Performance Study of a VH-3 Hybrid-Electric eCRM-002 Aircraft Comparing Reserve Energy and Range to Fully Electric and Conventional Propulsion Alternatives

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ABSTRACT

Using VerdeGo Aero's third generation VH-3-185 (VH-3) hybrid-electric powerplant to overcome the challenges of battery energy density, the future of urban air mobility via electrified propulsion may not be as distant as it seems. This paper explores the feasibility of retrofitting a modified Uber eCRM-002 airframe with four different approaches to aircraft propulsion: a fully electric battery-powered system, a VH-3 hybrid-electric system, and two separate conventional engine systems. Through an in-depth conceptual weight buildup, aerodynamic analysis, mission performance, and range evaluation study, this paper reveals how a hybrid design could yield a tenfold increase in range over a fully electric configuration of the same weight. While the conventional layouts were compromised by weight restrictions and the all-electric design critically limited in energy capacity, the VH-3 Hybrid CRM was the only aircraft configuration found capable of outperforming the base eCRM-002 design and achieving all FAA mandated reserve fuel regulations**.**

INTRODUCTION

Since the arrival of Mobility on Demand, the idea of local transit has undergone a profound transformation. Through the emergence of Transportation Network Company (TNC) services like Uber and Lyft, everyday people have gained access to effortless transportation and delivery by car, *anytime* and *anywhere*, with just a simple click. As a result, a mobile transit revolution has spread across the world, enhancing flexibility and connectivity at the ground-level like never before (Ref 1). In turn, such economic potential has captivated the interest of the aviation industry, and alongside recent advances in electric propulsion and regulatory standards, the aviation industry now anticipates a similar market soon taking to the skies. While many early visionaries first expressed overly optimistic goals for battery technology and aircraft certification, as seen in the Uber Elevate White Paper of 2016 (Ref 2), their efforts to promote Advanced Air Mobility (AAM) served as a catalyst for a tangible movement towards rethinking a more effective and sustainable mode of urban transportation.

At the same time, VerdeGo Aero emerged with a firm grasp of both the electric aircraft and regulatory landscapes. As the developer of several generations of hybrid-electric powerplants, VerdeGo Aero is currently rolling out its third-generation hybrid (VH-3-185) to bridge the gap between sustainable urban aviation and battery performance. Hence, this paper delves into a hybrid-inclusive powerplant design space for an early Uber eVTOL (electric Vertical Takeoff and Landing) concept known as the second electric Common Reference Model (eCRM-002) aircraft shown in Figure 1. Four configurations – two conventionally powered, a fully electric design as it was originally intended, and a VH-3-185 hybrid design – were considered, with the latter two evaluated in depth. The primary objective was to estimate the performance of each UAM aircraft by assessing their range capabilities with sensitivity to weight, payload, and the Federal Aviation Administration (FAA) reserve requirements.

Figure 1. Uber's second-generation electric Common Reference Model (eCRM-002)

The Impetus for Hybrid

Back in 2016 when Uber Elevate first launched its UAM agenda, perceptions of Uber becoming the all-encompassing platform for its ridesharing aircraft, infrastructure, and user interface were widespread. Meanwhile, the whereabouts of battery specific energy were relatively new, and many UAM

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advocates projected vast increases in battery energy density within the coming years. Moreover, because the sustainability implications and power density of batteries were so appealing, any specific energy deficits were easy to overlook.

Such evidence led Uber, like many others, to greatly miscalculate the pace of short-term improvements in battery specific energy and underestimate the enduring impact of low specific energy on aircraft performance. Furthermore, VerdeGo Aero's analysis in Figure 2 indicates that the annual improvement in battery specific energy not only fell short of Uber's expectations, but also witnessed a slowdown, declining from a prior 3% to a mere 1.5% over the last decade. A deceleration of this magnitude raises concerns, especially for large aircraft relying on fully electric propulsion, where a cell energy density difference of 1.5% could translate to hundreds of miles in range.

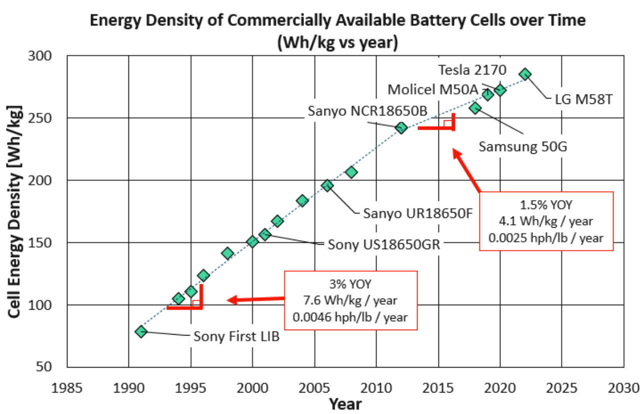

Figure 2. Energy density trends in commercial cells over the last 30 years

The range and endurance metrics of an aircraft are direct indicators of its performance and mission capability. Inadequate energy onboard an aircraft poses critical challenges and may hinder its ability to complete its designated mission, reach an alternate airport, and adhere to the 45-minute loitering requirement stipulated by Title 14 of the Code of Federal Regulations (CFR) §121.639. Possessing any of these limitations would not only jeopardize the safety of the entire crew but also the lives of the passengers onboard.

Introducing the VH-3-185

To address the challenges associated with limited mission range and reserve energy in fully electric UAM aircraft, without compromising their VTOL-enabling and low carbon emission features, VerdeGo Aero is currently in the advanced stages of developing its VH-3-185 (VH-3) piston hybrid as depicted in Figure 3. Poised as an alternative to large, battery-centric propulsion system architectures, the VH-3 caters to commercial and military applications for powering aircraft like the Uber eCRM-002 that rely on both high energy density and Distributed Electric Propulsion (DEP). Figure 3 illustrates VerdeGo's VH-3-185 hybrid package, while Table 1 provides a summary of some notable VH-3 performance figures, including its multi-modal power delivery options of 248 hp (185 kW) continuous power and an average specific fuel consumption of just 0.34 lbs/hp-hr (227 g/kWh) using Jet-A or Sustainable Aviation Fuel (SAF).

