

MISTRAL: Concept and Analysis of Persistent Airborne Localization of GHG Emissions

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In this study, we propose a concept for localizing and mitigating greenhouse gases and other emissions from areas of various sizes, using a multiscale, airborne localization fleet, supported by information from satellites. Our objective is a rapidly implementable capability for the reduction of atmospheric methane by empowering the communities in proximity to emissions to actively contribute to methane mitigation via fleet operations by local governments, first responders, and individuals. Fully autonomous operations are economically desirable and technically feasible now. However, the development of regulations for autonomous operations is in early stages. Since rapid impact is critical to reducing emissions, the concept starts with remotely controlled vehicles. As regulations for autonomous operations reach maturity, the concept can be easily transitioned from the remotely piloted to autonomous mode. We report on a preliminary system analysis of the concept. Localization of methane emissions from the Permian Basin oil and gas production site serves as the design reference mission; however, the airborne concept is applicable to a broad range of use cases, and we describe several in this analysis. We consider leveraging satellite and ground-based resources within the airborne concept of operations. The study analyses uninhabited aerial system localization operations under the most conservative assumptions on resources and available information. Even under these assumptions, the concept is shown to be viable for local community operations.

Nomenclature

CH ₄	=	Methane
GHG	=	Greenhouse Gas
CO ₂	=	Carbon dioxide
COTS	=	Commercial Off the Shelf
DAC	=	Direct Air Capture
DVF	=	Desirability, Viability, Feasibility
EMIT	=	Earth Surface Mineral Dust Source Investigation Mission
EPA	=	Environmental Protection Agency
GWP	=	Global Warming Potential
LiDAR	=	Light Detection and Ranging
LTO	=	Landing to take-off (a complete mission of an aircraft)
MMCF	=	Million cubic feet
RP-1	=	Rocket Propellant-1
SME	=	Subject Matter Experts
UAM	=	Urban Air Mobility
UAS	=	Uninhabited Aircraft System
UTM	=	UAS Traffic Management
VTOL	=	Vertical Takeoff and Landing Vehicle

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I. Introduction

Human activities have significantly altered the composition of the Earth's atmosphere, leading to a rise in greenhouse gases (GHGs), such as carbon dioxide and methane. Scientific analysis indicates that these two gases are responsible for the dramatic increase in Earth's average temperature [1]. The primary source of CO₂ emissions is the burning of fossil fuels, including coal, oil, and natural gas, for energy production. Deforestation, industrial processes, and cement production also contribute to CO₂ emissions [1].

Numerous on-going efforts in reducing carbon in the atmosphere, while essential, are not likely to have sufficient effect in preventing the average temperature increase from exceeding 1.5°C above preindustrial levels in less than five years – the value considered a tipping point for irreversible and unpredictable changes in the climate [107]. For instance, while ubiquitous electrification of transport is an important step toward reducing GHG emissions, it is a long-term solution requiring major developments in infrastructure and technology. Direct carbon removal, often termed direct air capture (DAC)—absorbing CO₂ from the air and sequestering it in the ground or re-purposing the gas for commercial applications—faces the challenge of scaling. For example, the now largest DAC installation, Mammoth, will be able to pull 36,000 tons of carbon from the atmosphere per year at full capacity, according to its developer. That is equivalent to taking approximately 7,800 gas-powered cars off the road for a year [2]. To put the scalability challenge in perspective, there are approximately 1,475 billion vehicles on the road on Earth, with 2.2% of electric vehicles in 2024 [54], making the number of gas-powered vehicles approximately 1,442,550,000. The 7,800 vehicles that the Mammoth DAC installation may effectively offset constitute only 0.0005% of the total, and it would require nearly 185,000 similar DAC installations to offset all gas-powered cars.

Additional limitations of DAC include the expense and extensive energy needs for building and operating the infrastructure. Some climate advocates are concerned that DAC could distract from policies to cut fossil fuels. A recent analysis [3] suggests that fossil-fuel companies' use of captured carbon dioxide to extract more fossil fuels leads to a net increase in atmospheric CO₂.

The inherent long-term nature of the approaches to CO₂ reduction and the need to make a *rapid impact* on GHG emissions has led us to consider a complementary approach: methane reduction alternatives. Methane, although present in smaller quantities than CO₂, has approximately 28 times the warming potential of CO₂ over a 100-year period, and over 80 times the warming potential of CO₂ over a 20-year period [4-6]. Two major sources of anthropogenic methane are agricultural activities, such as livestock farming, and the extraction and transportation of fossil fuels. Microbial biogas generation at landfills and wetlands resulting from, e.g., rice production, also contributes to methane emissions. Mitigation of various agricultural methane emission sources is in development (see, e.g., [55]). However, global warming has already initiated a vicious circle in methane release from natural sources: melting permafrost and warming oceans are releasing methane, which increases the warming, which in turn releases more methane from permafrost and oceans. Reducing anthropogenic methane emissions is crucial as it can have a significant impact on short-term climate change [4-6].

