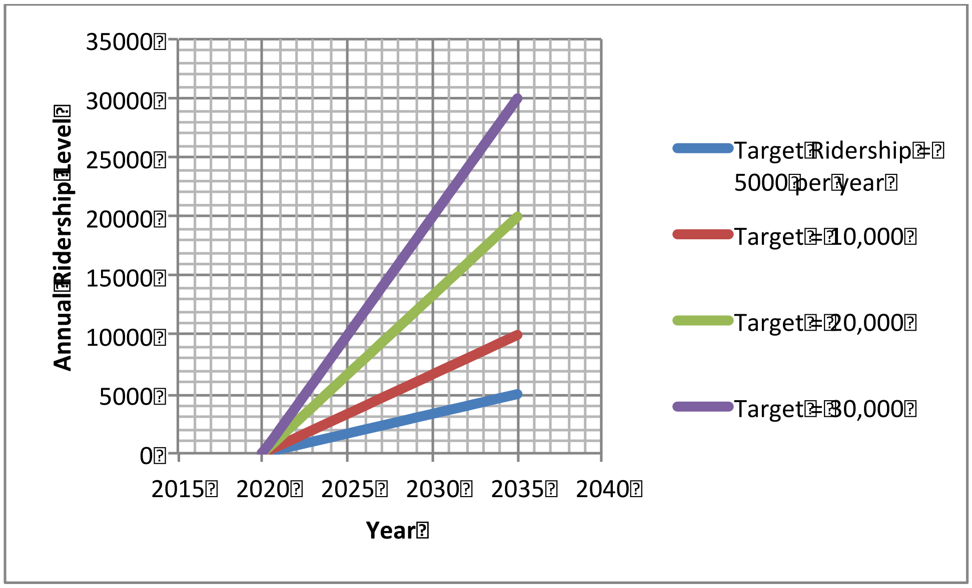


Figure C2. Assumed linear ridership growth trends.

2. Refined backcasting (beyond that of simple linear trends) can begin by presupposing the number of vertiport nodes as a function of time in a successive build-out of the Hopper network. Subsequently, all other aspects of the network operation and economics can be derived from the assumed network expansion profile. Figure C3 assumes nine nodes constructed in three discrete construction phases (three added vertiports per phase with an assumed uniform passenger ridership increase per completion of each construction phase).

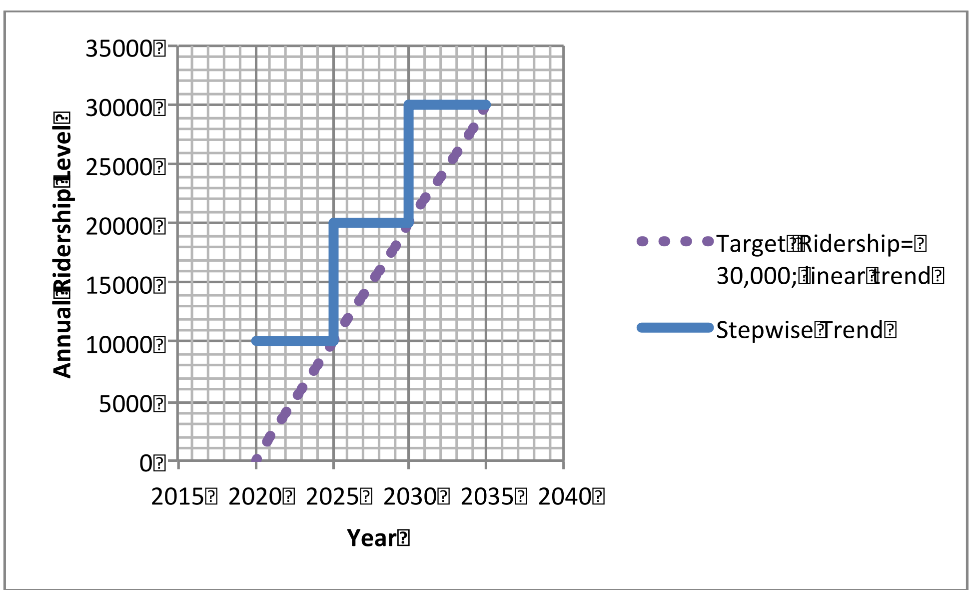


Figure C3. Assumed stepwise increase in ridership with discrete phases of vertiport node construction.

3. Further refinement of backcasting can be attempted using a combined S-function/ stepwise trend modeling (Fig. C4).

4. Finally, estimate ticket/ride revenue (for various assumed origin-destination fares) for one ridership target level (e.g., 30,000 passengers per day) (Fig. C5). A good range of potential fares for the 2035 time frame is probably $5 to $40 per ride (one given origin-destination); this range of fares approximately spans that of a public transit bus fare and a local automotive taxi fare.

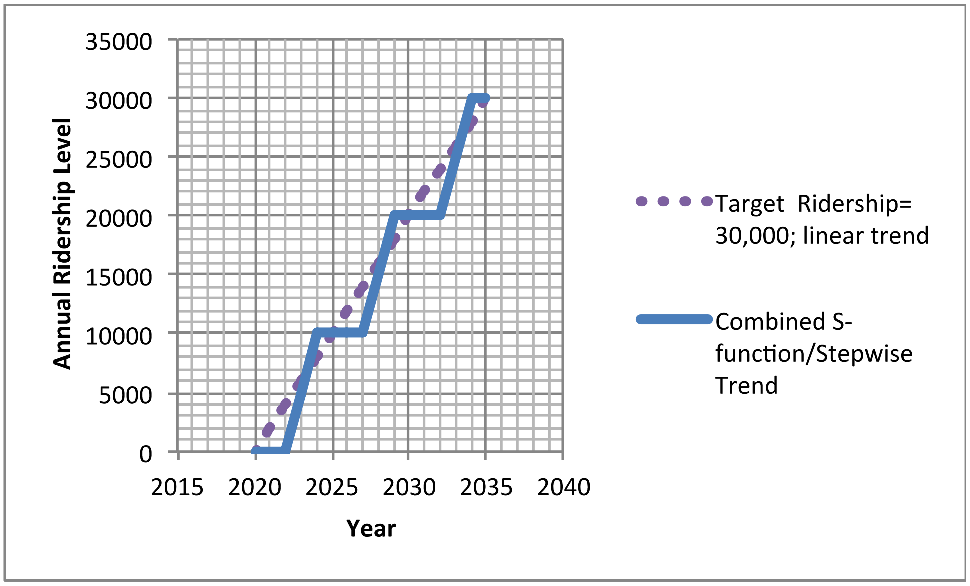


Figure C4. Assumed combined S-function/stepwise increase in ridership.

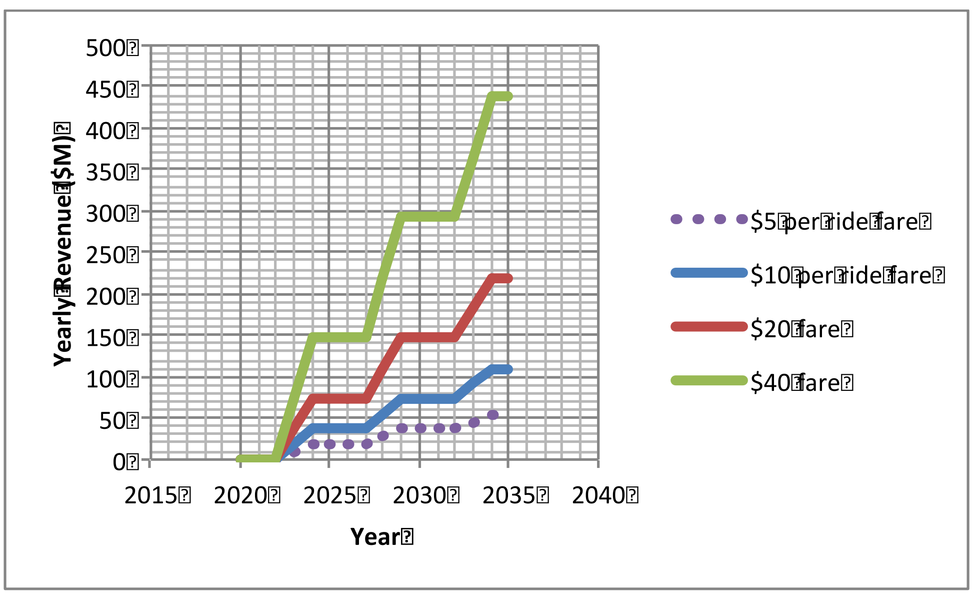


Figure C5. Projected yearly revenue for various assumed origin-destination fares.

Forecasting

The preceding "backcasting" analysis started with assumed target levels of daily Hopper ridership, circa 2035, and then performed a simple estimation of potential growth trends necessary to meet those target levels. Further, using a plausible range of per-ride fares—and the ridership growth trend estimates—yearly revenue was estimated. Alternatively, forecasting seeks to establish the growth in ridership using simple, first-order economic modeling. This forecasting model is an iterative estimation process summarized by the flow chart shown in Figure C6.

Each element of the Figure C6 forecasting flow chart is discussed next. Note that this Hopper network forecasting treatment is very preliminary in nature and only seeks to identify, in a non-definitive way, some of the key issues underlying the development of a metropolitan/regional aerial transportation system.

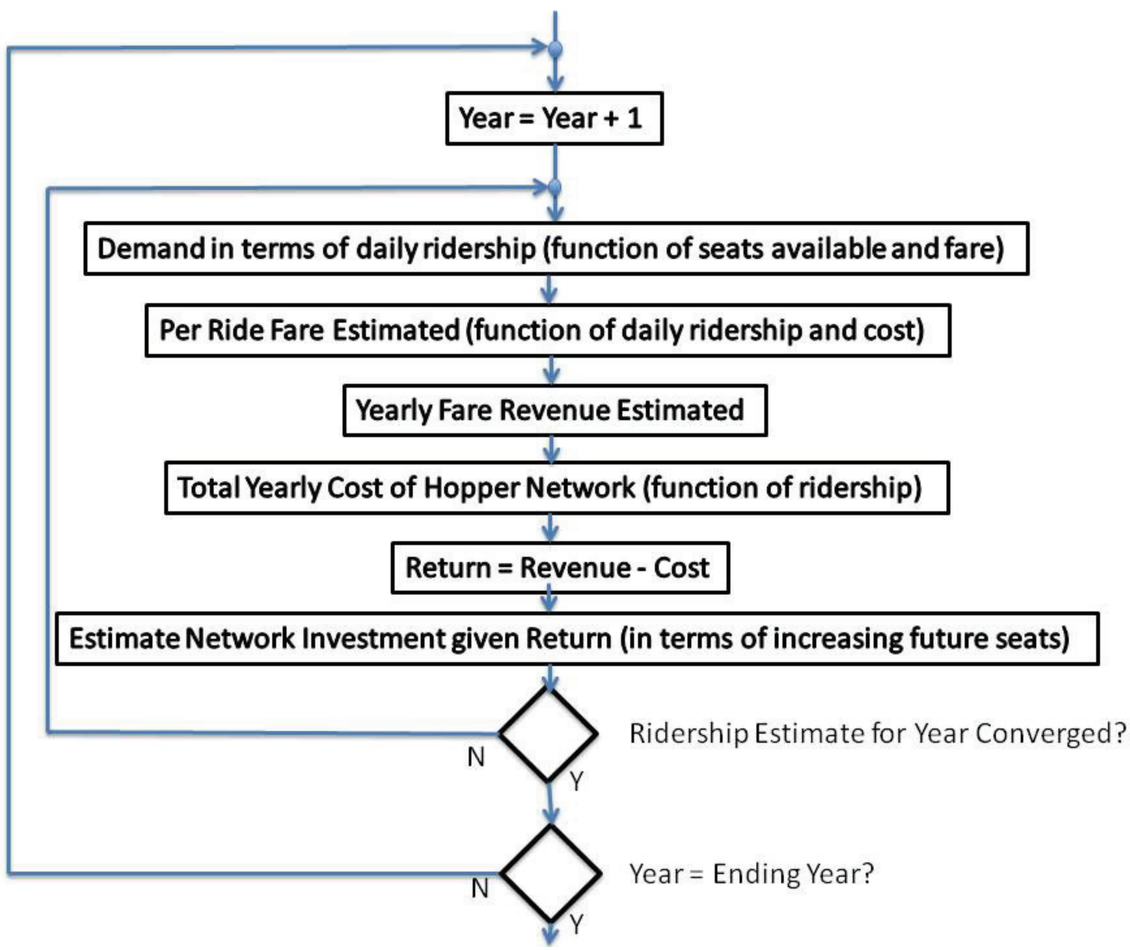


Figure C6. Forecasting model flow chart.

A simple demand model, as a function of seats available and fares, can be conjectured for the Hopper network.

Make the following foundational, ideal functional relationship assumption:

$$\begin{aligned} Ridership &= f(Profit) \\ &f(Revenue - Cost) \end{aligned} \tag{C1}$$

Equation C1 is ideal in the sense that there is no explicit subsidization of fares. A non-ideal (with fare subsidies) functional relationship would be

$$Ridership = f(Revenue + Direct\ \&\ Indirect Subsidies - Cost) \tag{C2}$$

Note, in general, that

$$Revenue = Fares + Direct\ \&\ Indirect\ Nonfare\ Income \tag{C3a}$$

An example of a direct non-fare income for a Hopper transportation network would be a Hopper subscription for transport during a set time period versus transport for a set number of trips or "hops" between vertiport stations. An example of an indirect non-fare income would be the income from co-located retail spaces at the vertiport stations. Another example of an indirect non-fare income would notionally be income generated by Hopper aircraft, in flight, acting as co-hosted cellular or wireless relay platforms in addition to their primary role as passenger carriers. A simple model for direct and indirect nonfare income is:

$$Direct\ \&\ Indirect\ Nonfare\ Income \approx a_{NFI1} a_{NFI2} \cdot Ridership \tag{C3b}$$

Where, in Eq. C3b, for the purposes of this simple analysis,

a_{NFI1} = The nonfare income per customer, in this case, $a_{NFI1} = 2 \cdot 10^{-5}$ \$M/customer.

a_{NFI2} = The fraction of riders who are customers (i.e. shops inside the vertiport station, etc.), assumed to be $a_{NFI2} = 0.25$.

Equation C4 represents a hypothetical/conjectured form of ridership dependence on profitability:

$$Ridership = \frac{a \cdot Profit^n + b}{Profit^n + 1} \tag{C4}$$

Where a, b, and n are prescribed constants, which for this preliminary analysis are: a = 30, b = 0.5, n = 0.1, and (for Eq. C5) m = 4.

If return-on-investment (ROI) is included in this conjectured ridership relationship, then the result might be

$$Ridership = \frac{a \cdot Profit^{n+m \cdot ROI} + b}{Profit^{n+m \cdot ROI} + 1} \tag{C5}$$

In general, as ROI increases, one could reasonably expect that investment would increase and, correspondingly, ridership would increase in response to infrastructure expansion as a consequence of increased investment. Figure C7 illustrates this ridership/profitability relationship.

Next follows a simple model of estimation of number of network nodes (vertiport stations) and the number of Hopper vehicles/aircraft on the basis of ridership levels (Fig. C8).

$$N = f(Ridership)$$

$$N_V = g(Ridership) \tag{C6a–b}$$

Where N is the number of nodes (vertiport stations) and N_V is the number of Hopper vehicles.

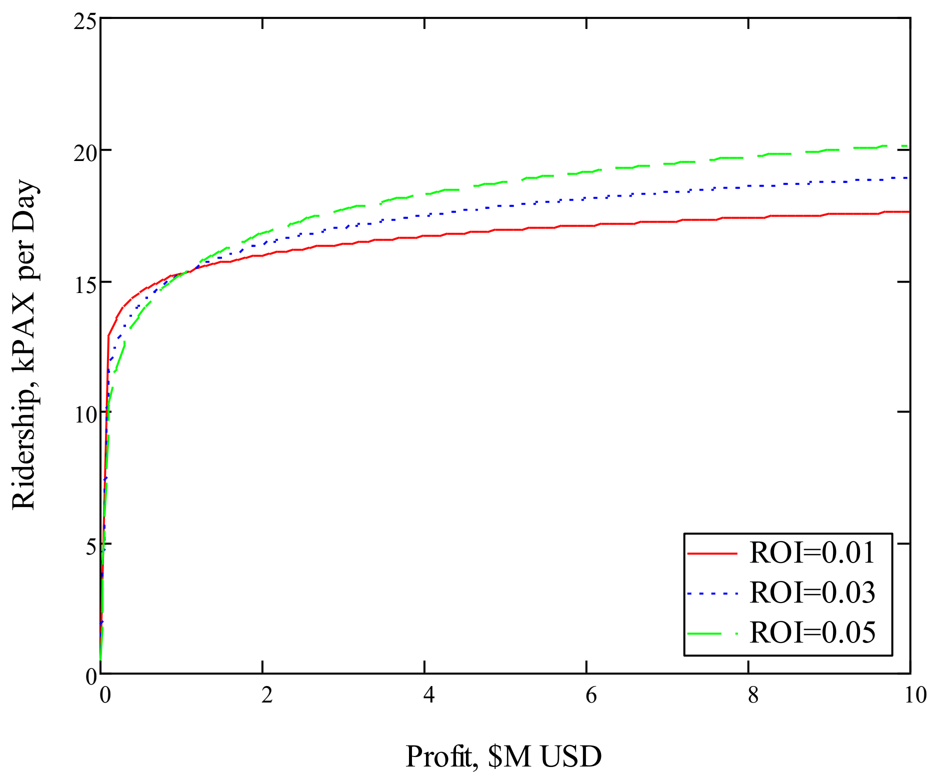


Figure C7. Hypothetical/conjectured form of ridership dependence on profitability and ROI.