Figure 3. Mock-up of the VH-3-185 hybrid powerplant

Table 1. VerdeGo's VH-3-185 Specifications

Specification	English	Metric
Maximum Continuous Power	248 hp	185 kW
Average SFC	0.34 lb/hp-hr	277 g/kWh
Package Weight	665 lbs	302 kg
SAF Compatible	Yes	
System Equivalent Energy Density	0.37-0.6+ hp-hr/lb	600-1000 Wh/kg

In contrast to the typical pack-level specific energy of batteries, which hovers just above 0.1 hp-hr/lb (150 Wh/kg) (Ref 3), conventional fuels exhibit an energy density almost 73 times greater at 7.3 hp-hr/lb (12,000 Wh/kg) (Ref 4). Even after factoring in efficiency considerations, liquid fuels remain 20 times more energy dense than batteries. VerdeGo Aero emphasizes the efficacy of integrating the power density of batteries with the energy density of liquid fuels into a single propulsion system as the most efficient and performance-driven solution for sustainable aviation. However, the innovative nature of hybrid-electric aircraft propulsion systems necessitates studies like this to comprehend the utility and potential advantages of employing hybrid systems to power UAM aircraft.

METHODOLOGY

The initial phase of sizing each of the four CRM aircraft involved defining the vehicle design requirements based on an early UAM reference mission outlined by Uber Elevate. Although the specific requirements of this Uber mission (Ref 5) underwent slight modification to streamline the four aircraft designs, a consistent level of expected performance was maintained across all configurations. The four CRM-

002 aircraft variants included a fully electric model, a VH-3-185 hybrid configuration incorporating a battery pack for boost power, a conventional piston layout with two larger engines transmitting power through mechanical shafts and gearboxes, and an alternative conventional design utilizing eight separate piston engines to directly drive the rotors and propellers. The newly established mission requirements, aligning with their intended compliance criteria, are presented in Figure 4 and Table 2.

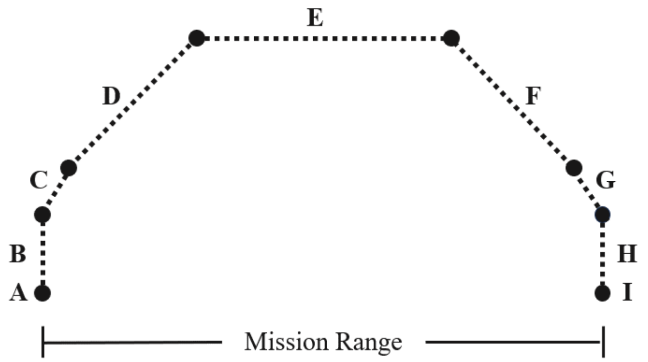

Figure 4. Depiction of the Uber Mission Profile presented in Table 2

Table 2. Base Uber Model Mission Requirements

	Segment	Distance [mi]	Vertical Speed [ft/min]	Horizontal Speed [kts]	AGL Ending Altitude [ft]
A	Ground Taxi	No Distance Credit	No Speed Credit		0
B	Hover Climb		0-500	0	50
C	Transition + Climb	60	500	0-1.2*Vstall	300
D	Accel + Climb		500	1.2*Vstall -130	1500
E	Cruise		0	130	1500
F	Devel + Descend		500	130-1.2*Vstall	300
G	Transition + Descend		500-300	1.2*Vstall	300
H	Hover Descend	No Speed Credit	300-0	0	50
I	Ground Taxi		No Speed Credit		0

Utilizing Uber's common reference model airframe for each of the CRM designs was another simplification to the vehicle design process, for two reasons: Firstly, it leveraged the pre-existing and readily accessible aircraft geometry from public domain data and NASA's Design and Analysis of RotorCraft (NDARC) software. Secondly, it established uniformity in the downstream propulsion elements of each aircraft, mitigating any bias among the vehicles with distinct upstream propulsion systems.

Nonetheless, mirroring the approach taken with the mission model, each of the four final aircraft configurations featured minor deviations from the original eCRM-002 design, even the fully electric case. For instance, removing the original dihedral from all designs and slightly increasing the disk area of all the rotors were two modifications aimed to standardize the calculation of aerodynamic power required and improve each vehicle's hover efficiency.

Furthermore, it was apparent that the original eCRM aircraft cabin was tightly constrained for accommodating four-passengers, offering limited space to integrate engines of substantial volume within the fuselage. To enhance the practicality of both the hybrid and conventional layouts, their fuselages were extended approximately 6 feet in length to internally house their associated engine systems and ensure sufficient legroom for passengers. Assuming a standard passenger weight of 200 pounds per person, the maximum payload capacity (including the pilot) was set to 1,000 pounds for all configurations. Figure 5 details the differences between the original eCRM design and the modified VH-3 Hybrid CRM model.

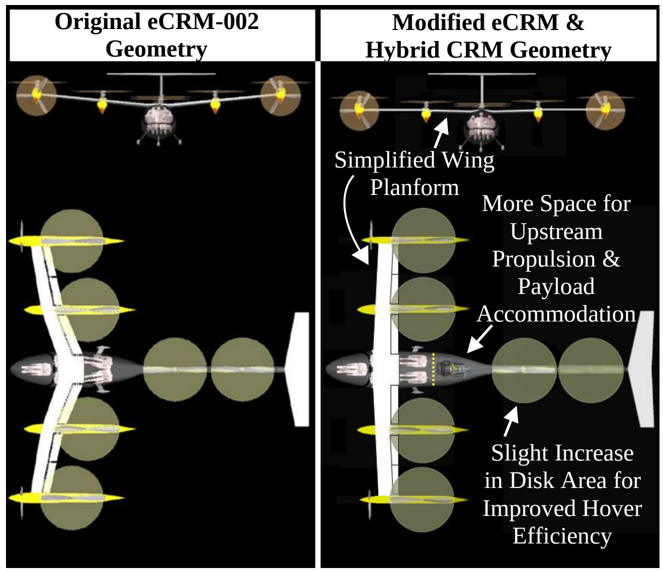

Figure 5. Comparison of the original vs. modified eCRM geometry (Ref 6)

Upon establishing the vehicle geometries, a comprehensive structural weight analysis of the four CRM aircraft was conducted. Table 3 provides a breakdown of the final structural weights of the four aircraft following iteration with the other weight categories.