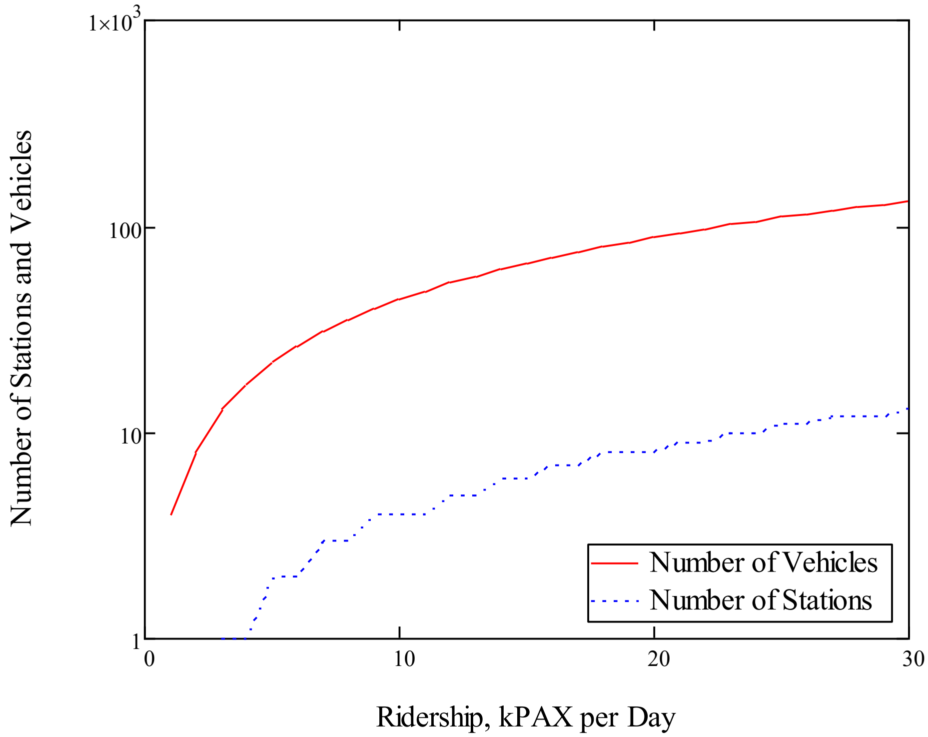


Figure C8. Number of vehicles and stations as a function of ridership.

Consistent with the preceding inferred relationships, simple models of the form below are proposed:

$$N = Int\left(\frac{N_V \Delta t_T}{N_G t_E}\right)$$

$$N_V = Int\left(\frac{N_F}{N_T}\right)$$

$$N_F = Int\left(\frac{1}{a_L} \cdot \frac{Ridership}{N_P}\right)$$

$$N_T = Int\left(\frac{t_E}{\Delta t_T}\right) \qquad \text{(C7a–d)}$$

Where

N_G = On average, maximum number of vehicles that can be supported at any given moment on the ground at a vertiport. For this analysis it is assumed that $N_G = 1$.

N_F = Number of daily flights (Fig. C9).

N_T = umber of flights (or turnarounds) per day for a given, individual vehicle.

And where the constants are defined as:

a_L = Average passenger load factor for Hopper fleet (fraction < 1). For this analysis it is assumed that $a_L = 0.75$.

N_P = Average passenger (maximum) capacity for a Hopper vehicle in the fleet. For this analysis it is assumed that $N_P = 30$.

Δt_T = Average turnaround time between flights for a given individual vehicle. For this analysis it is assumed that $\Delta t_T = 0.5\, hrs$.

t_E = "Effective" commute time period (time period in which 80 percent of passengers travel in a given day; $t_E < 24\, hrs$). For this analysis it is assumed that $t_E = 5\, hrs$.

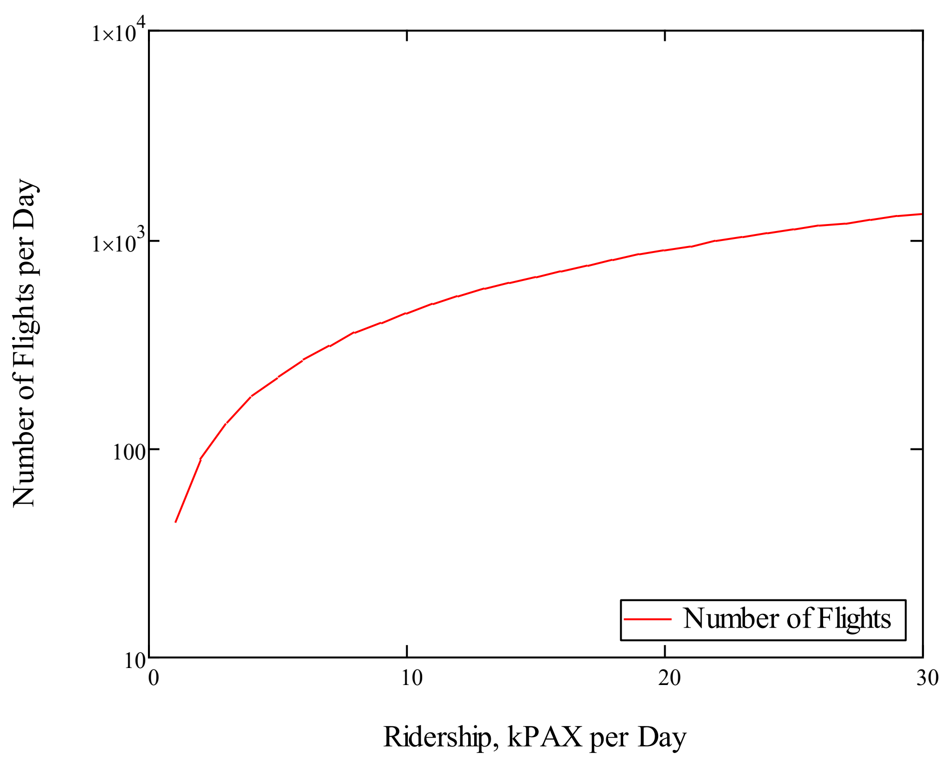


Figure C9. Number of flights per day as a function of ridership.

In this simplest forecast model, the fares, F, are estimated on the basis of ridership-per-annum levels as

$$F = h(Ridership) \tag{C8}$$

A fare estimation model is correspondingly proposed in which the fares are defined in terms of daily ridership and Hopper network total costs distributed daily.

$$Fares = F_1 + (F_0 - F_1)exp(-\alpha \cdot Ridership) \tag{C9}$$

Where

F_0 = Initial fare cost for a small number of riders; let F_0 = \$150 (representative of current tourism helicopter fares).

F_1 = Final fare cost for large daily ridership levels; let F_1 = \$10 (representative of current mass transit fares).

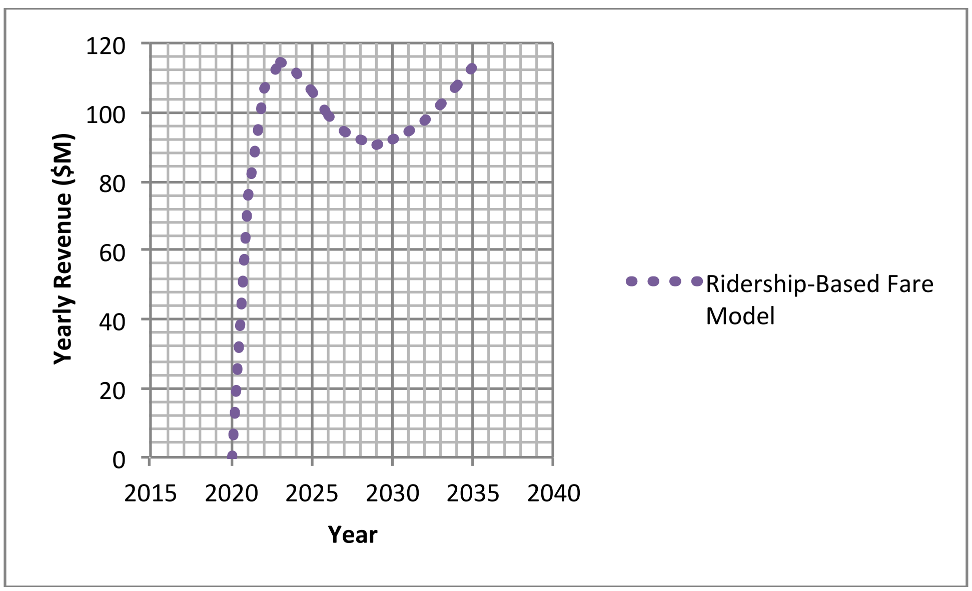


Figure C10. Alternate projected yearly revenue on basis of ridership-based fare model (Eq. C9 with α = 0.0002 and ridership consistent with linear trend from Fig. C2 for target ridership of 30,000 by circa 2035).

The following is an attempt to develop a cost model consistent with—and iteratively exercised in conjunction with—the simple ridership/fare model outlined previously (Fig. C10).

$$Cost \equiv C = C_{Stations} + C_{Vehicles} + C_{Personnel} + C_{Consumables} + C_{Taxes/Fees} + C_{DebtService}$$

$$C_{Stations} = a_{CS} N$$

$$C_{Vehicles} = a_{CV} N_V$$

$$C_{Personnel} = a_{CP1} N + a_{CP2} N_V$$

$$C_{Consumables} = a_{CC1} N + a_{CC2} N_F$$

$$C_{Taxes/Fees} = a_{CTF1} N + a_{CTF2} N_V + a_{CTF3} Profit$$

$$C_{DebtService} = 12 \sum_i Debt_i \left\{ \frac{r_i (1 + r_i)^{n_{Pi}}}{(1 + r_i)^{n_{Pi}} - 1} \right\} \rightarrow 12 Debt \left\{ \frac{r (1 + r)^{n_p}}{(1 + r)^{n_p} - 1} \right\} \rightarrow a_{DS} Debt \qquad \text{(C10a–g)}$$

Where the constants are defined as:

a_{CS} = Average yearly cost to acquire/maintain a single vertiport station. For this analysis it is assumed that $a_{CS} = \$10M / station$.

a_{CV} = Average yearly cost to acquire/maintain a single vehicle. For this analysis it is assumed that $a_{CSV} = \$1M / vehicle$.

a_{CP1}, a_{CP2} = Average yearly personnel cost (both supporting stations and/or vehicles). For this analysis it is assumed that $a_{CP1} = \$0.5M / station$ and $a_{CP2} = \$0.05M / vehicle$.

n_p = Total number of debt servicing payments. For this analysis it is assumed that $n_p = 10 \cdot 12 = 120$.

r = Percent interest rate per month of debt servicing. For this analysis it is assumed that $r = 0.05/12$.

a_{DS} = Effective constant coefficient to estimate net debt servicing monthly payments for a cumulative (and sometimes consolidated) debt spread over several years and several loans or bond issues. For this analysis it is assumed that $a_{DS} = 0.13$.

And where C is the cost (direct and indirect) of the total transportation system per annum. Note that all of these cost contributions can be affected by the employment of advanced technologies. For example, advanced battery technology could result in improved battery charge/discharge life, which, in turn, could significantly reduce the cost of consumables to support the Hopper transportation system. Another example of how advanced technology might positively affect costs is the introduction and wide adoption of advanced autonomous systems technologies for not only direct control of the Hopper vehicles, but also the overall support and maintenance of vehicles (including battery charging/swap-outs between flights, ground taxing, unloading and loading of passengers, etc.). A good initial cost estimating resource for rotary-wing vehicle acquisition costs is provided in reference 90. An initial analytical framework for examining in more detail, from a systems analysis perspective, the impact of advanced technology on Hopper transportation system costs is defined latter in this appendix.

A cumulative debt and loss model—employed to define the cost of debt servicing payments—is defined by the expressions

$$Loss = \sum (Cost - Revenue) \cdot u(Cost - Revenue) \tag{C11}$$

$$Debt = Loss + Obligations \tag{C12}$$

Note that $u(x)$ is the unit step function—where $u(x)=1$ when $x \geq 0$ and $u(x)=0$ when $x<0$—in Eq. C11. Given the above, then the cost of debt servicing can be assumed to be some direct function of current cumulative debt (i.e. Eq. C12). Obligations in the above expressions constitute outstanding loans and bonds.

The following expressions are a simplistic model for estimating future investments into the Hopper network given the past return on previous investments, relative to debt.

$$Return = Profit = Revenue - Cost$$

$$N_{i+1} = N_i + f(Return, Debt)$$

$$N_{V_{i+1}} = N_{V_i} + g(Return, Debt)$$

Where, in the above, the indices "i" represents the "current" i'th year of network operation and i+1 represents the following year's projection of investment in stations and vehicles. For simplicity, the following is employed in the modeling

$$N_{i+1} = N_i + if\left(\frac{Return}{Debt} > a, I, 0\right)$$

$$N_{V_{i+1}} = N_{V_i} + if\left(\frac{Return}{Debt} > b, J, 0\right) \tag{C13a–e}$$

Where the constants are defined as:

$$a = 0.001$$

$$b = 0.001$$

$$I = 1$$

$$J = 10$$

Equation C13 assumes that an incremental number of “I” vertiport stations and “J” vehicles can be built or acquired in 1 year in response to the previous years’ financial return.

This simple cost model, used in conjunction with Eqs. C1 through C13, completes this simple Hopper forecast model. More detailed and rigorous forecast models could be derived. One approach to developing an improved forecast model is to take the derived ridership information from the independent BaySim simulations of various node networks (evolving from small to larger) and the aircraft flight rates to support those networks and ridership levels. This more detailed modeling will be left to future work.

Future Work Related to IMPLEMENT

Future work related to IMPLEMENT will focus on improving the simple models incorporated in the current version of the analysis, as well as extending the analysis to account for the notional influence of technology advances on the economics of the Hopper network. In particular, technology factors (also known as tech factors) will be included in the analysis to assess whether the incorporation of certain new technologies or the advancement/improvement of current technologies can lead to substantial improvement in the overall economics of the transportation network.

For example, the influence of greater automation and autonomous system technology into the Hopper network can be modeled in a first-order sense by modifying Eq. C10d used to estimate the cost of personnel, $C_{Personnel}$, to support the Hopper network. The key feature of this equation modification/extension is to multiply the original expression, Eq. C10d, with a “tech factor” parameter that can be based off of a level-of-autonomy (LOA) scale (defined solely for the purpose of this IMPLEMENT advanced tech factor discussion) defined in Table C1. Note that the LOA scale in Table C1 is the same as that used in Table 8 in the main body of this report; Table 8, though, used only a qualitative narrative description/definition of the LOA scale and did not attempt to anchor the scale in terms of number of flights per individual personnel/staff member employed operating/enabling the Hopper network.

Table C1. Proposed Hopper Automation and Autonomous System Technology
"Tech Factor" Rating Scale

Hopper Level of Autonomy (LOA)	Autonomy Description (Flights Per Personnel)	Personnel Tech Factor
0	0.1	1
1	0.5	0.5
2	1	0.33
3	5	0.25
4	10	0.2
5	100	0.17

$$C_{Personnel} = \chi_{Personnel}\left(a_{CP1}N + a_{CP2}N_V\right) \tag{C14a}$$

Where, in the above equation, a simple model is used for the technology factor, $\chi_{Personnel}$:

$$\chi_{Personnel} = \frac{1}{1+LOA} \tag{C14b}$$

As another example, the influence of improvements in battery and/or other elements of all- or hybrid-electric propulsion can be modeled in a first-order sense as well by modifying Eq. C10e used to estimate the cost of consumables, $C_{Consumables}$, to support the Hopper network. The key feature of this equation modification/extension is again to multiply the original expression, this time Eq. C10e, with another "tech factor" parameter that is based off of a second rating scale (again defined solely for the purposes of this study) defined in Table C2. As shown in this simple model, the cost of consumables is assumed to be dominated by the acquisition and replacement costs of battery/electric-energy sources for the Hopper fleet. As in general with other aviation assets, it is further assumed that the battery/electric-energy-source costs are proportional with the mass/weight of the component. Accordingly, the proposed tech factor for Hopper cost of consumables is driven by the specific energy of the battery/electric-energy source relative to that of a conventional hydrocarbon-fuel-based propulsion system.

$$C_{Consumables} = \chi_{Consumables}\left(a_{CC1}N + a_{CC2}N_F\right)$$

Where

$$\chi_{Consumables} = \frac{1}{100}\left(\frac{Specific\ Energy\ of\ Hydrocarbon\ System}{Specific\ Energy\ of\ Electric\ System}\right) \tag{C15a–b}$$

Table C2. Proposed Hopper Electric-Propulsion "Tech Factor" Rating Scale

Ratio of Specific Energy of All- or Hybrid-Electric Propulsion System Relative to All-Hydrocarbon Fuel System	Electric-Propulsion System Technology Factor
0.01	1.00
0.05	0.20
0.1	0.10
0.5	0.02
1	0.01

Future work will build on this methodology to extend the simplified models presented herein to include the effects of other technologies on the economics of the Hopper network. Future work includes assessing the influence of: advanced safety measures, high-strength and infinite-life structures, and health and usage monitoring system (HUMS) technologies on the cost of taxes and fees (including insurance fees), $C_{Taxes/Fees}$; noise reduction technologies affecting the cost of vehicles (likely to increase with adoption of noise reduction technologies) and vertiport stations (likely to decrease because of easier zoning and issuing of other permits) and ridership (likely to increase at a faster rate because of greater community acceptance); advanced air traffic management technologies affecting the cost of vehicles and vertiport stations (likely to increase with adoption of advanced ATM technologies) and ridership (likely to increase at a faster rate and overall greater final magnitude because of passenger, community, and commercial/ generation aviation acceptance). The tech factor methodology employed to assess these additional technology influences on Hopper network economics is assumed to be generally the same approach as that outlined for automation/autonomy and electric-propulsion adoption and overall advances. Future work with respect to the influence of advanced technology on Hopper system costs and overall utility can also begin to incorporate system analysis methodologies outlined in references 19, 86, and 91.

Appendix D—BaySim Simulation Analysis

BaySim is a discrete element simulation with individual passenger and flight vehicle software agents. It is a fast-time simulation of surface and air travel for metropolitan commuting. It models passenger transition through 12+ daily states during commutes from home-to-work-back-to-home. There are heuristic rules and Gaussian inputs for queuing up for flights and other Hopper network operation tasks. BaySim creates estimates of demand for Hopper flights and provides subsequent inputs for fleet assignment and optimization using third-party software tools. BaySim models the ridership/passenger populations as shown in Table D1.

Significant Phase II BaySim upgrades include: Bay Area populations from census/zip codes; network expansion and Dijkstra path algorithm; ATM integration via (Appendix E) vehicle time-of-day flight trajectory look-up tables (aka "speed tables"); and new tools for population creation and network visualization.