The next design phase involved the upstream and downstream propulsion systems. In the fully electric CRM, its entire upstream propulsion system comprised of a single battery pack. However, for the VH-3 Hybrid CRM, the upstream components included the VH-3 engine, its engine oil, the engine's hybridizing elements, and total fuel onboard. A thorough review of the power requirements further revealed the VH-3 alone could not generate enough power for VTOL operation in rotorcraft mode, necessitating a supplemental battery pack in its upstream propulsion system for boost power. In the case of the conventional engine layouts, the upstream systems encompassed the dry engines, engine accessories, oil, and fuel. For the twin engine model, each rotor was to be powered by one of two Lycoming 720 engines, whereas each rotor in the eight-engine configuration was directly driven by a separate Rotax 912.

Table 3. Structural Weight Breakdown

Component	DEP		Conventional	
	eCRM	*VH-3 Hybrid CRM*	*Twin-Engine CRM*	*Eight-Engine CRM*
Fuselage	456	510	562	583
Wing	265	265	265	498
Horizontal Tail	53	53	53	53
Vertical Tail	14	14	14	14
Rotor Supports	235	235	235	235
Landing Gear	251	251	268	290
Fuel System	0	20	40	85
Total (lbs)	1,274	1,348	1,437	1,758

The choice of battery type for both fully electric and hybrid vehicles was determined using a decision matrix and process of elimination. While all chemistries and cell types were initially considered, the application of electric aircraft propulsion quickly reduced the available batteries to those that were rechargeable, lightweight, and compatible with high power and high energy needs. Additionally, preference was given to those with a reliable chemistry, proven performance, and accessibility as a commercially available product. The criteria effectively narrowed down the options to secondary, cylindrical cell batteries exclusively, and after performance data from the top manufacturers of 18650 and 21700 cells was collected, Figure 6 was generated to compare their critical densities of energy and power.

Considering the specific energy of a hybrid aircraft utilizing the VH-3 would be inherently high, the desired battery for the VH-3 Hybrid CRM battery pack was one targeting high specific power. In contrast, the fully electric CRM would find a cell balanced in high specific energy and power most suitable, as it not only required a high discharge rate but also substantial capacity from its batteries. However, if achieving maximum range becomes the mission priority, then the preferred battery would be the one providing the most energy for the least weight. Thus, the authors opted for the Molicel P28B as the high-power density cell for the VH-3 Hybrid CRM, the Molicel P45B as the high energy-power balance for the eCRM, and the LG M58T as a high-energy alternative best suited for long range applications with the eCRM.

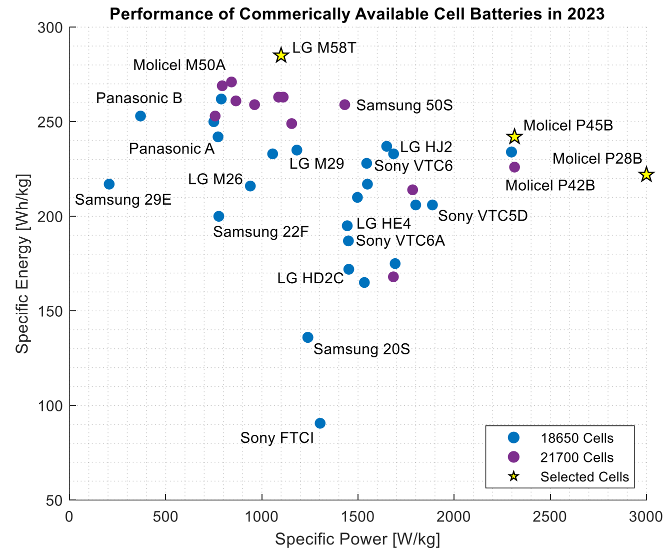

Figure 6. Specific energy vs. specific power of some commercial cells

With the cell types identified for each vehicle, the upstream propulsion systems for the eCRM and Hybrid VH-3 CRM were established. However, to calculate the total pack weights, some additional consideration for Battery Management Systems (BMS), cooling, and packaging was necessary beyond the total weight in cells. Therefore, a competitive aerospace cell-to-packaging weight ratio of 70% was assumed based on (Ref 7). Consequently, it was determined that 30% of each aircraft's battery would be unusable due to efficiency losses and performance degradation over time. The conclusive iteration of the upstream propulsion system weight (excluding liquid fuels) is presented in Table 4.

Table 4. Upstream Propulsion System Weight Breakdown

Component	DEP		Conventional	
	eCRM	*VH-3 Hybrid CRM*	*Twin-Engine CRM*	*Eight-Engine CRM*
Dry Engine(s)	-	452	1,194	1,346
VH-3 Hybrid Elements	-	198	-	-
Engine Oil	-	15	52	63
Battery Cells	998	330	-	-
Other (Packaging, Cooling, Accessory)	299	137	40	103
Total (lbs)	1,297	1,132	1,286	1,512

The downstream components, responsible for transmitting power generated by the upstream components to the rotors and other electrically dependent aircraft systems, were composed of two primary assemblies: the power distribution elements and the rotor subsystems. Given that each CRM configuration was to utilize the same rotor subsystems, the greatest discrepancies in downstream propulsion weight were attributed to the power distribution components. For the conventional two and eight engine designs, this power transmission segment involved various gearbox and driveshaft weights which, although akin in nature, were significantly higher for the twin engine design requiring a series of gearboxes and mechanical links than the direct drive eight-engine case.

Similar to the conventional configurations, accuracy in the gross weight predictions of the eCRM and VH-3 Hybrid CRM aircraft significantly influenced their electric motor selection, as the decision required a reasonable expectation of the motors' torque and power output a priori. Moreover, the priority of passenger safety led to the decision of sizing the electric motors to withstand the complete loss of at most two motors onboard the aircraft midflight while maintaining a controlled descent to a safe landing. Accordingly, eight power-dense H3X HPDM-250 motors, each designed with an anticipated continuous power of 200 kW (proven up to 180 kW) and integrated motor controllers (Ref 8), were selected to drive the eight equally sized rotors. Lastly, the hubs, hinges, and miscellaneous assemblies associated with the rotors themselves were estimates taken from NDARC. The total breakdown of downstream components is presented in Table 5.