BaySim ridership population improvements were developed over the course of the Phase II effort. Extensive use of census and zip code databases were used to develop this improved ridership population model. Zip codes provide appropriate geographic granularity for the Hopper network problem. Zip and census data are readily available via websites. Commute and business employment demographics are included in 2010 census data. Populations within zip codes were created via iterative process according to several constraints: homesite network node equal to worksite network node; estimated flying time less than estimated driving time; number of workers at jobsite scaled and limited using local zip code employment statistics; and residents and worksites within user-specified distance from station nodes.

Table D1. Ridership Population Used for BaySim Modeling

• How many daily passengers?		
– Tech industry employs 386K workers in Bay Area		
– Caltrain serves roughly 42K passengers per day		
– BART serves roughly 370K passengers per day		
• Population sizes: 5K, 10K, 15K, 20K, 25K, 30K		
• PAX Distribution	Starting Times	Workday Length
– 65% Day	4 to 10 AM	7 to 9 hours
– 20% Swing	1 to 6 PM	7 to 9 hours
– 5% Graveyard	9 to 2 AM	7 to 9 hours
– 10% Other	8 AM to 3 PM	4 to 5 hours

Figure D1 shows the population density of 483 zip codes in the greater Bay Area, extracted using: latitude_min = 36.0; latitude_max = 39.0; longitude_min = –124.0; longitude_max = –121.0. The figure is colored by the square root of the population density using the 25- to 64-year-old range for potential commuters (total of 5,920,170 potential riders). White rectangles indicate previous Hopper station locations. Graphics created in Javascript/HTML5.

Figures D2 and D3 illustrate some the demographic data assessment with respect to likely Hopper commuter residences and worksites, and their relative location with respect to the notional vertiport stations. This improved demographic data and associated analysis represents a major improvement in BaySim modeling for Phase II versus Phase I of this study.

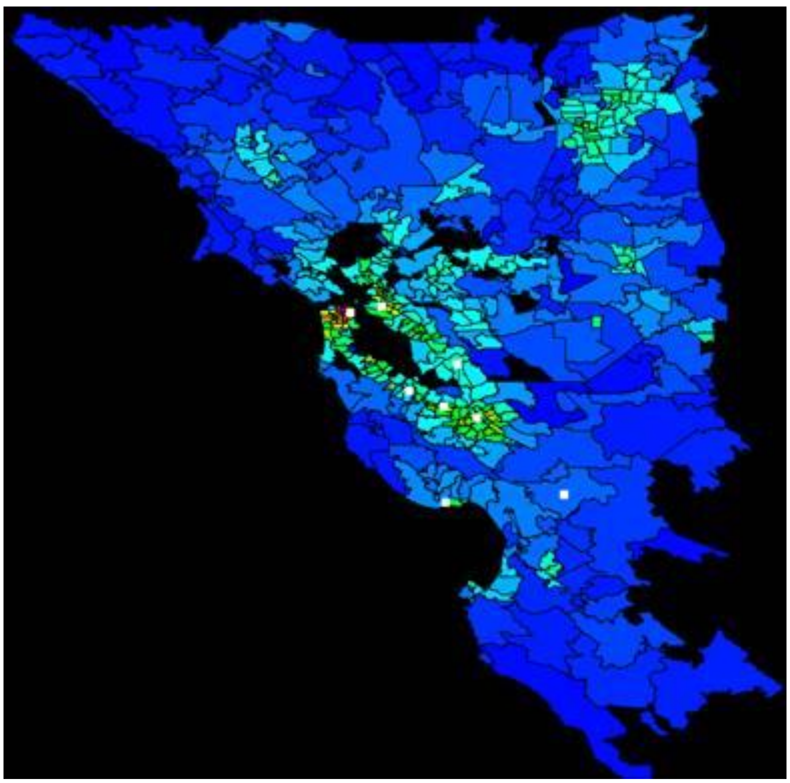


Figure D1. Bay Area, and surroundings, population distribution (organized around postal codes).

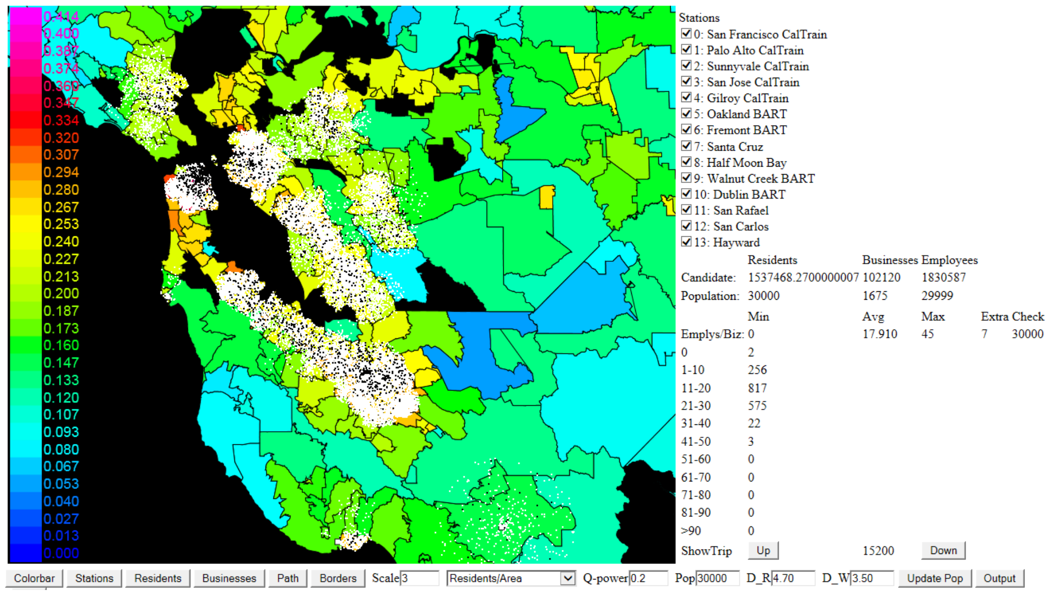


Figure D2. Demographic data assessment—likely Hopper commuter residences and worksite locations.

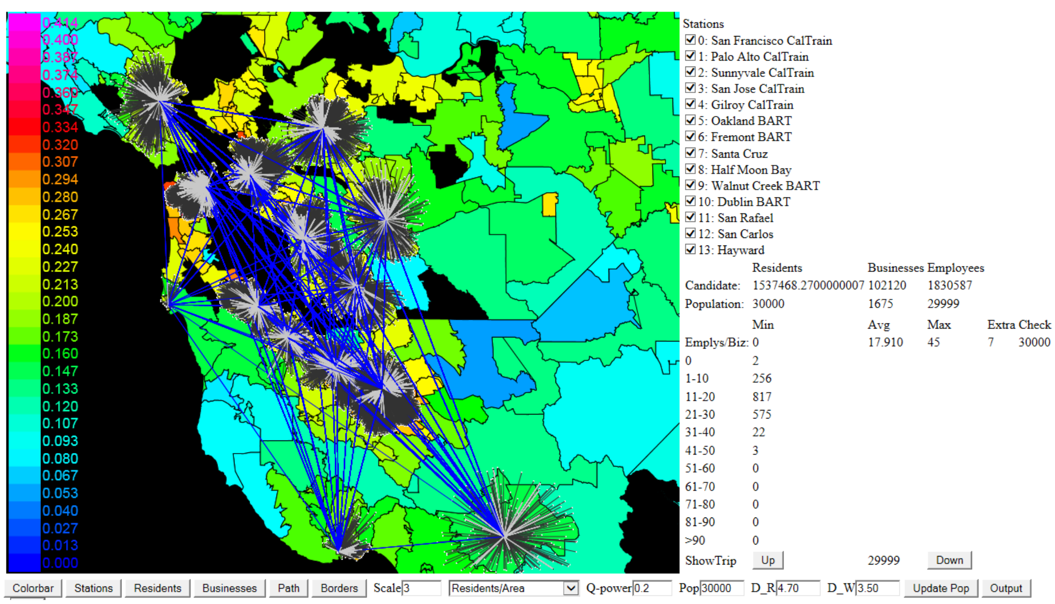


Figure D3. Demographic data assessment—relative location of residences and worksites with respect to notional vertiport stations.

As noted earlier, the Phase II version of BaySim also incorporated the Dijkstra algorithm and "speed tables" derived from air traffic analysis (of conventional fixed-wing aircraft) of the Bay Area. Each passenger chooses flights attempting to minimize transit time between home and work (including estimates of queue times); Dijkstra leg weights (transit times) updated immediately after each flight arrival, and best route made available to each passenger before queuing; and leg transit times from hourly table look-up are based on routes that minimize traffic conflicts with current SJC, SFO, and OAK patterns. Figure D4 provides a high-level summary of the BaySim operational assessments of the Hopper fleet.

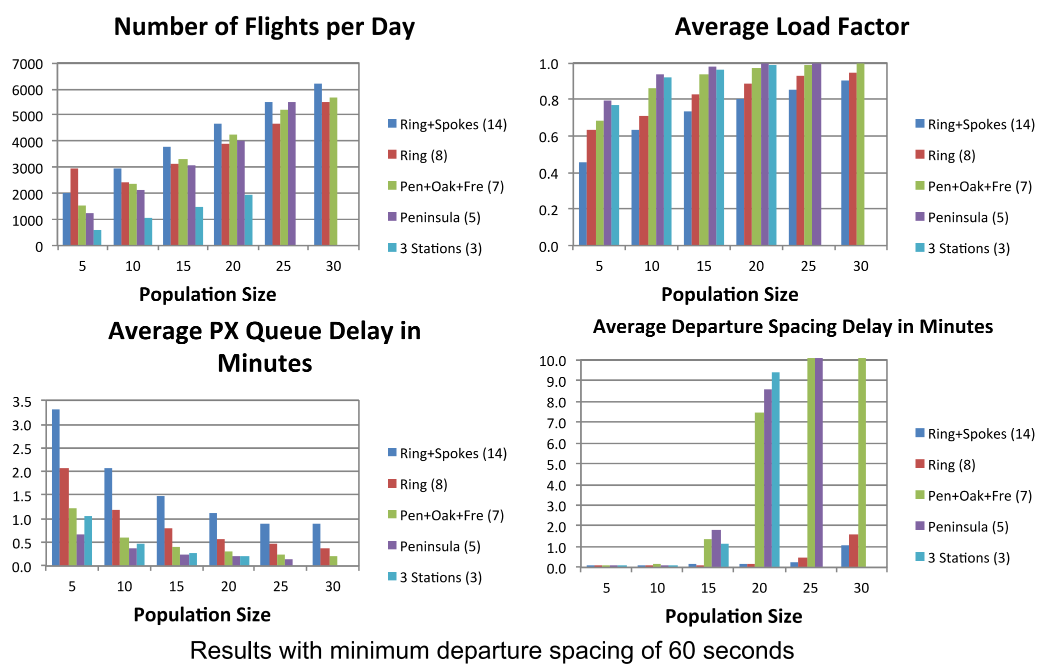


Figure D4. Operational assessments of Hopper fleet.

Comments on Vehicle and System Energy Requirements

Given vehicle performance metrics from the vehicle sizing tools employed in this study, BaySim was modified to estimate total energy use for different electric-propulsion options, various assumed ridership levels, and different network configurations. Figures D5 and D6 show the estimated energy expenditures in British Thermal Units (BTU's) per passenger-mile for the gas-turboshaft-engine vehicles and battery-powered vehicles, respectively.

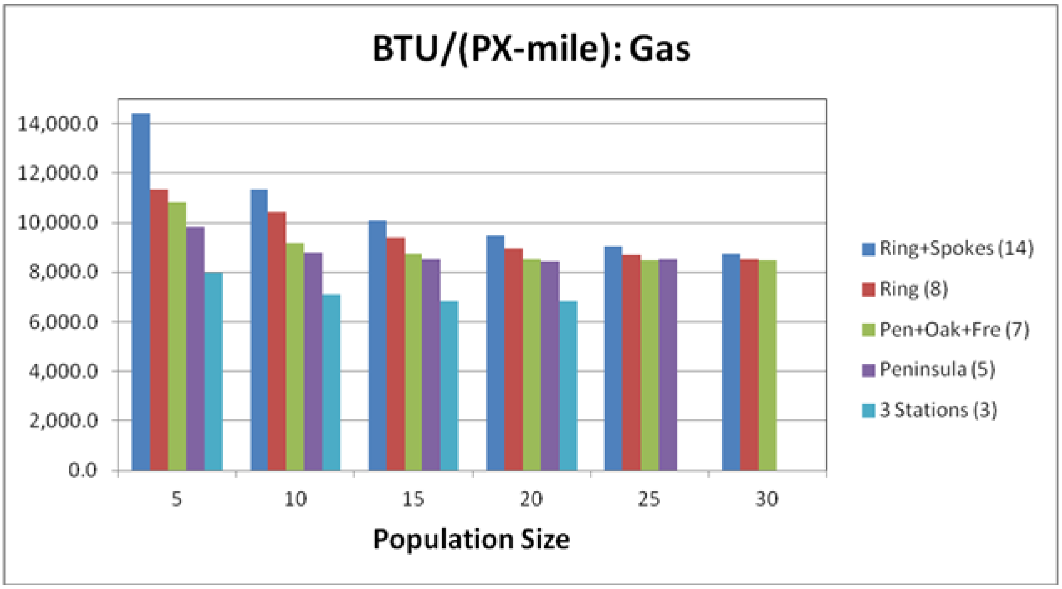


Figure D5. Estimated BTU's per passenger-mile for the gas-turboshaft-engine vehicles.

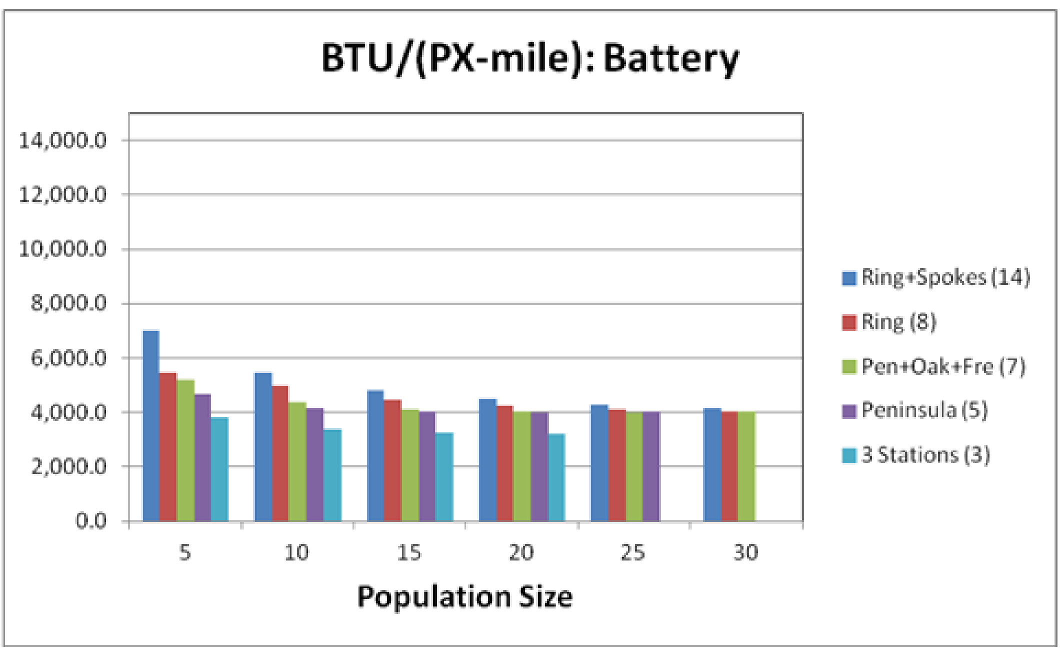
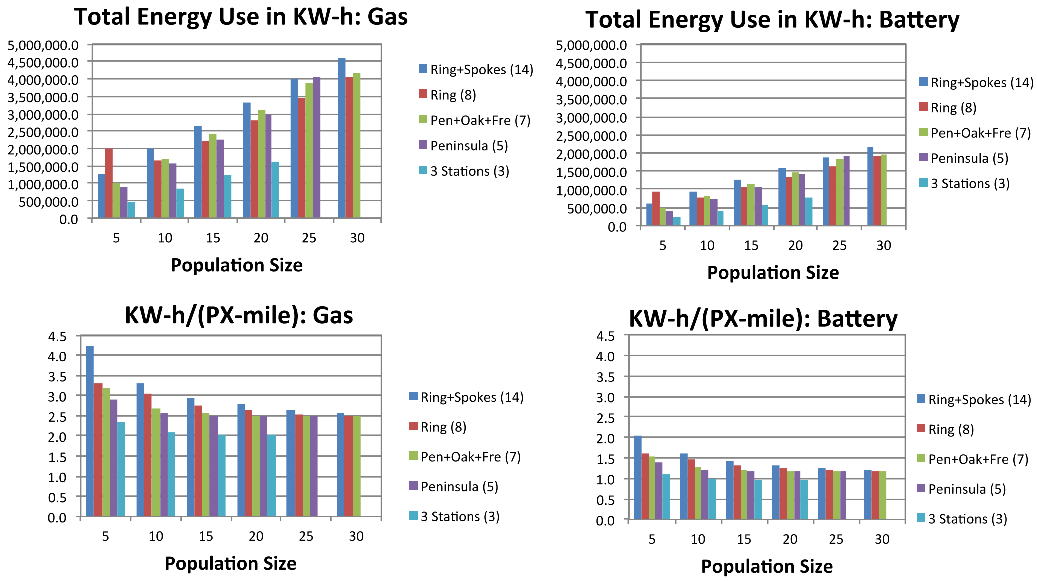


Figure D6. Estimated BTU's per passenger-mile for battery-powered vehicles.



Results with minimum departure spacing of 60 seconds

Figure D7. Energy expenditure estimates for Hopper fleet operations.

Figure D7 provides an alternate perspective of these first-order energy expenditure estimates in kilowatt-hours and kilowatt-hours per passenger mile. As anticipated, total energy expenditure for Hopper operations linearly scales with assumed ridership level. The large difference in relative energy expenditure between gas-turboshaft-engine vehicles and battery-powered vehicles is due to the significantly better energy conversion efficiency of batteries over that of fossil-fuel-based systems.