Table 5. Downstream Propulsion System Weight Breakdown

Component	DEP		Conventional	
	eCRM	*VH-3 Hybrid CRM*	*Twin-Engine CRM*	*Eight-Engine CRM*
Gearboxes & Driveshafts	-	-	545	388
High Voltage Wires	24	24	-	-
Power Distribution Box	65	65	-	-
Electric Motors & Controllers	292	292	-	-
Cooling System	48	48	48	48
Rotor Blade Assemblies	197	197	197	197
Hubs & Hinges	75	75	75	75
Total (lbs)	701	701	865	708

The only component of the total aircraft weight remaining was the equipment weight fraction. It was presumed that all configurations included a standard equipment weight of 564 pounds, which included flight control, instrument, hydraulic, electrical, avionics, furnishing, A/C, and anti-ice systems according to (Ref 9). However, the eCRM model carried an additional 20 pounds of electrical weight to integrate its electrical equipment with its particularly large battery pack. By incorporating the final iteration of equipment weight into the assessment, a complete weight breakdown of each aircraft was assembled into Table 6. This table lists each weight category contributing to a total aircraft weight of precisely 4,856 pounds, or the exact weight of the base eCRM required to fly the modified 60-mile Uber mission with 1,000 pounds of payload. If the total weight of any other configuration without fuel exceeded this value, fuel weight was removed until the 4,856-pound maximum threshold was met.

Table 6. Total Weight Breakdown

Component	DEP		Conventional	
	eCRM	*VH-3 Hybrid CRM*	*Twin-Engine CRM*	*Eight-Engine CRM*
Structure	1,274	1,348	1,437	1,758
Upstream Propulsion	1,297	1,132	1,286	1,512
Downstream Propulsion	701	701	865	708
Equipment	584	564	564	564
Payload (+ Pilot)	1,000	1,000	1,000	1,000
Fuel	0	111	-296	-686
Total (lbs)	4,856			

Lastly, some commentary on volumetric constraints were warranted in the conceptual design of the hybrid CRM configuration. Figure 7 and Table 7 offer a glimpse of the original eCRM-001 aircraft next to the VH-3 hybrid powerplant and a stack of P28B batteries – 20 cells in length, 12 cells wide, and 13 cells tall with some space in between (slightly more than that required by the supplemental battery pack of the VH-3 Hybrid CRM) – to scale. Since a side view rendering of the eCRM-002 aircraft was not available, Figure 7 presents a side view of the eCRM-001 instead since the two vehicles have identical fuselage geometries. The VH-3 package could easily be housed in the aft cabin of the eCRM-001 (identical in length to the eCRM-002) following a minor extension of the fuselage. Likewise, the cells themselves being so modular and small could easily fill empty space within the fuselage or wings. Although not shown, extrapolating the total number of cells required by the base eCRM configuration suggests the fully electric version would also experience no airframe conformity issues.

Figure 7. Sizing perspective of the eCRM-001, VH-3 and battery pack volumes

Table 7. Volumetric Comparison of the VH-3 Hybrid CRM Elements in Figure 7

Dimensions	Aircraft Fuselage	VH-3 System	Stacked Battery Cells
Max Length [ft]	42.75	5.08	1.18
Max Width [ft]	5	2.92	0.71
Max Height [ft]	6.25	2.75	2.77
Total Volume [ft^3]	~670	~40	~2.3

RESULTS & DISCUSSION

From the assumptions and decision methodology adopted for sizing the four selected CRM aircraft, the converged gross weights of all configurations were within 700 pounds of the base eCRM. The VH-3 Hybrid CRM concluded a weight 111 pounds lighter than the eCRM and the difference of 111 pounds was allocated to fuel. The twin and eight-engine conventional layouts were about 296 and 686 pounds heavier than the eCRM without fuel, respectively, resulting in negative fuel capacities. For this reason, no further analysis on the two conventional engine aircraft was undertaken. The most significant disparities across all configurations were found in the upstream and downstream propulsion system weight categories, where the battery cells and their packaging in the eCRM constituted 33.6% of the vehicle's empty weight, surpassing the VH-3 Hybrid CRM's entire upstream propulsion system weight by 165 pounds. Collectively, the VH-3 hybrid package, lighter battery pack, and downstream elements accounted for only 37.8% of the gross aircraft weight, in contrast to propulsion weight fractions of 44.3% in the twin-engine and 45.7% in the eight-engine configurations.

Aerodynamic Analysis

Figures 8 and 9 depict several aerodynamic performance results of the 4,856-pound eCRM operating at International Standard Atmospheric (ISA) Standard Sea Level (SSL) conditions. In Figure 8, the total lift-to-drag ratio (L/D) of the eCRM is presented as a function of airspeed, representing the aircraft's overall aerodynamic efficiency. Modeling L/D for the eCRM involved a combination of the aircraft generating lift from its wing (like an airplane) and generating lift from its rotors (like a helicopter). The distinct airplane and helicopter L/D curves are designated as "wing lift" and "rotor lift" in Figure 8, respectively.

Given that the eCRM was designed to operate in rotor lift mode at low speeds and wing lift mode during cruise, the L/D curve illustrates the eCRM's gradual transition from rotor lift to wing lift between 38 and 96 knots. The upper limit of this range was fixed under the assumption that the aircraft required a 20% increase in airspeed over its calculated 80 knot stall speed to fully transition to wing lift mode, while the lower limit (wing lift to rotor lift transition) was defined as 40% of the upper limit. Furthermore, the maximum L/D of the eCRM was found to be approximately 10.7. In comparison to aircraft of similar size, such as the Cessna 310 or Beechcraft Baron 55, which can achieve L/D ratios closer to 13 (Refs 10 & 11), the eCRM inherits a significant reduction in cruise efficiency by storing its open rotors in the freestream.

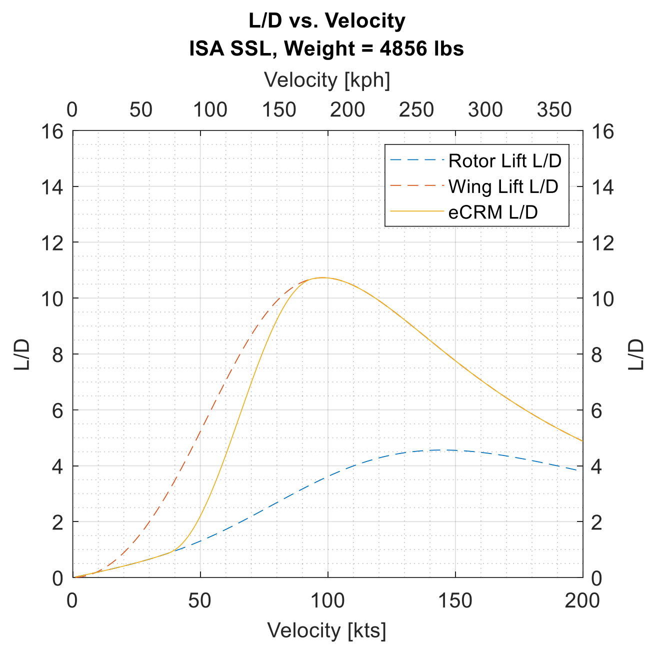

Figure 8. L/D vs. Airspeed plot of the eCRM aircraft

The power required curve for the eCRM, presented in Figure 9, distinguishes the rotor and wing lift components in an analogous manner to Figure 8, again clearly displaying the transition region between 38 and 96 knots. Each total power curve was further dissected into its induced, parasitic, and profile power curves, elucidating the predominant influence on the power required at each airspeed. Considering the base eCRM aircraft was only intended to reach 130 knots in cruise according to the modified Uber mission profile, Figure 9 suggests the main contributor to the total power required at most operating points was the induced power. The influence of induced power was particularly evident during rotor lift flight, where the drag associated with lift production was most pronounced. This result can be attributed to the large downwash induced by the rotors during rotor lift mode and wingtip-induced vortices during wing lift flight (Ref 12).

The total power curve reveals that the eCRM only required 210 hp (157 kW) during cruise, resulting in 85% of the VH-3's maximum continuous output. During hover, however, the aircraft required as much as 763 hp (569 kW), nearly four times that of cruise. Such a power demand during hover was the main rationale for equipping the VH-3 Hybrid CRM with a supplemental battery pack for boost power.

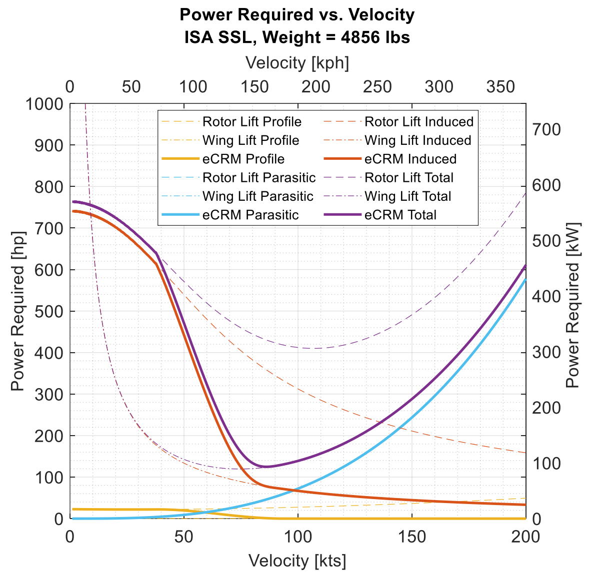

Figure 9. Required power vs. airspeed plot of the eCRM

Mission Performance

Figure 10 illustrates the performance of the eCRM during the modified 60-mile Uber mission. The solid line plot with the left axis represents the altitude over time, while the dotted line (right axis) depicts the total power required over time. Altogether, the entire mission was completed in just over 27 minutes following the flight path outlined below.

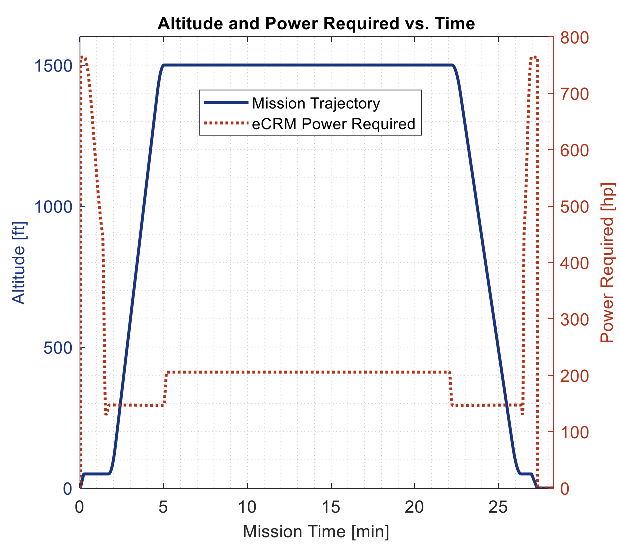

Figure 10. Altitude and power required as a function of mission time

Due to the VH-3 Hybrid CRM and eCRM aircraft's ability to support the same gross weight, their power requirement profiles were identical. Between sea level and 1,500 feet, the discrepancies in power required due to altitude effects were negligible, and the airspeed difference between the climb/descent vs. cruise mission segments was only about 25 knots. However, as illustrated by Figure 10, climb and descent during the mission at a horizontal speed of 105 knots resulted in substantially less power required than during the higher-speed cruise segment at 130 knots.

Considering the base eCRM aircraft configuration was specifically tailored to the bare minimum mission requirements, the depletion of the fully electric vehicle's battery down to 10% State of Charge (SOC) by the end of its mission was an expectation of its minimal design. It was assumed, for a realistic cycle life of an aircraft battery pack, that the maximum attainable SOC over time would be about 90%, and for the purpose of extending the battery packs' health, the packs were limited to draining their charge down to a minimum 10% SOC. Hence, Figure 11 shows the eCRM consumed its entire 80% available battery capacity over the course of its 27-minute mission.

In comparison, the VH-3 Hybrid CRM only needed 37 pounds of fuel to complete the mission, meaning the additional 74 pounds it could carry translated to pure reserve energy. Additionally, because the VH-3 had not maxed out its available power during climb and cruise, it was possible to use additional engine power to recharge its battery midflight and restore its maximum SOC within the first 20 minutes of the mission.