Comments on Network Operation Counts

BaySim simulation results were assessed from the perspective of network operation "counts" for various assumed ridership levels and network topologies. Given these BaySim results, refinement of the Hopper/commercial aviation airspace management challenges in terms of ATM workload, required system automation, controller workload, etc., could begin to be evaluated.

Figures D8 and D9 summarize the estimated daily flight departures by station for various network configurations and assumed ridership levels. The departures from the outlying "spoke" (Gilroy, Santa Cruz, Half Moon Bay, etc.) stations are relatively low; note that in the BaySim simulations no attempt has been made to project the future population growth of these outlying communities (Fig. D10).

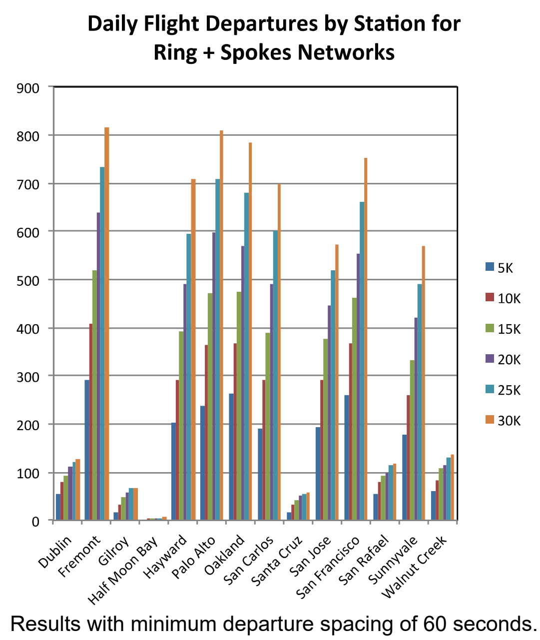


Figure D8. Daily station departures (ring + spokes network).

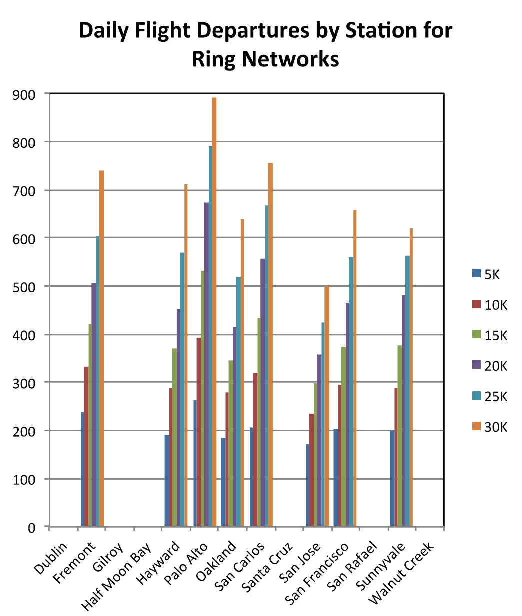


Figure D9. Daily station departures (ring network).

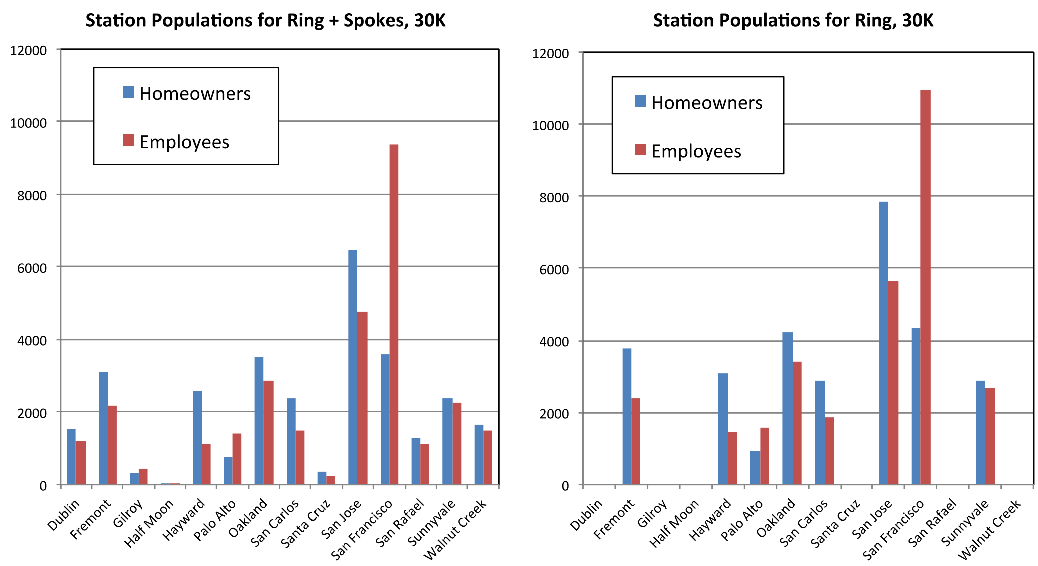


Figure D10. Station populations.

Comparisons With Autos, Rail, and Bus

From an energy expenditure perspective, given Figures D5 and D6, Hopper metro-regional aerial transportation operations are comparatively energy intensive; refer, for example, to counterpoint examples of energy expenditures for other modes of mass transportation from reference 92. Reference 92 cites a low energy expenditure per passenger mile of a motor coach as being ~800 BTU/PAX-mile. Correspondingly, reference 92 also suggests the energy expenditure of commuter rail as being ~1600 BTU/PAX-mile, domestic air travel as being ~3100 BTU/PAX-mile, transit buses as being ~4200 BTU/PAX-mile, and a car with one person as being ~5000 BTU/PAX-mile.

Potential Future Extensions of BaySim

To be applicable to future studies, a DES tool such as BaySim requires routine updates to the demographic input information. Additional granularity (down to the city block level) is entirely possible, and while the current version of BaySim runs in a serial manner, there are many calculations within BaySim that could be easily parallelized for reduced simulation turnaround time.

Daily Operations Counts per Leg of Network

Figures D11–D20 and Tables D2–D6 summarize daily operations counts for each leg of each network. This simulation results dataset from BaySim could be used in future work to refine evaluation of an evolutionary approach to the notional implementation of a Hopper network in that station development and network evolution could be prioritized/weighted on the basis of these preliminary daily operations count data.

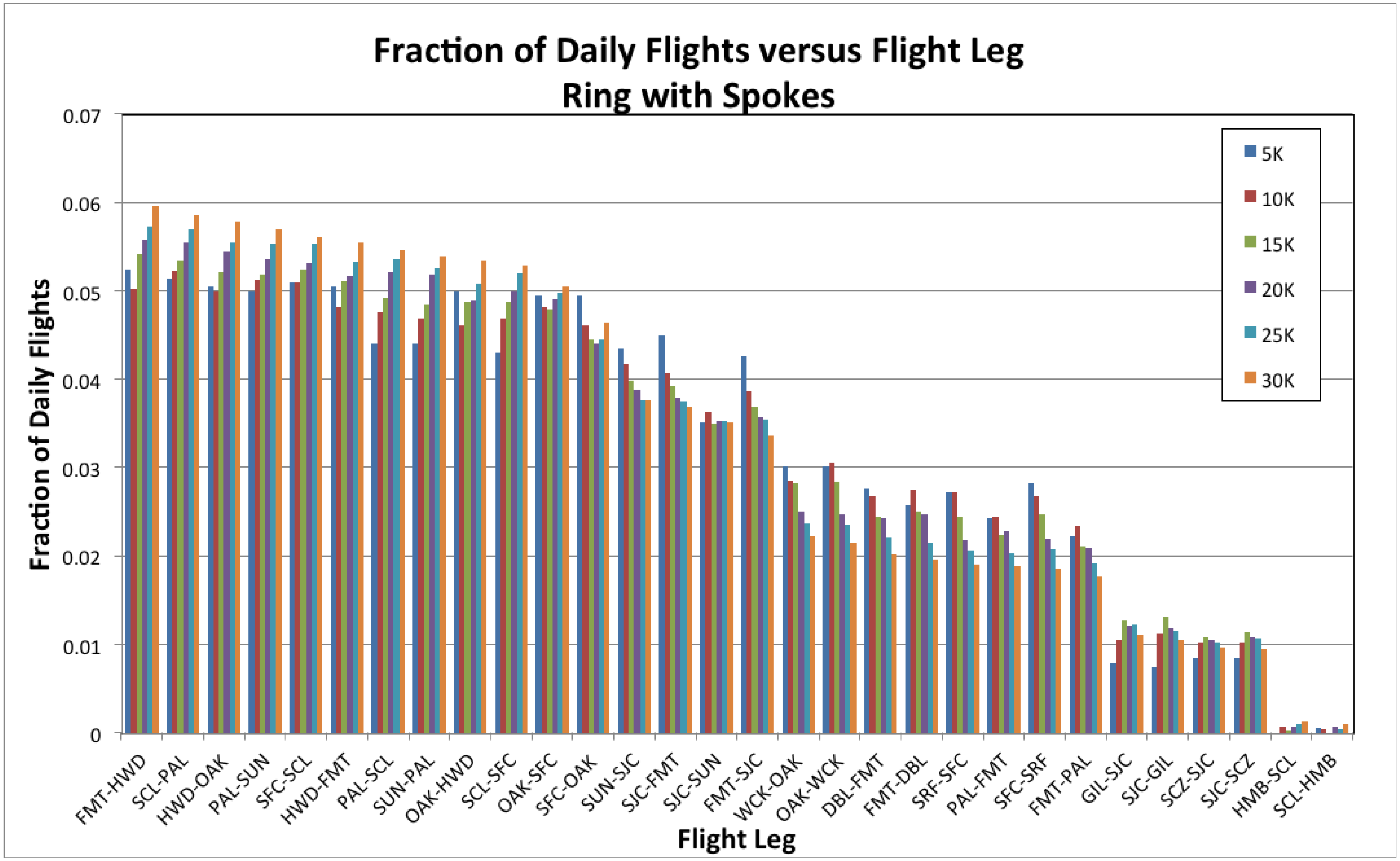


Figure D11. Fraction of daily flights vs. flight leg (ring with spokes).

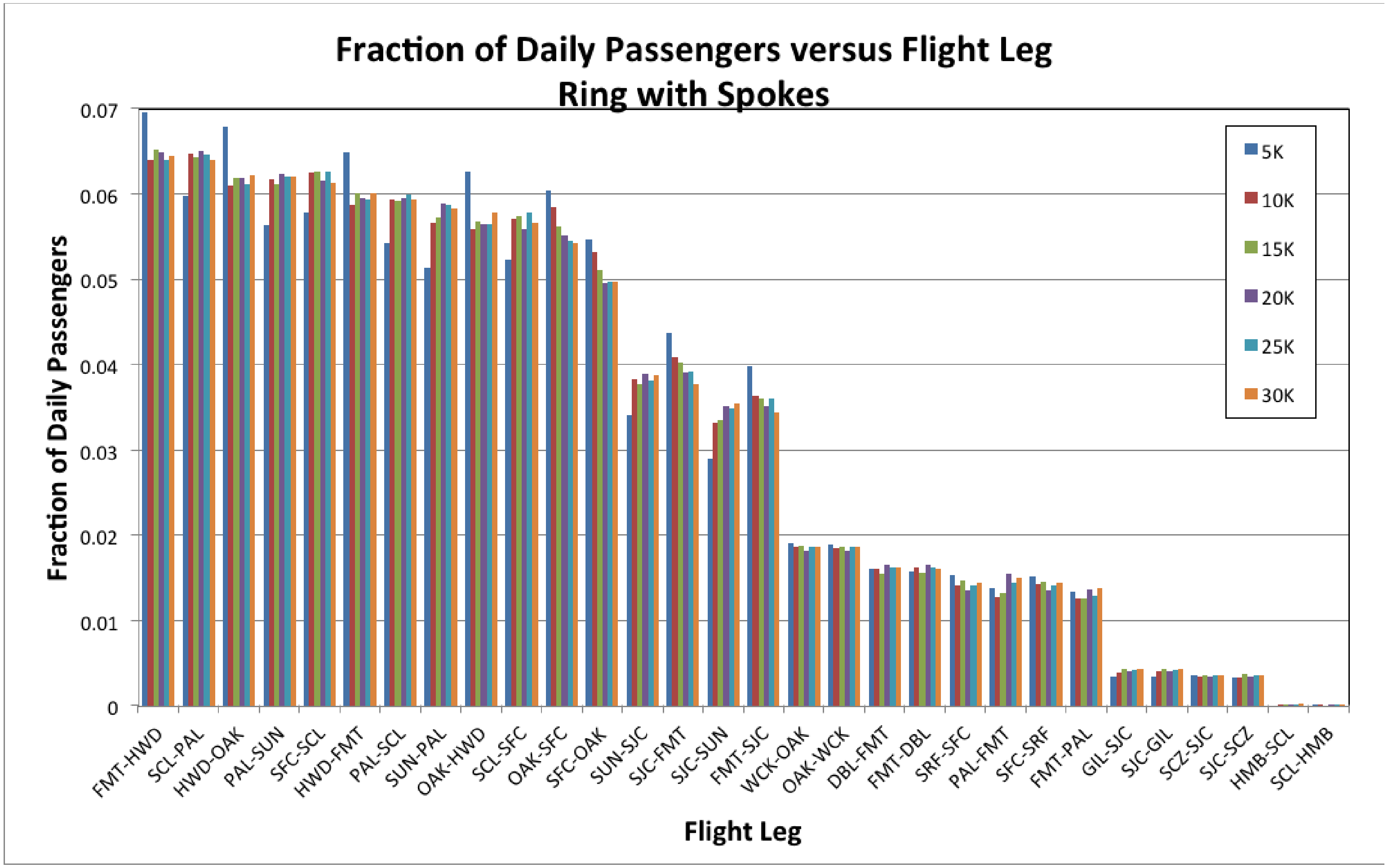


Figure D12. Fraction of daily passengers vs. flight leg (ring with spokes).

In the following table, the numeric data for each leg is formatted as X/Y, where X is fraction of daily flights and Y is the fraction of daily passengers.

Table D2. Operations Count for Ring-With-Spokes Network

	Ring with Spokes					
Population Size	**5K**	**10K**	**15K**	**20K**	**25K**	**30K**
Daily Flights	2022	2947	3800	4648	5480	6229
Daily PX	27702	55739	84079	112458	140643	168608
F/P:FMT-HWD	0.05242 / 0.06953	0.05022 / 0.06394	0.05421 / 0.06518	0.05572 / 0.06486	0.05730 / 0.06395	0.05956 / 0.06439
F/P:SCL-PAL	0.05143 / 0.05978	0.05226 / 0.06471	0.05342 / 0.06423	0.05551 / 0.06503	0.05693 / 0.06457	0.05860 / 0.06398
F/P:HWD-OAK	0.05045 / 0.06783	0.04988 / 0.06103	0.05211 / 0.06188	0.05443 / 0.06193	0.05547 / 0.06121	0.05779 / 0.06221
F/P:PAL-SUN	0.04995 / 0.05639	0.05124 / 0.06172	0.05184 / 0.06109	0.05357 / 0.06232	0.05529 / 0.06210	0.05699 / 0.06198
F/P:SFC-SCL	0.05094 / 0.05790	0.05090 / 0.06249	0.05237 / 0.06260	0.05314 / 0.06163	0.05529 / 0.06261	0.05603 / 0.06130
F/P:HWD-FMT	0.05045 / 0.06494	0.04818 / 0.05879	0.05105 / 0.06009	0.05164 / 0.05945	0.05328 / 0.05938	0.05555 / 0.06003
F/P:PAL-SCL	0.04402 / 0.05426	0.04751 / 0.05935	0.04921 / 0.05912	0.05207 / 0.05954	0.05365 / 0.05992	0.05458 / 0.05929
F/P:SUN-PAL	0.04402 / 0.05137	0.04683 / 0.05659	0.04842 / 0.05729	0.05185 / 0.05895	0.05255 / 0.05874	0.05394 / 0.05835
F/P:OAK-HWD	0.04995 / 0.06270	0.04615 / 0.05590	0.04868 / 0.05672	0.04884 / 0.05643	0.05073 / 0.05643	0.05346 / 0.05787
F/P:SCL-SFC	0.04303 / 0.05223	0.04683 / 0.05712	0.04868 / 0.05737	0.04991 / 0.05591	0.05201 / 0.05790	0.05282 / 0.05663
F/P:OAK-SFC	0.04946 / 0.06032	0.04818 / 0.05847	0.04789 / 0.05624	0.04905 / 0.05519	0.04982 / 0.05450	0.05057 / 0.05429
F/P:SFC-OAK	0.04946 / 0.05462	0.04615 / 0.05314	0.04447 / 0.05104	0.04410 / 0.04964	0.04453 / 0.04969	0.04640 / 0.04970
F/P:SUN-SJC	0.04352 / 0.03415	0.04174 / 0.03830	0.03974 / 0.03766	0.03873 / 0.03895	0.03759 / 0.03818	0.03757 / 0.03881
F/P:SJC-FMT	0.04500 / 0.04368	0.04072 / 0.04087	0.03921 / 0.04032	0.03787 / 0.03903	0.03741 / 0.03925	0.03692 / 0.03774
F/P:SJC-SUN	0.03511 / 0.02895	0.03631 / 0.03319	0.03500 / 0.03355	0.03528 / 0.03508	0.03522 / 0.03483	0.03516 / 0.03547
F/P:FMT-SJC	0.04253 / 0.03982	0.03868 / 0.03638	0.03684 / 0.03611	0.03571 / 0.03516	0.03540 / 0.03600	0.03371 / 0.03432
F/P:WCK-OAK	0.03017 / 0.01913	0.02850 / 0.01866	0.02816 / 0.01870	0.02496 / 0.01818	0.02372 / 0.01855	0.02215 / 0.01864
F/P:OAK-WCK	0.03017 / 0.01888	0.03054 / 0.01851	0.02842 / 0.01861	0.02474 / 0.01815	0.02354 / 0.01857	0.02151 / 0.01866
F/P:DBL-FMT	0.02770 / 0.01603	0.02681 / 0.01602	0.02447 / 0.01552	0.02431 / 0.01658	0.02208 / 0.01628	0.02023 / 0.01615
F/P:FMT-DBL	0.02572 / 0.01581	0.02749 / 0.01620	0.02500 / 0.01554	0.02474 / 0.01657	0.02153 / 0.01615	0.01959 / 0.01606
F/P:SRF-SFC	0.02720 / 0.01534	0.02715 / 0.01417	0.02447 / 0.01465	0.02173 / 0.01358	0.02062 / 0.01411	0.01894 / 0.01438
F/P:PAL-FMT	0.02423 / 0.01386	0.02443 / 0.01274	0.02237 / 0.01323	0.02281 / 0.01549	0.02026 / 0.01434	0.01878 / 0.01504
F/P:SFC-SRF	0.02819 / 0.01523	0.02681 / 0.01428	0.02474 / 0.01459	0.02194 / 0.01352	0.02080 / 0.01409	0.01862 / 0.01447

Table D2. Operations Count for Ring-With-Spokes Network (cont.)