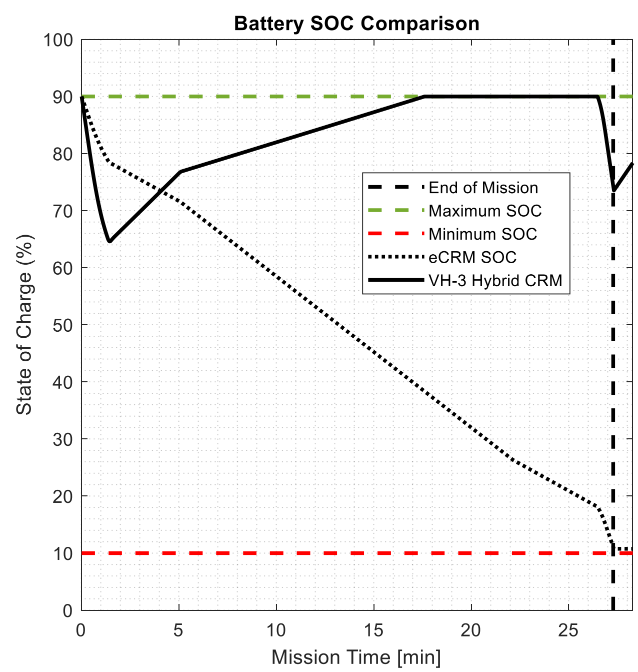

Figure 11. Battery SOC of the two CRM configurations over mission time

Figure 12 provides a detailed examination of the C-rate for the eCRM and VH-3 Hybrid CRM battery packs throughout the mission. C-rate signifies the rate at which a battery is discharged and is proportional to power output. During vertical takeoff and landing, the two CRM aircraft batteries required considerably higher C-rates than in cruise to generate the necessary rotor lift power required.

Despite the eCRM demanding more power from its battery during hover, Figure 12 reveals it was the VH-3 Hybrid CRM's battery with the highest discharge rate. This was due to the VH-3 Hybrid CRM utilizing the smallest battery feasible for hover, limiting its battery capacity, and consequently increasing the rate at which its energy was depleted. Compared to the high-capacity eCRM battery, exceeding the maximum discharge rate of the P28B was the primary limitation preventing the VH-3 Hybrid CRM's battery from getting any lighter. Nevertheless, the VH-3 Hybrid CRM distinguishes its advantageous aerial recharging capability in Figure 12, with negative points on the hybrid aircraft C-rate line representing its rate of recharge.

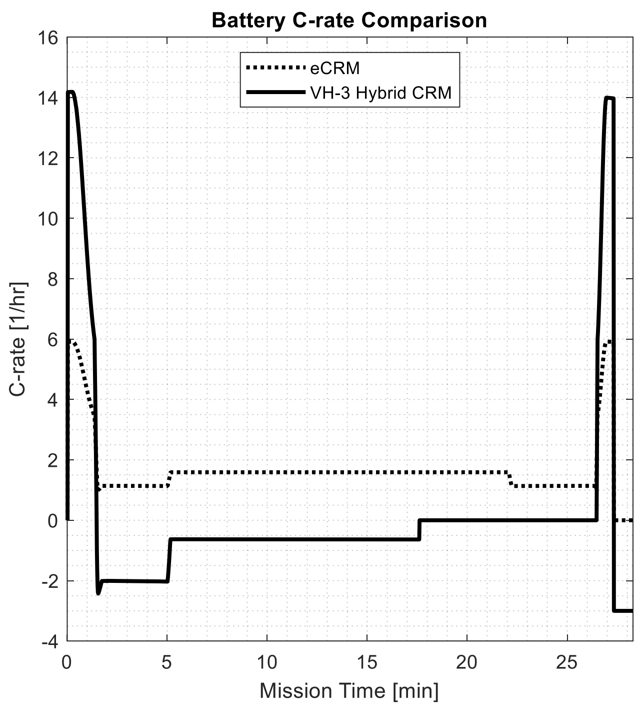

Figure 12. Battery C-rate of the two CRM configurations over mission time

Range Evaluation

By design, the base eCRM configuration was allotted the bare minimum battery energy necessary to complete the modified, 60-mile, point-to-point Uber mission. However, this case assumed a perfect, pinpoint flight could be executed without any traffic delays, loiter time, adverse wind, or contingency to reroute or hold in hover for more than a combined total of two minutes. In other words, the base configuration included no reserve energy.

This idealized expectation for even a single flight is exceedingly impractical and lacks any safety buffer for potential range-extending factors. The FAA mandates that all commercial aircraft certified in the U.S. abide by the strict reserve fuel requirements depicted in Figure 13. The stipulated reserve fuel required for each aircraft is contingent upon the type of flight conducted, type of aircraft flown, and, under Visual Flight Rules (VFR), differs between day and nighttime operation.

In accordance with 14 CFR §91.151, under VFR, all rotorcraft are required to carry sufficient fuel onboard to fly for at least 20 minutes beyond their intended point of arrival. For VFR airplanes, this requirement extends to 30 minutes of reserve fuel in daylight and 45 minutes for nighttime operations. If the flight falls under Instrument Flight Rules (IFR), however, 14 CFR §91.151 states that all rotorcraft must be able to fly to an alternate airport after reaching their intended arrival point and for an additional 30 minutes thereafter. Meanwhile, the regulation for IFR airplanes requires 15 minutes of reserve fuel beyond that of the IFR rotorcraft. Thus, if it is assumed that an unspecified alternate airport takes at least 20 minutes to reach from the intended arrival point, any commercial UAM aircraft classified as an airplane flying IFR would require a minimum of 65 additional minutes of reserve energy onboard in addition to that required to complete the original mission. Figure 13 summarizes the extent of these reserve energy regulations via illustration.