F/P:FMT-PAL	0.02226 / 0.01343	0.02341 / 0.01258	0.02105 / 0.01256	0.02087 / 0.01372	0.01916 / 0.01294	0.01766 / 0.01385
F/P:GIL-SJC	0.00791 / 0.00350	0.01052 / 0.00389	0.01263 / 0.00436	0.01205 / 0.00406	0.01223 / 0.00419	0.01108 / 0.00441
F/P:SJC-GIL	0.00742 / 0.00339	0.01120 / 0.00400	0.01316 / 0.00440	0.01183 / 0.00407	0.01150 / 0.00420	0.01044 / 0.00437
F/P:SCZ-SJC	0.00841 / 0.00354	0.01018 / 0.00339	0.01079 / 0.00359	0.01054 / 0.00337	0.01022 / 0.00354	0.00963 / 0.00360
F/P:SJC-SCZ	0.00841 / 0.00325	0.01018 / 0.00334	0.01132 / 0.00370	0.01076 / 0.00338	0.01058 / 0.00354	0.00947 / 0.00355
F/P:HMB-SCL	0.00000 / 0.00000	0.00068 / 0.00014	0.00026 / 0.00006	0.00065 / 0.00012	0.00091 / 0.00018	0.00128 / 0.00026
F/P:SCL-HMB	0.00049 / 0.00014	0.00034 / 0.00007	0.00000 / 0.00000	0.00065 / 0.00012	0.00036 / 0.00006	0.00096 / 0.00020

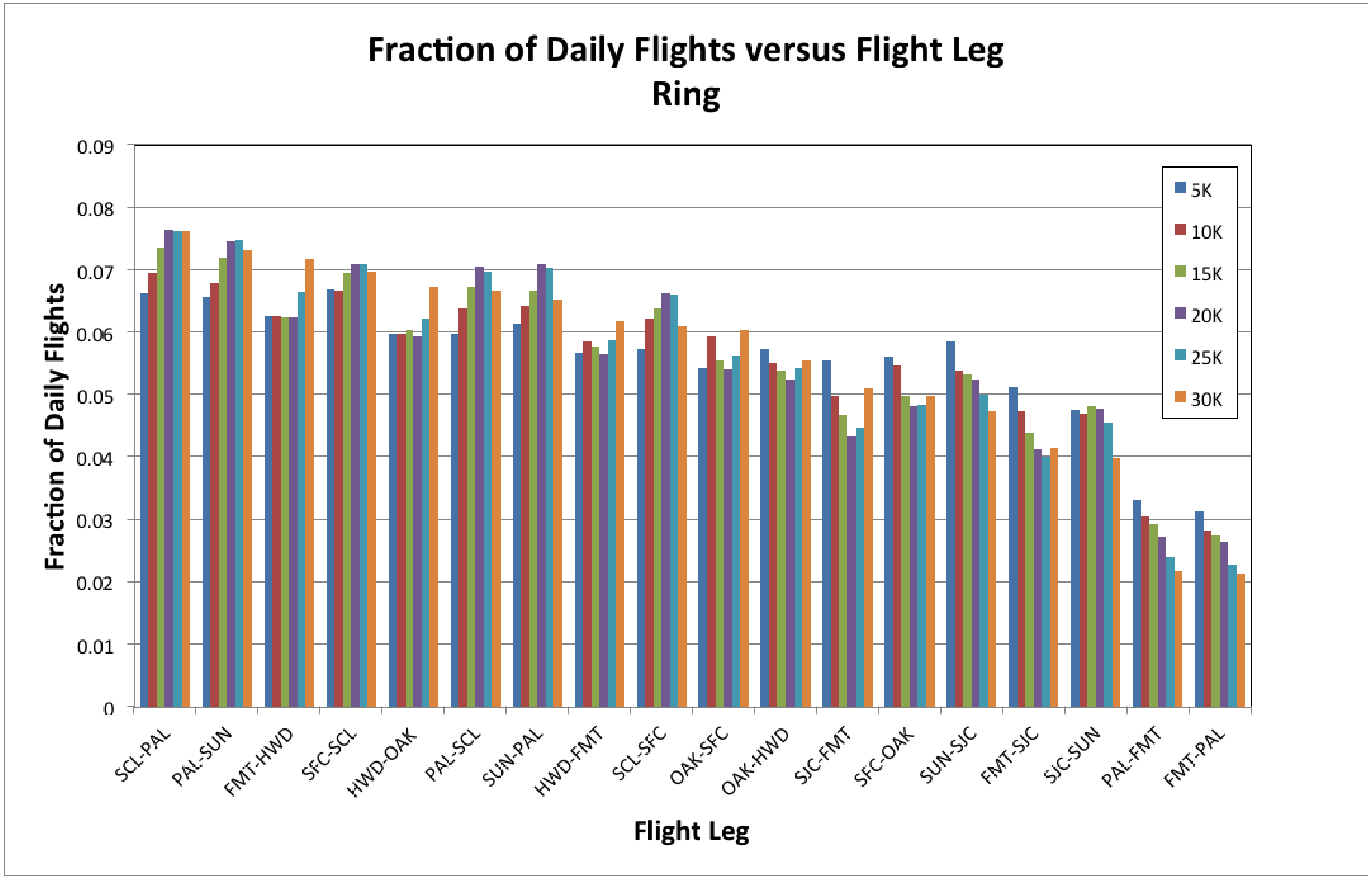


Figure D13. Fraction of daily flights vs. flight leg (ring).

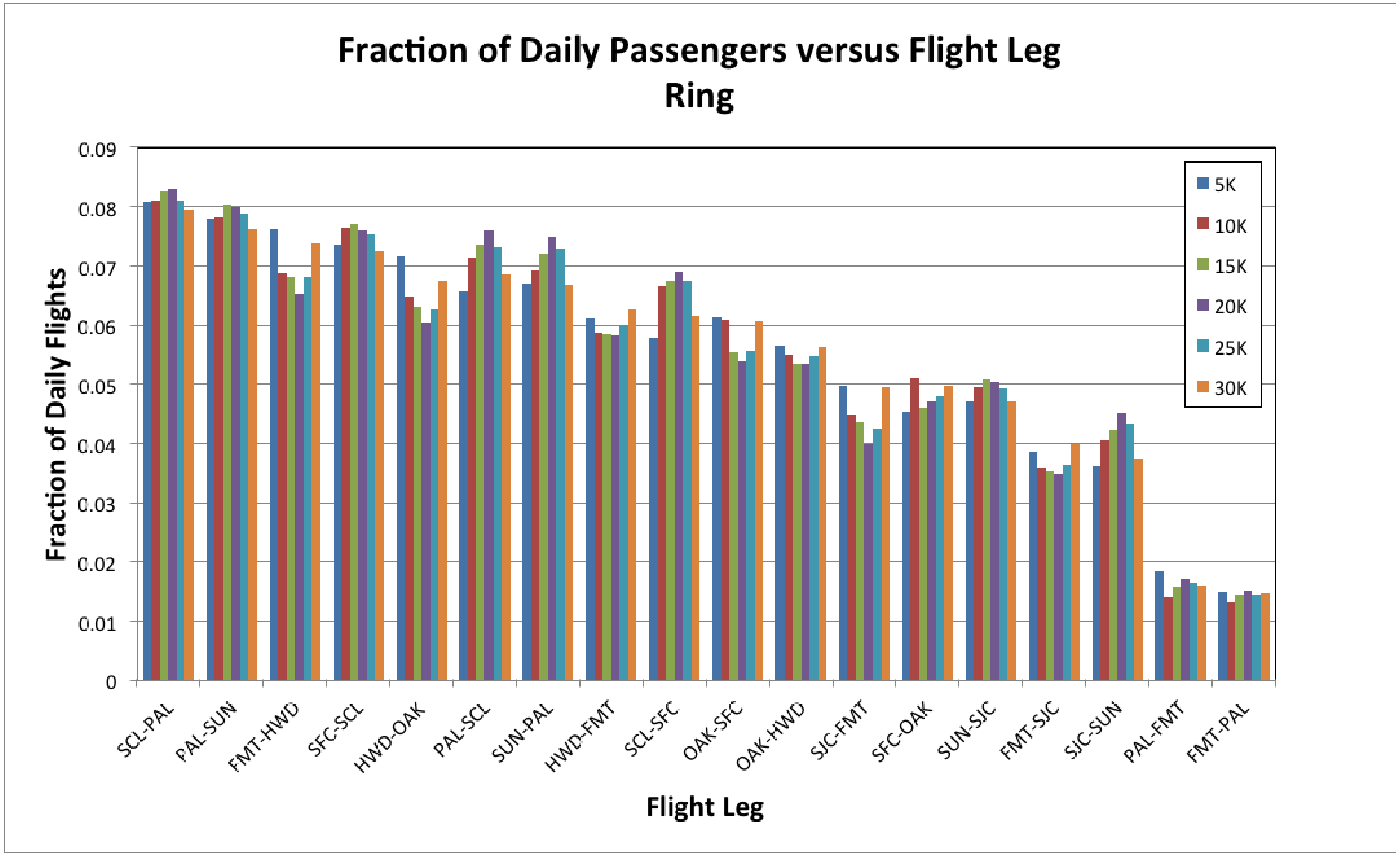


Figure D14. Fraction of daily passengers vs. flight leg (ring).

Table D3. Operations Count for Ring Network

			Ring			
Population Size	**5K**	**10K**	**15K**	**20K**	**25K**	**30K**
Daily Flights	1661	2431	3155	3913	4702	5517
Daily PX	26244	52010	78152	104168	130655	157146
F/P:SCL-PAL	0.06623 / 0.08089	0.06952 / 0.08102	0.07353 / 0.08266	0.07641 / 0.08297	0.07614 / 0.08095	0.07613 / 0.07958
F/P:PAL-SUN	0.06562 / 0.07796	0.06787 / 0.07814	0.07195 / 0.08039	0.07462 / 0.08001	0.07465 / 0.07873	0.07305 / 0.07615
F/P:FMT-HWD	0.06261 / 0.07617	0.06253 / 0.06883	0.06244 / 0.06817	0.06236 / 0.06525	0.06635 / 0.06816	0.07178 / 0.07371
F/P:SFC-SCL	0.06683 / 0.07358	0.06664 / 0.07639	0.06941 / 0.07711	0.07079 / 0.07609	0.07082 / 0.07528	0.06960 / 0.07246
F/P:HWD-OAK	0.05960 / 0.07171	0.05965 / 0.06487	0.06022 / 0.06315	0.05929 / 0.06047	0.06210 / 0.06258	0.06725 / 0.06742
F/P:PAL-SCL	0.05960 / 0.06577	0.06376 / 0.07135	0.06719 / 0.07369	0.07053 / 0.07599	0.06976 / 0.07312	0.06670 / 0.06855
F/P:SUN-PAL	0.06141 / 0.06702	0.06417 / 0.06929	0.06656 / 0.07201	0.07079 / 0.07487	0.07018 / 0.07286	0.06525 / 0.06680
F/P:HWD-FMT	0.05659 / 0.06108	0.05841 / 0.05880	0.05769 / 0.05857	0.05648 / 0.05828	0.05870 / 0.06007	0.06163 / 0.06263
F/P:SCL-SFC	0.05719 / 0.05788	0.06211 / 0.06666	0.06371 / 0.06738	0.06619 / 0.06907	0.06593 / 0.06741	0.06090 / 0.06152
F/P:OAK-SFC	0.05418 / 0.06131	0.05923 / 0.06080	0.05547 / 0.05537	0.05392 / 0.05391	0.05615 / 0.05567	0.06036 / 0.06057
F/P:OAK-HWD	0.05719 / 0.05658	0.05512 / 0.05493	0.05388 / 0.05334	0.05239 / 0.05344	0.05423 / 0.05475	0.05546 / 0.05626
F/P:SJC-FMT	0.05539 / 0.04961	0.04977 / 0.04501	0.04659 / 0.04362	0.04344 / 0.03990	0.04466 / 0.04242	0.05093 / 0.04953
F/P:SFC-OAK	0.05599 / 0.04542	0.05471 / 0.05093	0.04976 / 0.04591	0.04804 / 0.04699	0.04828 / 0.04800	0.04966 / 0.04964
F/P:SUN-SJC	0.05840 / 0.04717	0.05389 / 0.04941	0.05325 / 0.05085	0.05239 / 0.05044	0.04998 / 0.04931	0.04731 / 0.04719
F/P:FMT-SJC	0.05117 / 0.03848	0.04731 / 0.03586	0.04374 / 0.03524	0.04114 / 0.03492	0.03998 / 0.03644	0.04133 / 0.03977
F/P:SJC-SUN	0.04756 / 0.03608	0.04689 / 0.04053	0.04818 / 0.04238	0.04779 / 0.04521	0.04551 / 0.04335	0.03970 / 0.03749
F/P:PAL-FMT	0.03311 / 0.01844	0.03044 / 0.01405	0.02916 / 0.01578	0.02709 / 0.01701	0.02382 / 0.01643	0.02175 / 0.01605
F/P:FMT-PAL	0.03131 / 0.01482	0.02797 / 0.01311	0.02726 / 0.01438	0.02632 / 0.01518	0.02276 / 0.01447	0.02121 / 0.01467

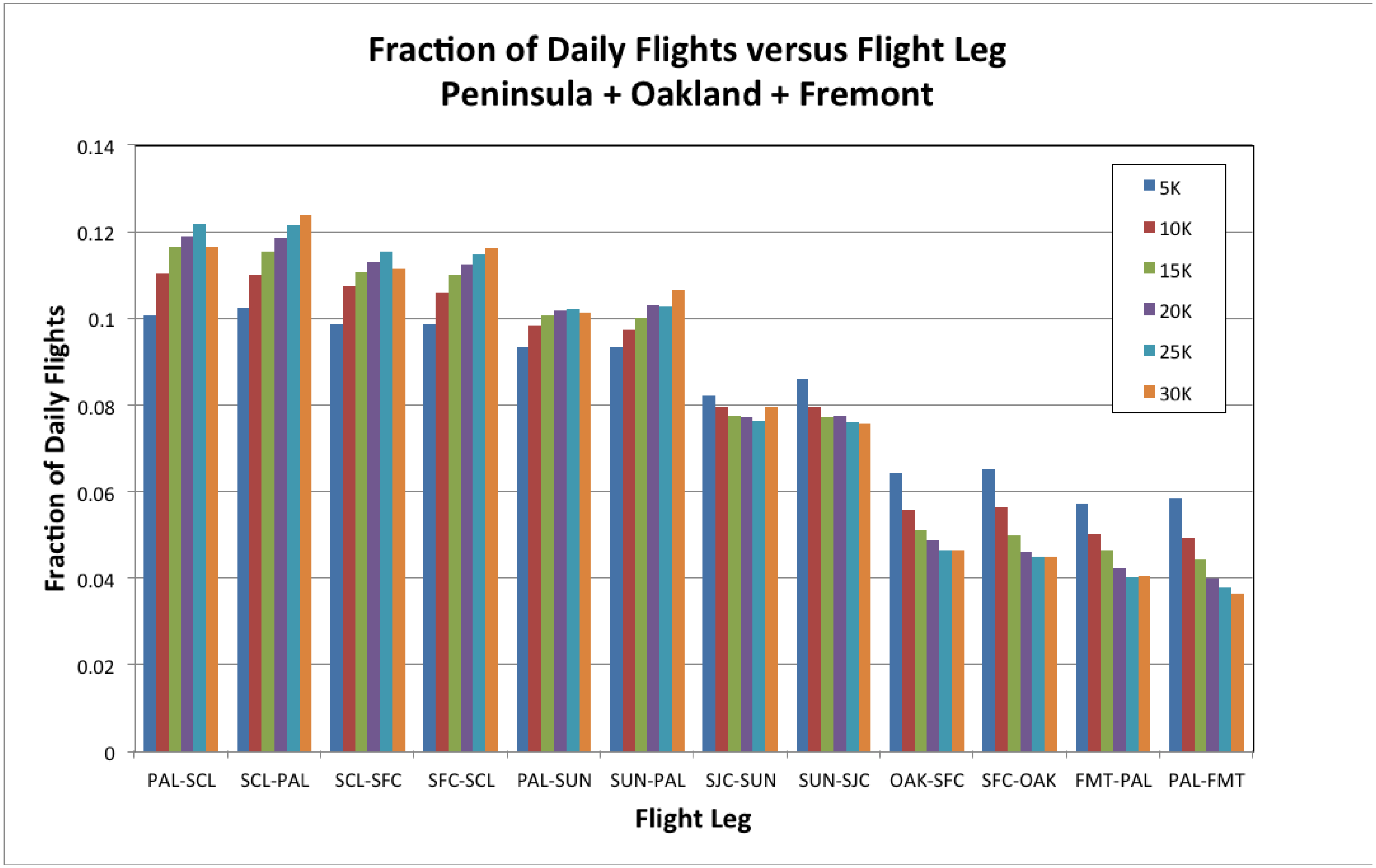


Figure D15. Fraction of daily flights vs. flight leg (Peninsula + Oakland + Fremont).

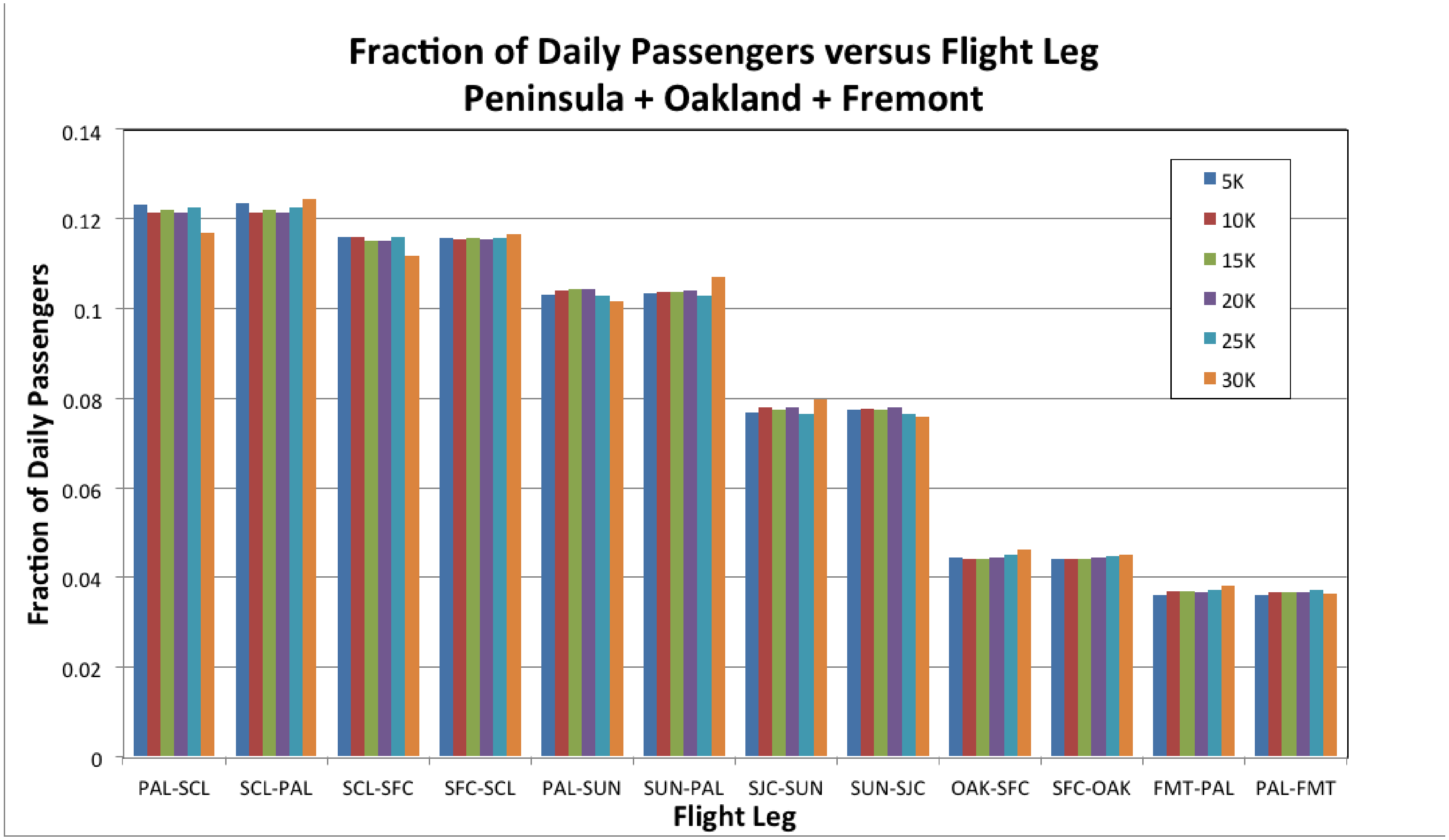


Figure D16. Fraction of daily passengers vs. flight leg (Peninsula + Oakland + Fremont).

Table D4. Operations Count for Peninsula + Oakland + Fremont Network

	Peninsula + Oakland + Fremont					
Population Size	**5K**	**10K**	**15K**	**20K**	**25K**	**30K**
Daily Flights	1522	2391	3326	4244	5223	5663
Daily PX	31075	61923	93246	123679	155436	169343
F/P:PAL-SCL	0.10053 / 0.12319	0.11041 / 0.12149	0.11666 / 0.12210	0.11899 / 0.12152	0.12177 / 0.12251	0.11655 / 0.11692
F/P:SCL-PAL	0.10250 / 0.12338	0.11000 / 0.12152	0.11545 / 0.12204	0.11852 / 0.12152	0.12158 / 0.12255	0.12396 / 0.12428
F/P:SCL-SFC	0.09855 / 0.11607	0.10749 / 0.11603	0.11064 / 0.11517	0.11310 / 0.11506	0.11526 / 0.11596	0.11160 / 0.11196
F/P:SFC-SCL	0.09855 / 0.11566	0.10581 / 0.11530	0.11004 / 0.11578	0.11239 / 0.11532	0.11488 / 0.11580	0.11637 / 0.11675
F/P:PAL-SUN	0.09330 / 0.10330	0.09829 / 0.10398	0.10072 / 0.10443	0.10179 / 0.10429	0.10205 / 0.10285	0.10136 / 0.10169
F/P:SUN-PAL	0.09330 / 0.10343	0.09745 / 0.10382	0.10012 / 0.10362	0.10297 / 0.10416	0.10262 / 0.10293	0.10666 / 0.10694
F/P:SJC-SUN	0.08213 / 0.07688	0.07946 / 0.07787	0.07757 / 0.07726	0.07729 / 0.07793	0.07639 / 0.07658	0.07964 / 0.07987
F/P:SUN-SJC	0.08607 / 0.07736	0.07946 / 0.07776	0.07727 / 0.07740	0.07752 / 0.07806	0.07601 / 0.07651	0.07558 / 0.07582
F/P:OAK-SFC	0.06439 / 0.04441	0.05563 / 0.04418	0.05111 / 0.04429	0.04877 / 0.04438	0.04652 / 0.04491	0.04644 / 0.04615
F/P:SFC-OAK	0.06505 / 0.04412	0.05646 / 0.04423	0.04991 / 0.04429	0.04618 / 0.04444	0.04499 / 0.04476	0.04485 / 0.04493
F/P:FMT-PAL	0.05716 / 0.03607	0.05019 / 0.03709	0.04630 / 0.03685	0.04241 / 0.03673	0.04021 / 0.03728	0.04061 / 0.03819
F/P:PAL-FMT	0.05848 / 0.03614	0.04935 / 0.03671	0.04420 / 0.03677	0.04006 / 0.03660	0.03772 / 0.03733	0.03638 / 0.03649

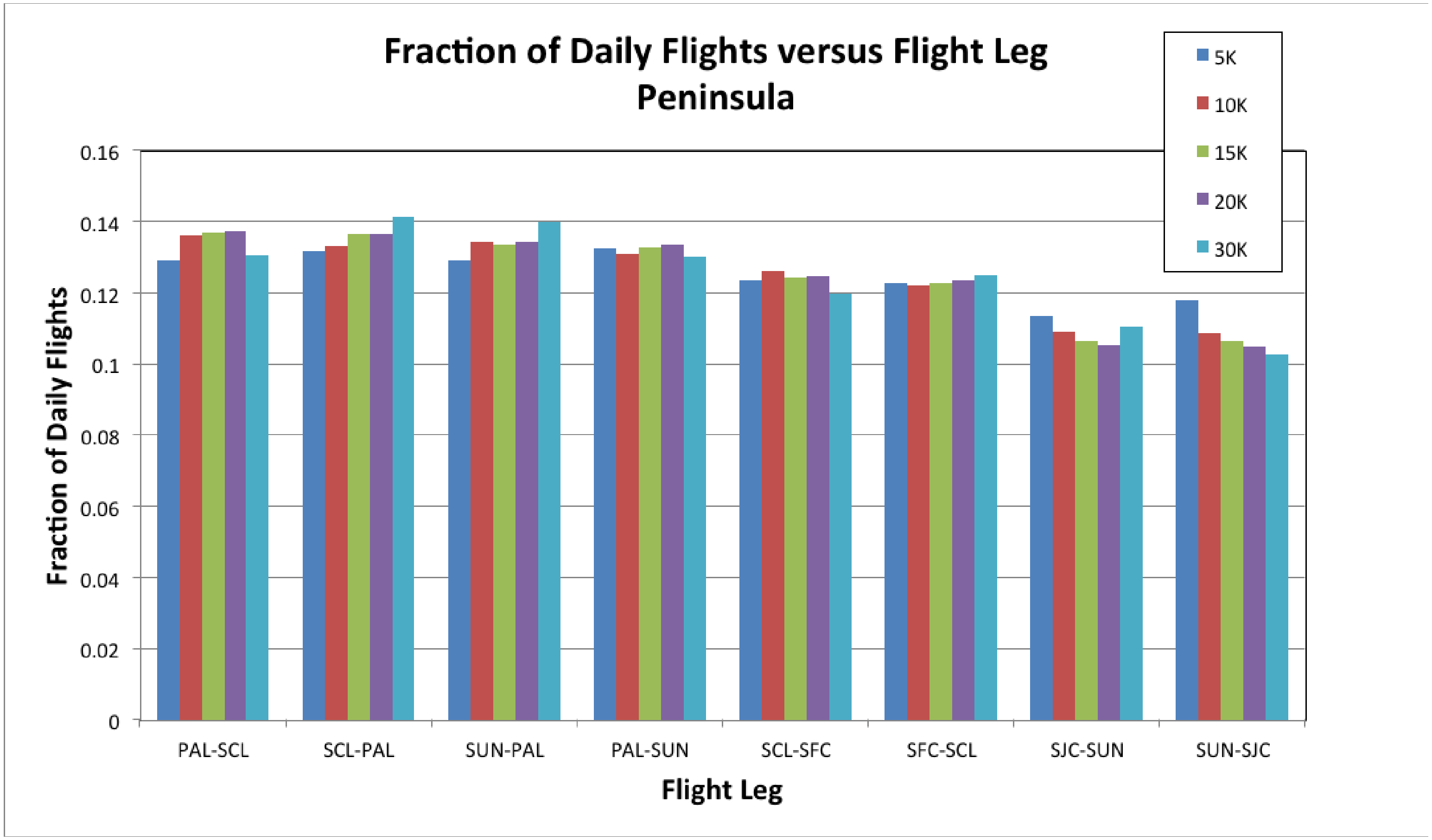


Figure D17. Fraction of daily flights vs. flight leg (Peninsula).

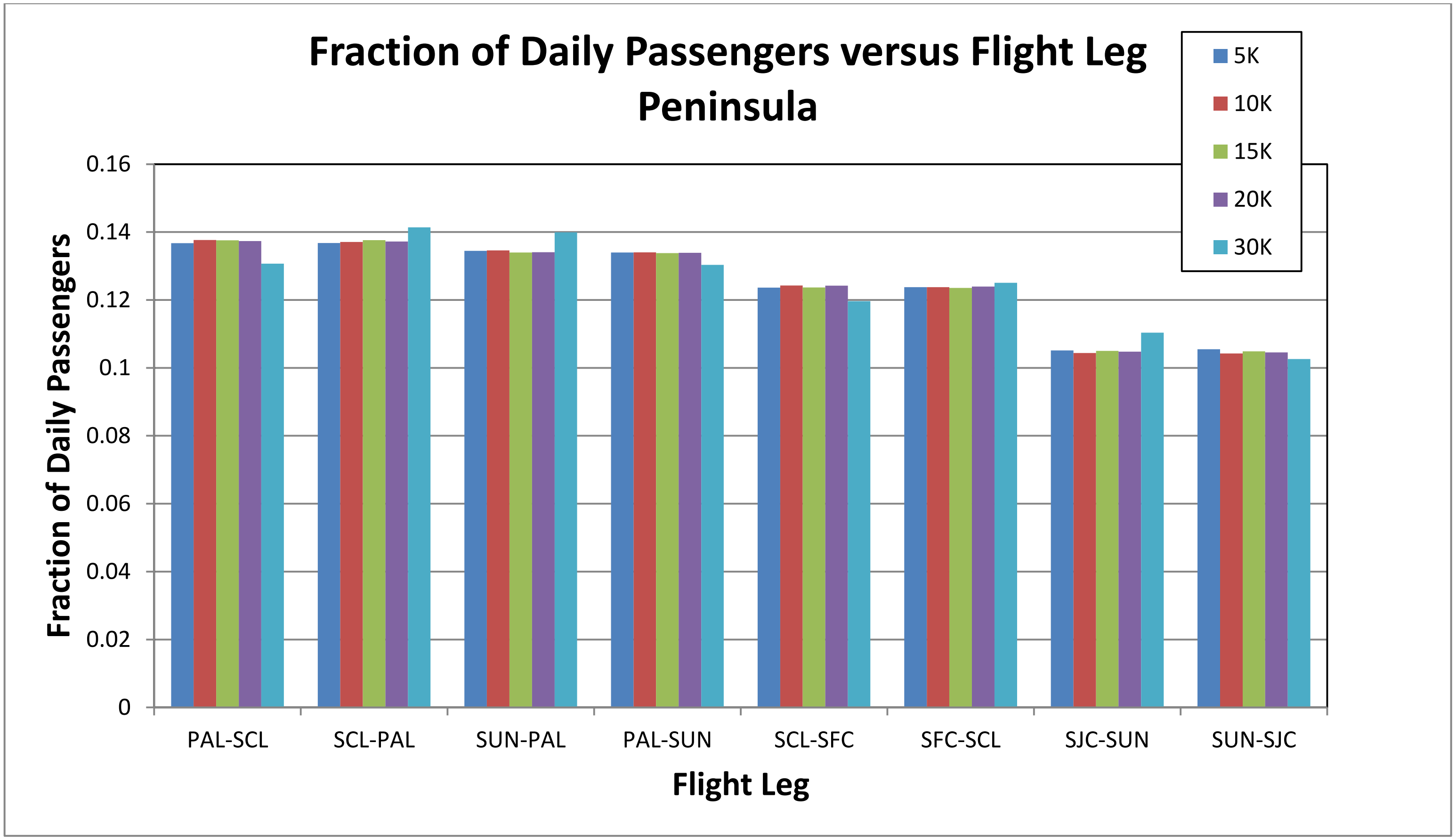


Figure D18. Fraction of daily passengers vs. flight leg (Peninsula).

Table D5. Operations Count for Peninsula Network

	Peninsula				
Population Size	**5K**	**10K**	**15K**	**20K**	**30K**
Daily Flights	1262	2147	3078	4031	5517
Daily PX	29923	60115	90304	120254	165510
F/P:PAL-SCL	0.12916 / 0.13675	0.13600 / 0.13764	0.13710 / 0.13757	0.13743 / 0.13735	0.13069 / 0.13069
F/P:SCL-PAL	0.13154 / 0.13678	0.13321 / 0.13707	0.13645 / 0.13760	0.13669 / 0.13723	0.14138 / 0.14138
F/P:SUN-PAL	0.12916 / 0.13448	0.13414 / 0.13459	0.13353 / 0.13399	0.13421 / 0.13406	0.13993 / 0.13993
F/P:PAL-SUN	0.13233 / 0.13398	0.13088 / 0.13401	0.13288 / 0.13378	0.13347 / 0.13387	0.13032 / 0.13032
F/P:SCL-SFC	0.12361 / 0.12365	0.12622 / 0.12428	0.12443 / 0.12366	0.12453 / 0.12421	0.11963 / 0.11963
F/P:SFC-SCL	0.12282 / 0.12375	0.12203 / 0.12376	0.12281 / 0.12355	0.12354 / 0.12395	0.12507 / 0.12507
F/P:SJC-SUN	0.11331 / 0.10514	0.10899 / 0.10440	0.10656 / 0.10500	0.10518 / 0.10476	0.11039 / 0.11039
F/P:SUN-SJC	0.11807 / 0.10547	0.10852 / 0.10425	0.10624 / 0.10485	0.10494 / 0.10457	0.10259 / 0.10259

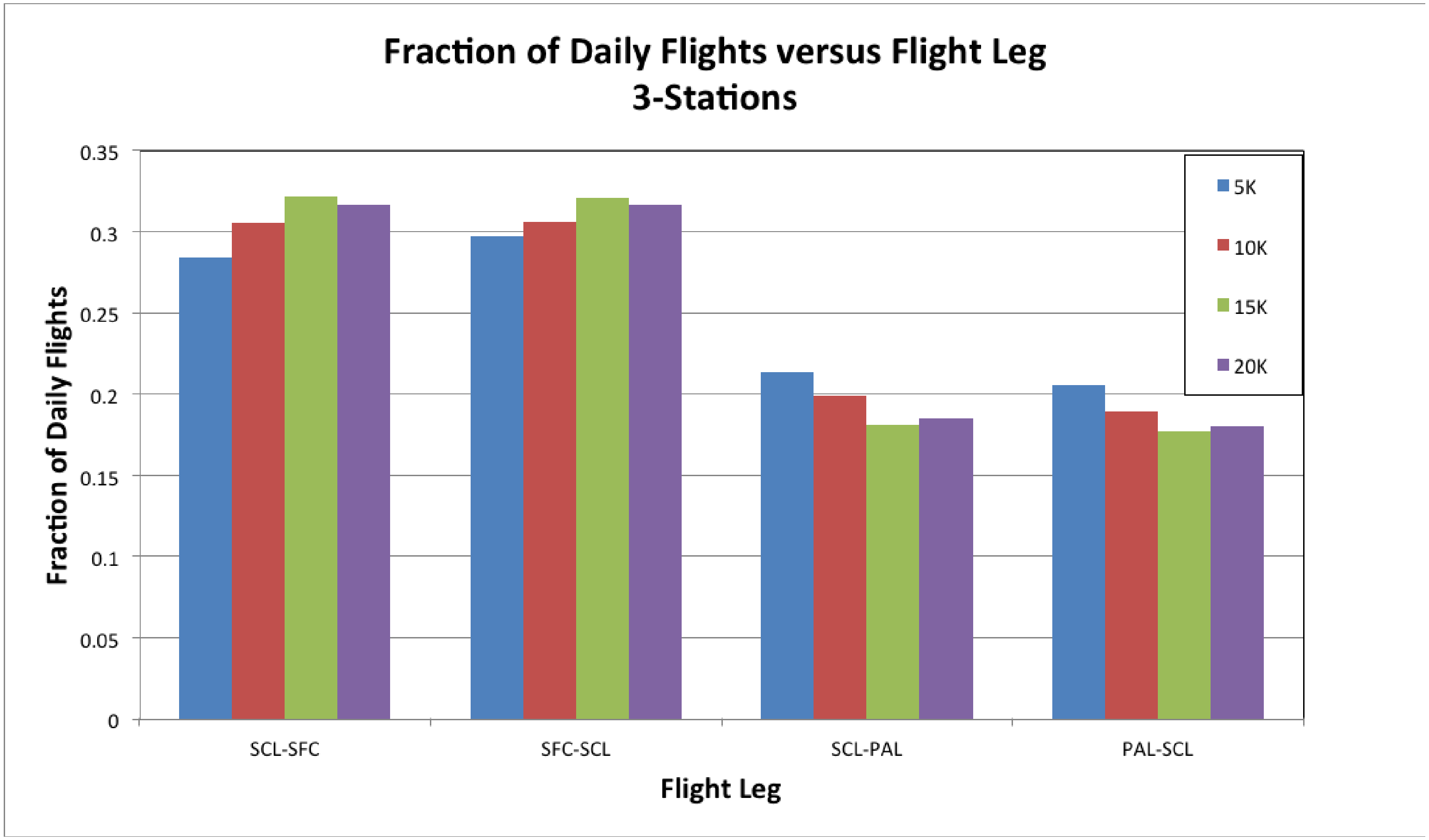


Figure D19. Fraction of daily flights vs. flight leg (three stations).