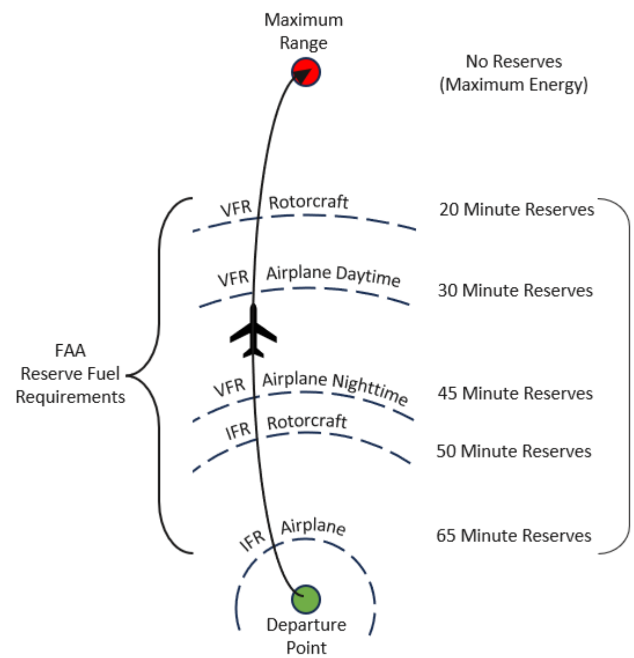

Figure 13. Illustration of the FAA commercial reserve fuel requirements

While mandating a commercial airliner to carry 65 minutes of reserve Jet A is now commonplace, devising a lightweight battery with sufficient C-rate to power an eVTOL aircraft and ample capacity for a 27-minute mission plus 65-minute reserve would seem an insurmountable challenge. Nevertheless, a comparative analysis was deemed essential to evaluate the potential range capabilities of an envisioned eCRM against those of a prospective VH-3 Hybrid CRM. As a result, Table 8 was compiled to present a comprehensive range study comparing the eCRM and VH-3 Hybrid CRM aircraft.

To summarize the final objective of this study, Table 8 shows the maximum percentage of usable energy and ranges the base eCRM and VH-3 Hybrid CRM configurations would be restricted to in order to meet each specified FAA reserve requirement. For instance, the "No Reserves" row displays the usable energy and range possible if both vehicles were to fully utilize their maximum energy capacity and neglect all mission segments but cruise. The second row portrays the same information, except when 20 minutes of available range capacity must be traded for reserve energy to meet the VFR Rotorcraft requirement, and so on. The results in Table 8 also assumed it takes 20 minutes of flight to reach the nearest alternate airport after the point of arrival as per the federal regulations. Accordingly, the IFR Rotorcraft and IFR Airplane requirements amounted to 50 and 65 minutes of reserve energy, respectively.

Table 8. Reserve Energy and Range Comparison

Reserve Requirement	**eCRM**		**VH-3 Hybrid CRM**	
	Useable Battery	*Range*	*Useable Fuel*	*Range*
No Reserves	80%	74 mi	100%	286
VFR Rotorcraft	27%	25 mi	81%	229
VFR Airplane – Day	No Solution		73%	201
VFR Airplane – Night	No Solution		56%	160
IFR Rotorcraft	No Solution		50%	144
IFR Airplane	No Solution		36%	103

The most striking observation from Table 8 was that the eCRM had no solution for the four most rigorous FAA reserve requirements. This meant that regardless of battery size, there was no gross weight at which the aircraft both had enough power from its battery to takeoff and enough energy from its battery to fly for more than the VFR Rotorcraft reserve requirements. Furthermore, even if the eCRM were to be categorized as a rotorcraft operating under VFR, the mere 27% of usable battery would only permit the aircraft to cruise a maximum of 25 miles before landing, not accounting for any hover, climb, or descent mission segments which would only further dimmish its attainable range.

Another imperative to highlight was that the eCRM results in Table 8 were derived only by supplying the fully electric aircraft with the most energy dense, commercially available cylindrical cell from the author's research: the LG M58T. With a tested cell energy density of 285 Wh/kg, even this state-of-the-art 21700 cell failed to provide more than 20 minutes of reserve energy after a knockdown in pack level specific energy.

On the contrary, the VH-3 Hybrid CRM effortlessly met the most demanding FAA reserve requirement, preserving 36% of the total fuel onboard as useable mission energy. A closer examination of Table 8 reveals an incremental decline in usable energy of the VH-3 Hybrid CRM, a consequence of allocating more total energy to the progressively stricter reserve requirements. As opposed to trading limited battery energy, exchanging fuel weight for reserve energy capacity had a drastic impact on weight savings and attainable reserve range. As depicted in Table 8, the VH-3 Hybrid CRM still offered 103 miles in cruise range after reserving well over half its total fuel energy.

Figure 14 puts a regional perspective on the outcomes of Table 8, showing just how much range translates to reserve energy if Orlando, Florida (in red) were to be the designated point of departure. Since the fully electric eCRM was forced to dedicate a significantly larger percentage of its total energy to reserves than the hybrid aircraft, the eCRM's range coverage is notably more limited than the equivalent VH-3 Hybrid CRM's. Only by expending its full energy capacity under perfectly ideal conditions could the eCRM possibly access the Daytona Beach and Tampa areas. Conversely, Figure 14 demonstrates how the VH-3 Hybrid with 65 minutes of reserve fuel onboard could travel as far as Jacksonville or St. Augustine. Without reserves, it is possible the VH-3 Hybrid CRM could even reach South Carolina, Alabama, and the Bahamian Islands.

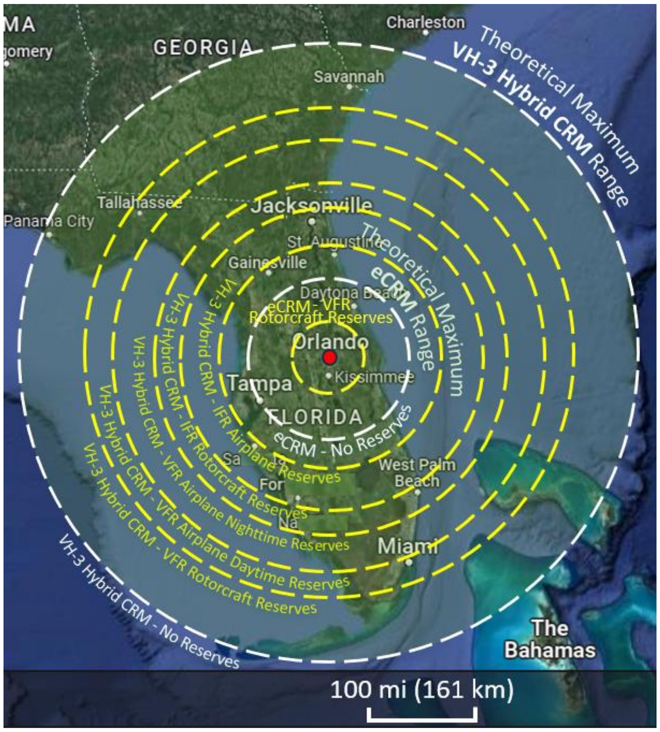

Figure 14. Illustration of the range implications in Table 8 out of Orlando, FL

Finally, a study examining the tradeoff between payload weight and range was conducted comparing the base eCRM and VH-3 Hybrid CRM aircraft. The findings of this investigation were compiled into the payload vs. range diagram shown by Figure 15. Under the assumptions of a 1,000-pound maximum payload weight limit and 60 U.S. gallon maximum fuel tank storage in the wings (Ref 11), the resulting shape of the payload weight vs. range diagram took the form of the pentagon depicted in Figure 15.