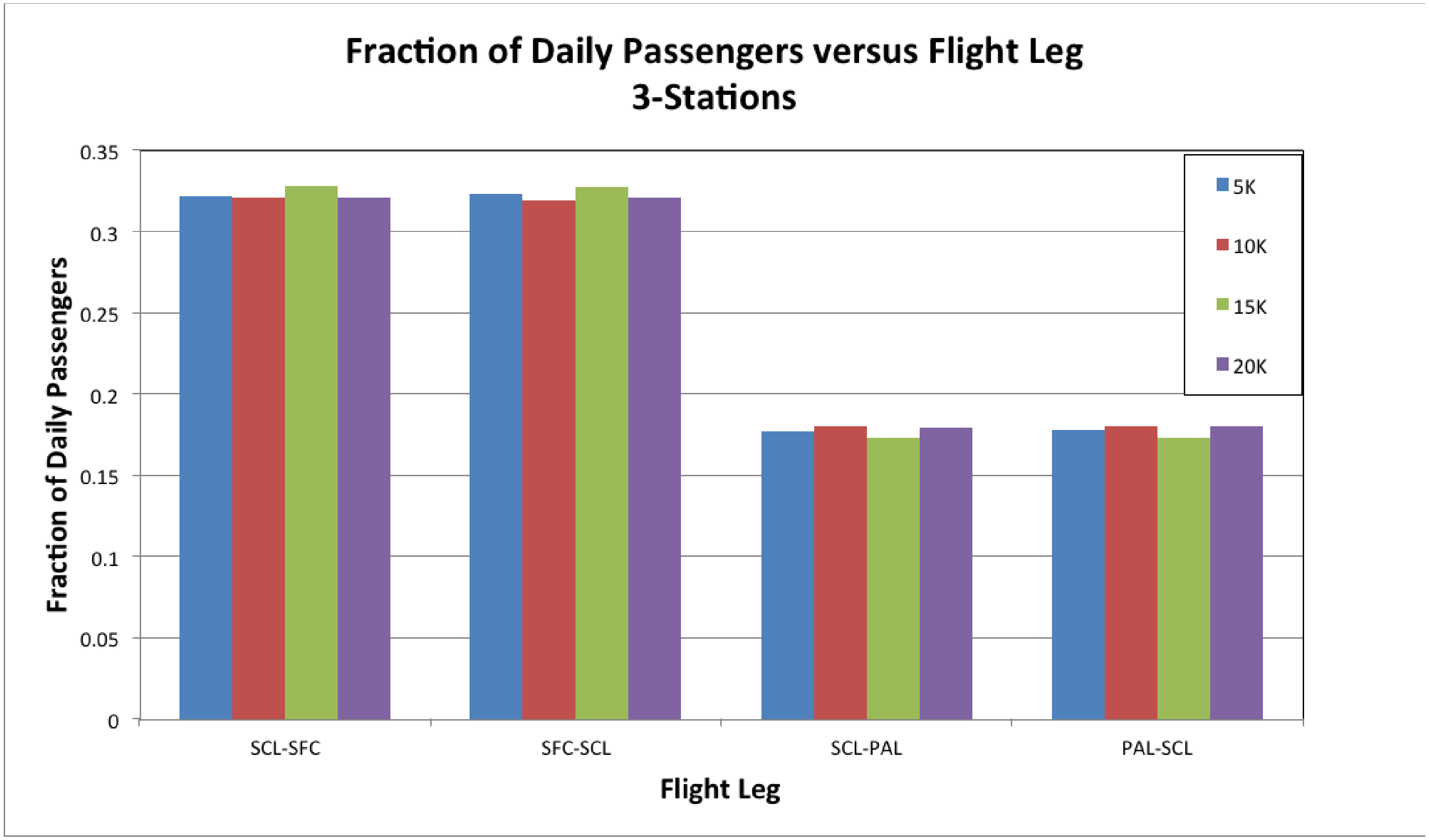


Figure D20. Fraction of daily passengers vs. flight leg (three stations).

Table D6. Operations Count for Three-Station Network

	3-Station			
Population Size	**5K**	**10K**	**15K**	**20K**
Daily Flights	619	1039	1466	1937
Daily PX	14298	28651	42481	57348
F/P:SCL-SFC	0.28433 / 0.32172	0.30510 / 0.32044	0.32128 / 0.32784	0.31699 / 0.32043
F/P:SFC-SCL	0.29725 / 0.32326	0.30606 / 0.31940	0.32060 / 0.32732	0.31699 / 0.32038
F/P:SCL-PAL	0.21325 / 0.17709	0.19923 / 0.18010	0.18076 / 0.17245	0.18534 / 0.17929
F/P:PAL-SCL	0.20517 / 0.17793	0.18961 / 0.18006	0.17735 / 0.17238	0.18069 / 0.17990

Appendix E—Fleet Assignment/Optimization Network Analysis

The major output from BaySim is a schedule of flights and the number of passengers flying on each flight. Using this schedule, the next step is to determine which Hopper size should fly each flight. This is called the fleet assignment problem and is well known in the Operations Research literature. In the fleet assignment problem, the goal is to assign one fleet (Hopper size) to fly each flight in the schedule such that cost is minimized. During Phase I of this study (ref. 1), the schedule consisted of a set of flights, F, that fly between the stations, N; the Hopper vehicles in Phase I could fly from any station to any station, and therefore the fleet assignment problem was *N*x*N*. During Phase II, a more practical set of network topologies was considered: i.e. ring, ring with spokes, etc. However, analyzing these new network topologies required additional care. First, it should be noted that each flight has a demand, p_f, which must be serviced. For Phase I this demand for flights between origin and destination station pairs was only moderately influenced by the particular station pair considered. For Phase II, though, station pairs that were not consistent with the network topology being considered at a given time had their demand set to very low prescribed values (i.e. as close to zero as the optimization software could numerically handle and still yield a converged solution).

To satisfy the demand for flights, there are a set of aircraft types, K, which each have a cost, $C_{f,k}$, to fly each flight, a cost of $W_k$to own (which includes both procurement and maintenance costs), and a capacity of b_k passengers. The optimization is over binary decision variables, $y_{f,k}$, which equal one if fleet k is flying flight f, and zero otherwise. The objective is to minimize the total sum of costs, subject to each flight being flown. Of course, for a flight to be flown with a certain fleet, an aircraft of that type must be present at the station. A set of variables, $G_{n,k,t}$, is used to represent the number of aircraft in fleet k on the ground at station n at time t. In the fleet assignment problem, time is not measured in seconds, but rather by the number of flights that have either taken off or landed at that station. As a result, each station has its own "clock," where time 0 is the beginning of the day, time 1 is after the first arrival or departure, time 2 is after the second arrival or departure, etc., and time T is after the last takeoff or departure of the day. A set of constants, $S_{n,t}$, mark the type of event, with a value of one when the event at time t is an arrival, and a value of negative one when the event is a departure. Lastly, to ensure that the schedule can be flown more than once, an additional constraint is added that requires that the number of Hoppers of each type on the ground at the end of the day is equal to the number that started on the ground. This study used a modified version of the fleet assignment problem, which also includes a set of repositioning flights, H, that allow empty Hoppers to be flown between stations. These are especially useful at the end of the day to meet the periodicity constraint, and during rush hour, when, for example, there may be more demand going into San Francisco than out of it. The repositioning flight variables are represented by $z_{h,k}$, which are binary variables that equal one if the flight is flown and zero otherwise. Each repositioning flight has a cost of $D_{h,k}$ to fly, but unlike flights in the true schedule, there is no requirement that repositioning flights be flown. Written out in equation form, Eq. E1, the fleet assignment problem is:

$$Minimize:$$

$$\sum_{k \in K}\left(\sum_{f \in F} C_{f,k} y_{f,k} + \sum_{h \in H} D_{h,k} z_{h,k} + \sum_{n \in N} W_k G_{n,k,0}\right)$$

$$Subject\ to:$$

$$\sum_{k \in K} y_{f,k} = 1 \quad \forall\, f \in F \quad (All\ scheduled\ flights\ flown)$$

$$\sum_{k \in K} b_k\, y_{f,k} \geq p_f \quad \forall\, f \in F\ (Flight\ demand\ met)$$

$$G_{n,k,t-1} + \sum_{f \in F} S_{n,t}\, y_{f,k} = G_{n,k,t} \quad \forall\, n \in N, t \in T, k \in K \ \ (Aircraft\ continuity)$$

$$G_{n,k,t} \geq 0 \quad \forall\, n \in N, t \in T, k \in K \ \ (Non-negative\ number\ of\ aircraft)$$

$$G_{n,k,0} = G_{n,k,T} \ \ (Periodicity)$$

$$y_{f,k} = \{0,1\} \quad \forall\, f \in F, k \in K$$

$$z_{h,k} = \{0,1\} \quad \forall\, h \in H\,, k \in K\,. \tag{E1}$$

Three different objective functions were analyzed: minimum total cost, minimum number of aircraft, and minimum operating cost. The most realistic case is minimum total cost—accounting for both the cost to fly and the cost to own the Hoppers. The optimal result is a balance between the extra cost to own each aircraft and the additional flexibility gained by having each new aircraft. The second objective function is an edge case in which the total number of aircraft needed is minimized. For this objective function, all of the flight costs ($C_{f,k}$, $D_{h,k}$) are equal to zero, and the ownership costs (W_k) are equal to one. This objective examines the smallest feasible fleet, and also represents the worst-case scenario for air traffic, as lots of repositioning flights will be used. The third objective function is also an edge case, where the total direct operating costs are minimized and the ownership costs are ignored. This is expressed by setting all of the W_k's equal to zero. This is the best scenario for air traffic, as a minimal number of repositioning flights will be used, and also gives an upper bound on the number of desired Hoppers. The optimization was done using the Gurobi commercial optimization software suite, a software tool designed specifically for mixed integer linear programs (http://www.gurobi.com).

Appendix F—Hopper Conceptual Design and Refined Design Analysis

A considerable amount of research work is currently being directed towards electric-propulsion aviation (refs. 93–95). However, only a limited amount of work related to electric propulsion for VTOL platforms has been conducted to date; references 36 and 62 are noteworthy examples of such work. Figures F1–F6 outline additional details as to the electric-propulsion system modeling occurring during the course of this study.

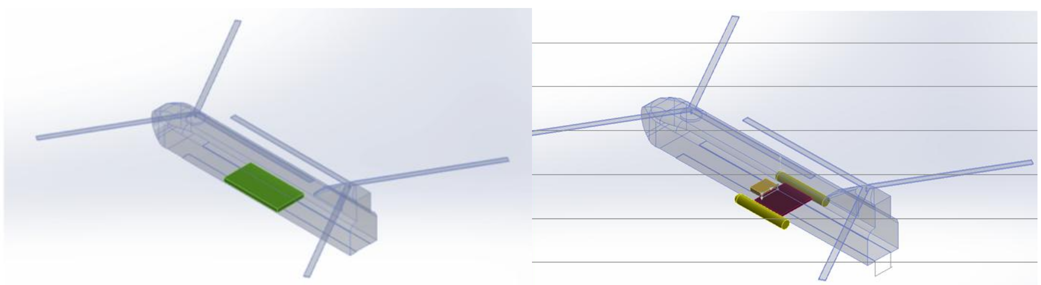
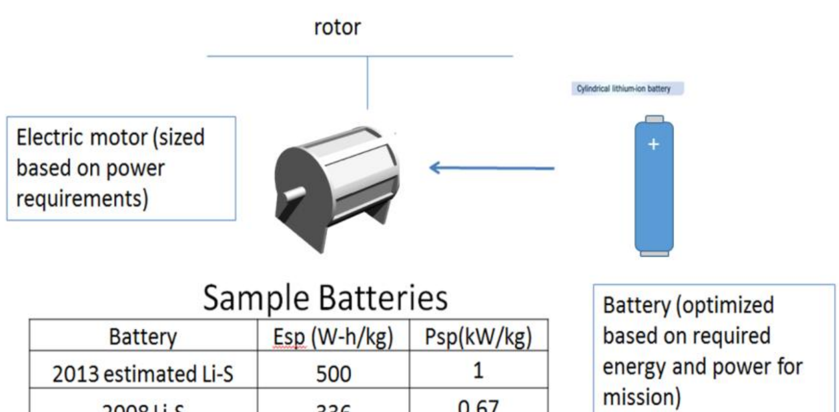


Figure F1. Different types of electric-propulsion systems modeled (battery system on the left and fuel-cell system on the right).

Battery Propulsion Model

$$W_{empty} = W_{struct} + W_{fixed} + W_{motor}$$
$$W_{gross,battery} = W_{empty} + W_{payload} + W_{battery}$$



Sample Batteries

Battery	Esp (W-h/kg)	Psp(kW/kg)
2013 estimated Li-S	500	1
2008 Li-S	336	0.67
2005 Li-S	246	0.52
Li-air~2020	1,300	0.66
Li-air DOE design goal	2,000	0.4
Jet-A	12,000	

Figure F2. Electric battery power system.

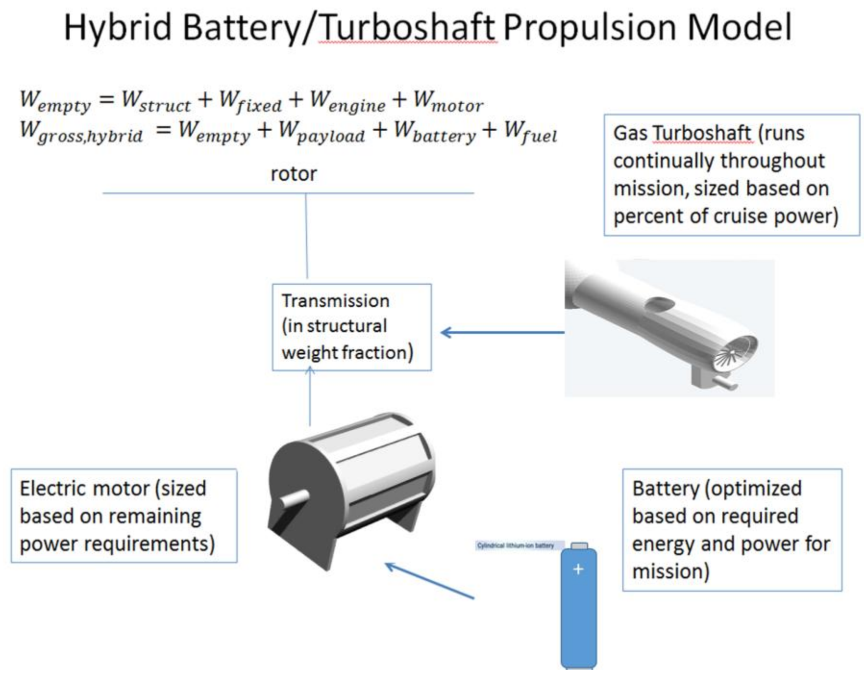


Figure F3. Parallel hybrid power system.

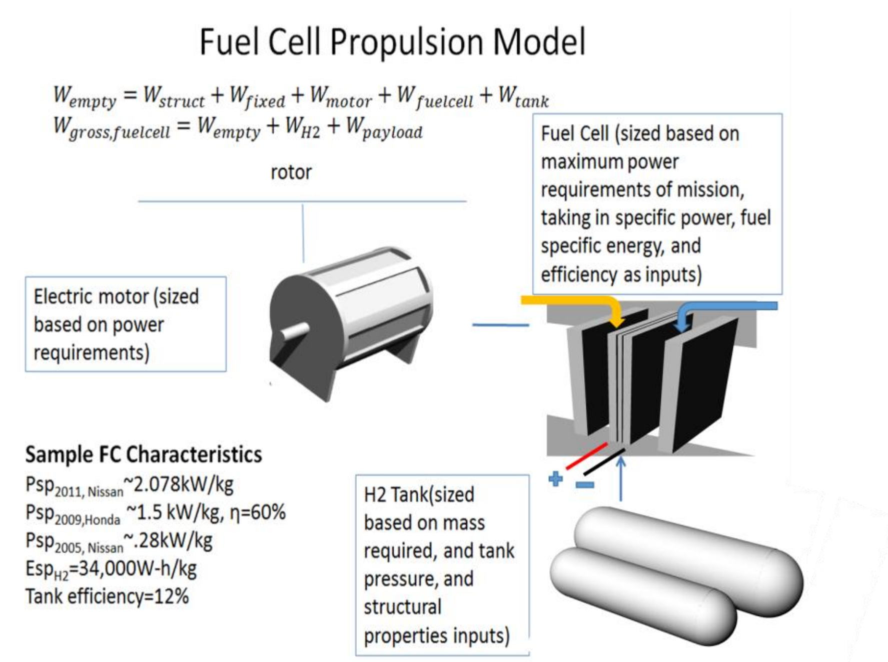


Figure F4. Fuel-cell power system.