Figure 15 shows the addition of fuel weight to the VH-3 Hybrid CRM and the summation of payload and fuel weight as fuel was traded for payload to further increase range. Initially, with 1,000 pounds of payload and zero fuel, the VH-3 Hybrid CRM achieved no range (Point 1). However, with the allotted 111-pound (4.5-gallon) fuel allowance from the modified Uber mission, the VH-3 Hybrid CRM could transport 1,000 pounds of payload over 286 miles (Point 2). Beyond that point, payload could be proportionally exchanged for fuel up to the maximum 60-gallon (403 pound) fuel limit, reaching a range of 1,037 miles with up to 733 pounds of payload (Point 3). If further range yet was desired, eliminating all payload weight would result in a net gain of 79 extra miles for a total range of 1,116 miles (Point 4).

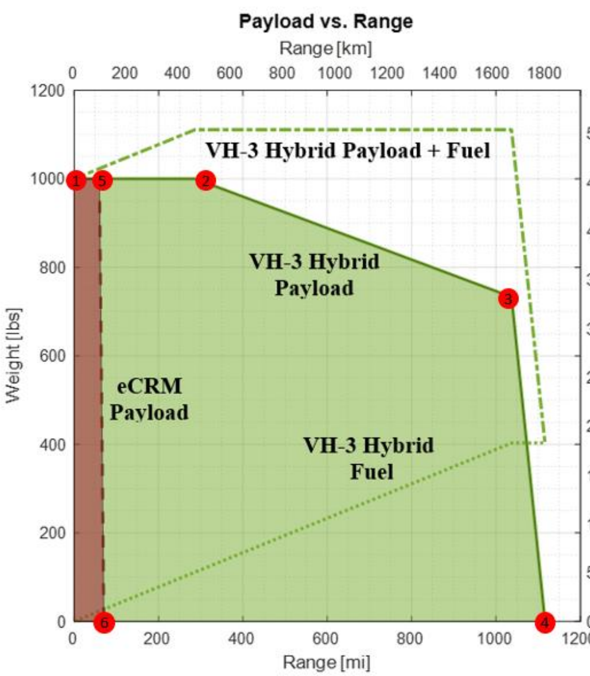

Figure 15. Payload vs. Range diagram of the eCRM and VH-3 Hybrid CRM

Constrained to its minimalistic design, there was very little room for the eCRM aircraft to achieve additional range beyond that of its intended 60-mile mission with 1,000 pounds of payload (Point 5). Due to the substantial weight penalty linked to incorporating more energy dense batteries, the range vs. payload analysis for the eCRM was conducted using its original battery pack comprised of P45B cells. Even so, without significantly increasing the aircraft gross weight or integrating fuel tanks, the most range-optimal option for the eCRM was to shed its entire payload weight and two-minute hover capacity for an additional 10 miles of range to total 70 miles altogether (Point 6).

CONCLUSIONS

Through a detailed, yet simple weight buildup methodology of designing four CRM aircraft with vastly different propulsion systems around the same mission profile and weight restrictions, the following conclusions were drawn:

1. Discrepancies between the upstream, downstream, and structural support components for the propulsion systems were responsible for the greatest variation in overall gross weight among the four different configurations. However, because the empty weights of the two conventional engine layouts exceeded the total empty weight of the base eCRM, they were deemed overly complex and heavy, thus eliminating them from further analysis.

2. With a mere 111 pounds separating the empty weights of the eCRM and VH-3 Hybrid CRM, the two vehicles exhibited comparable aircraft geometry and aerodynamic performance. Yet, notable differences began to surface during the mission performance study, particularly after examining each vehicle's battery pack characteristics. Upon closer review of their mission profiles, it became evident that the larger capacity eCRM battery yielded a lower C-rate during the rotor lift mission segments compared to the VH-3 Hybrid CRM, an advantage for the eCRM that could lead to fewer thermal stresses and cooling requirements for its battery. Conversely, the VH-3 Hybrid CRM's aerial recharging capability enabled its battery to remain well above the minimum SOC for the entire duration of its mission, translating to more end-of-mission discharge capacity for emergency reserve power and better overall health of the battery pack.

3. In the range evaluation studies, discrepancies between eCRM and VH-3 Hybrid CRM layouts had radically emerged. In accordance with the FAA's reserve fuel regulations, the eCRM could only converge on a battery weight that would satisfy the VFR Rotorcraft requirements using one of the highest energy density cells commercially available and offered minimal range beyond that required for its standard 60-mile mission. In the hybrid CRM configuration, not only did the VH-3 meet the required commercial IFR Airplane reserve requirements with substantially more range than the eCRM, but by increasing the percentage of useable fuel energy, the aircraft could even travel out-of-state from Orlando. Benefiting from its remarkable system energy density, the VH-3 Hybrid CRM was

depicted in a payload-range diagram outperforming the base eCRM configuration with a roughly tenfold increase in range by trading payload for fuel.

Future Work

Future work to improve the results herein must expand upon the simplifications and assumptions made in this paper. This entails delving deeper into the conventional configurations, volumetric constraints for the non-VH-3 propulsion elements, higher fidelity in the rendering of the airframe geometry, and further considerations for improvements in battery technology. To account for future advances in battery specific energy and power, it may be worth considering experimental and theoretical battery cell performance in addition to the commercially available cells examined here. Moreover, future work must investigate the effects of other influential performance factors such as nonideal weather conditions and alternate mission types. Specifying a range tolerance for a diversion to an alternate airport, for example, would better account for variations in the actual fuel and energy reserve requirements as specified by the FAA.

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