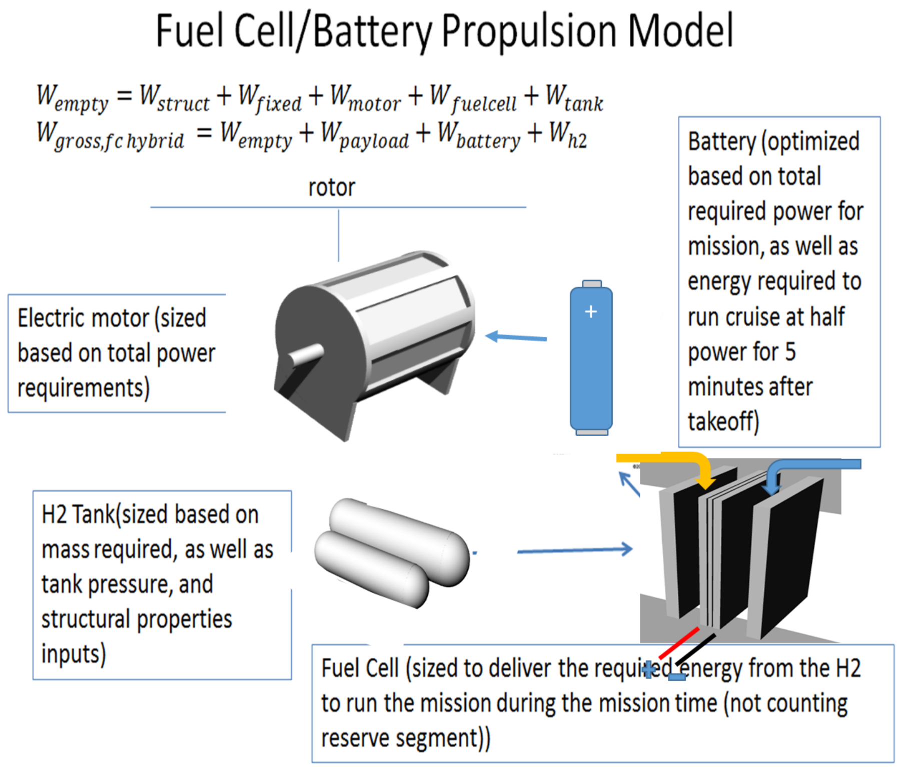


Figure F5. Fuel-cell hybrid power system.

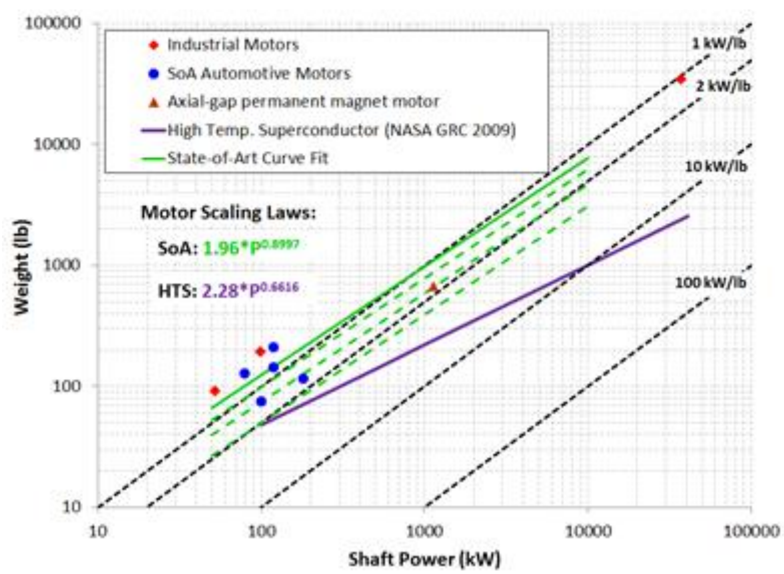


Figure F6. Electric motor scaling.

Figures F7–F13 detail some of the electric vehicle results stemming from the improved electric-propulsion system modeling. Figure F7 shows validation results for the Phase II Stanford-developed vehicle sizing analysis tool versus the Phase I NASA-developed NDARC sizing tool; good agreement is seen between the two sets of results.

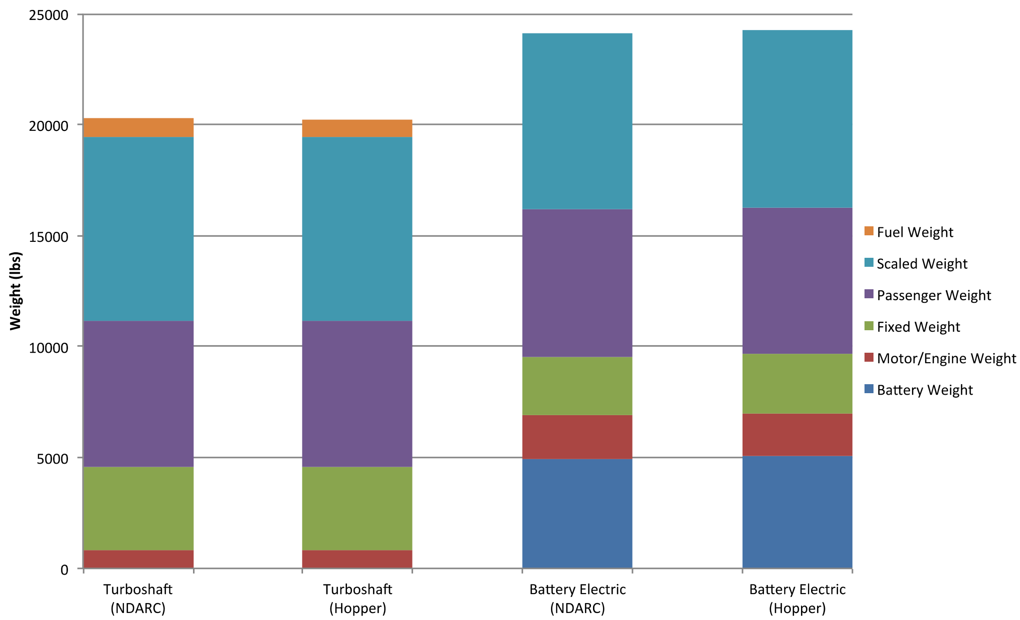


Figure F7. Validation of Phase II sizing analysis (Hopper) against Phase I NDARC analysis (refs. 2 and 7).

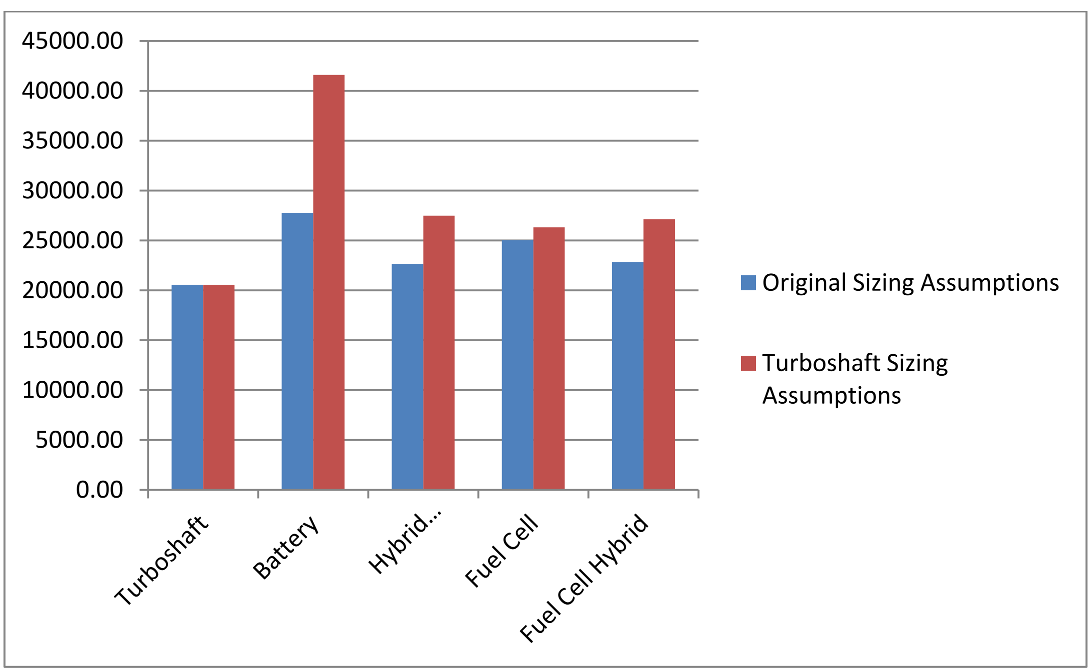


Figure F8. Sizing assumption comparison.

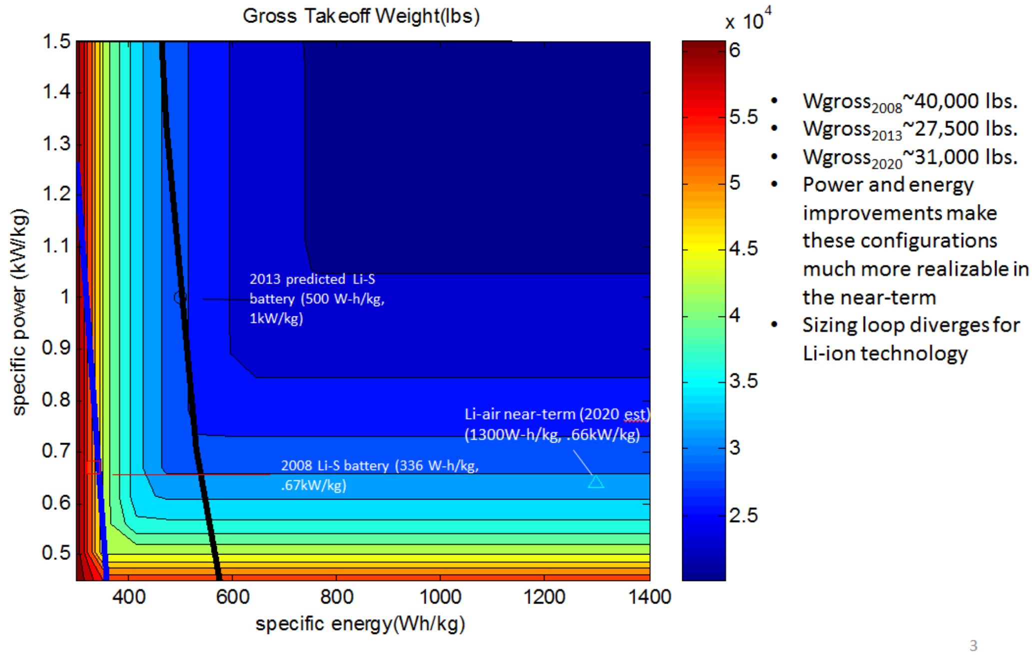


Figure F9. Battery sizing results (65 nautical miles).

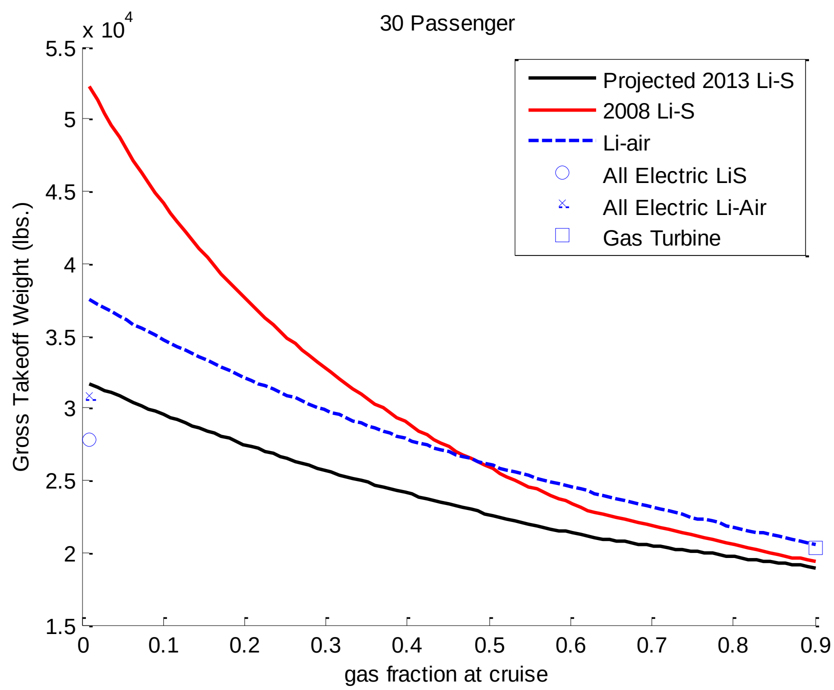


Figure F10. Hybrid sizing results (65 nautical miles).

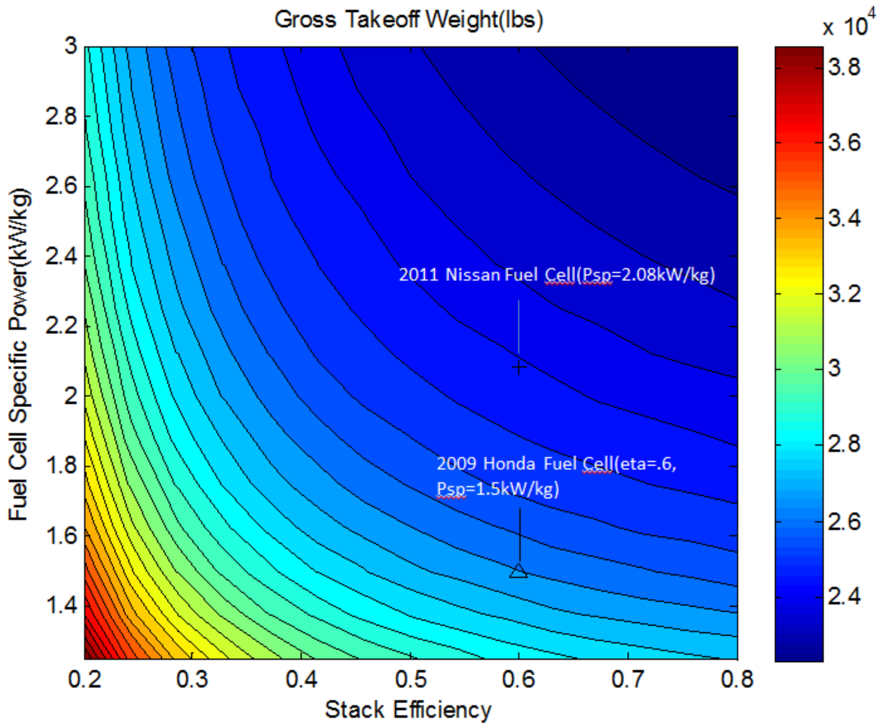


Figure F11. Fuel-cell sizing results (65 nautical miles).

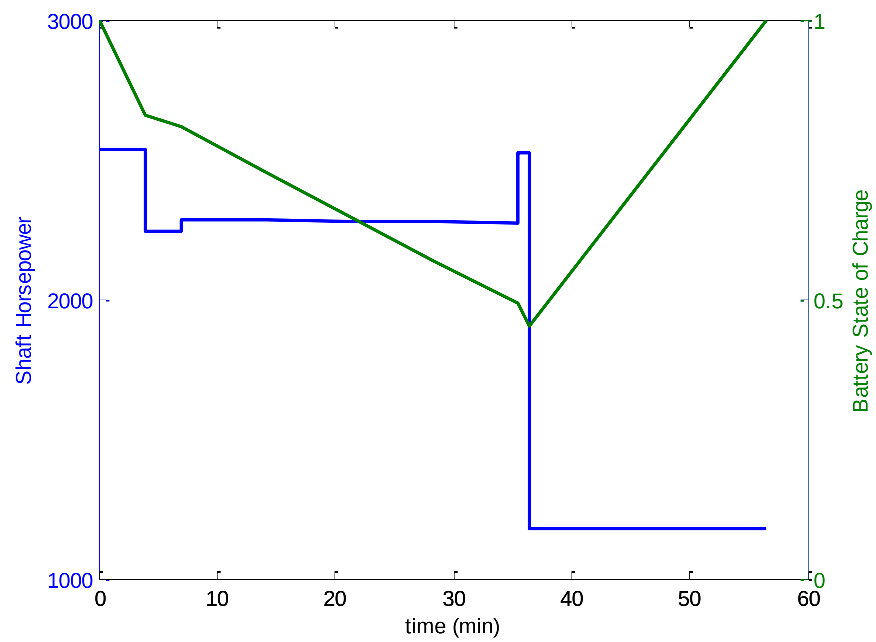


Figure F12. Fuel-cell hybrid mission diagram.

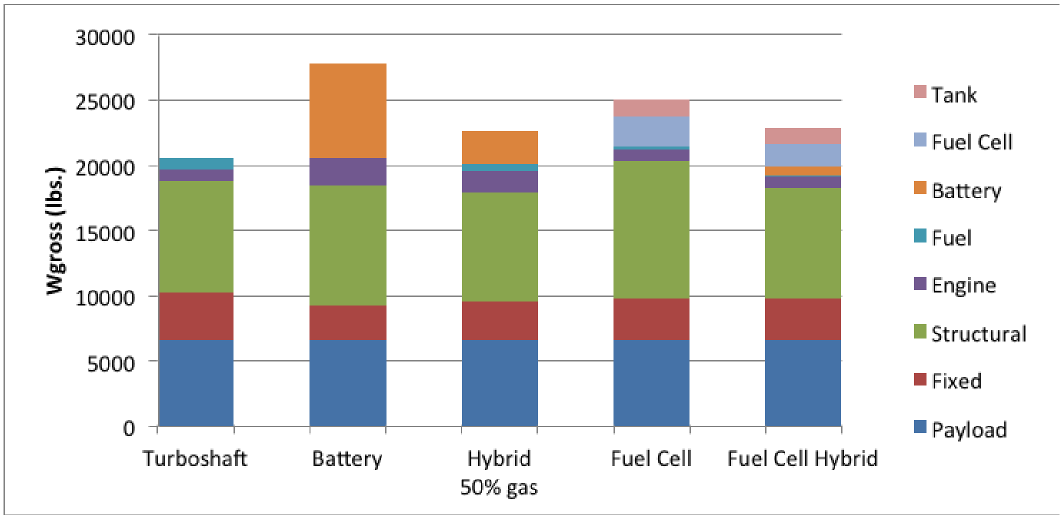


Figure F13. Design weight breakdown (65 nautical miles).

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