In this study, we focus on a source of emissions with high contribution of methane to the atmosphere, as well as a high potential for preventing the emissions – large oil and gas production sites, such as the Permian Basin in the United States. NASA's recent Earth Surface Mineral Dust Source Investigation (EMIT) mission identified the Permian Basin as one of the “super-emitters” of methane [7].

Discussions with subject matter experts (SME) at oil and gas production firms have revealed that much of methane emission at the production sites is the result of various mechanical failures, such as leaks in the pipelines and equipment or unobserved cessation of methane flaring (the practice of burning excess natural gas associated with oil production). Unlit flare emission rates observed in emission studies ranged from 500 to 2000 kg of methane per hour [64]. Per industry SME input, the localization of leaks is the major unsolved problem.

In this study, we propose a concept that combines persistent airborne operations that provide pointers to emission sources at sufficiently high resolution to ensure the repair of the hardware and removal of leaks. The airborne operations are supported by satellite-based information to reduce the localization area for airborne assets.

The trend of growing methane emissions is well known, and there is much heated discussion about the need to reduce emissions. In practice, the trend in methane emissions is growth and re-distribution [1]. Re-distribution refers to the reduction of emissions in some areas and growth in others. We believe that to make necessary, rapid reductions in emissions requires empowering the communities most affected by emissions to localize and report emissions.

Therefore, ***our objective is a rapidly implementable, low-cost capability for the reduction of atmospheric methane by empowering the communities in proximity to emissions to localize methane emissions via fleet operations by local governments, first responders, and individuals; and to actively engage in the Environmental Protection Agency's (EPA) methane reporting projects.***

Local communities may share emission information with EPA via two lines of reporting. Under the Super Emitter Program [10], third parties may apply to EPA to become certified to report data about large methane emissions to the agency. Individuals may also report environmental events that may pose threat to the environment or human health to EPA environmental enforcement personnel [108].

In this report, we start with a brief history of the project and a comparison of current localization methods. The goals for the proposed localization concept follow, defining the ultimate evaluation criteria for the concept. In the subsequent sections, we describe the concept, which is generally applicable to observation and localization of any emission or phenomenon, and its components – vehicles, sensors, operations. We present preliminary analysis results as well as a preliminary assessment of the desirability, viability, and feasibility (DVF) of the general concept space. A section on risks in return on investment describes diverse and simultaneous dual-use applications of a localization airborne fleet. Finally, concluding remarks outline the steps that would bring the concept into practical use.

II. Background: A History of Pivots

The initial intent of the effort described in this study was to develop an approach for direct *airborne* cleanup of carbon dioxide from the atmosphere. The original idea was to use an airship or other appropriate vehicles to loiter over high-concentration emission areas and absorb or adsorb CO₂ via dual means: a biomass, such as green paint [56], covering a significant part of the airship's surface and a chemical air scrubbing apparatus, to be developed, carried as cargo.

On consultation with several atmospheric science SMEs, the idea proved to be not scalable to meaningful cleanup levels, due to swift dissipation of the gas, followed by extremely low concentration in the atmosphere for the purposes of adsorption or absorption, depending on the scrubbing technology. At the time of the initial proposal, the largest ground DAC facility, Orca [57], captured just 11% of gas captured by the Mammoth facility described above, which was already shown to have minimal impact.

The investigation turned to direct airborne cleanup of methane. A GHG even more potent than CO₂, methane appeared to be a more plausible target for direct airborne cleanup, because an aircraft can loiter relatively close to high-concentration emission sources, such as oil and gas production sites and landfills, potentially capturing methane before it dissipates to low concentrations impractical for direct cleanup. Despite immediate reservations about the scalability of direct cleanup, the atmospheric science SME had not dismissed this option as obviously infeasible. However, on further research, direct methane capture was found to face serious difficulties, at odds with the objective of rapid implementation, as follows.

Although several key approaches to capturing methane are being explored, they are in their infancy. Catalytic oxidation uses catalysts to convert CH₄ into CO₂ and water [58]. Materials with high surface area, such as zeolites and metal-organic frameworks, can adsorb methane from the air [59]. Methanotrophic bacteria, which consume methane as their energy source, are also being explored [60]. Photocatalysis uses light-activated catalysts to break down CH₄ into less harmful substances [60]. While these methods are promising, they face the challenges of the apparatus size/weight, scalability, substantial energy requirements (and therefore, a significant carbon footprint), and great expense. Biological methods demand less energy than chemical approaches, but maintaining favorable conditions for bacterial growth and activity still requires energy. Of course, should methane capture methods evolve sufficiently for practical use and become miniaturized and light for a “green” aircraft payload, an airborne localization fleet can carry the scrubbing apparatus in addition to localization sensors.

Nonetheless, even if the energy challenges of direct methane capture can be overcome, the low concentration and the ensuing scalability issues remain. The following back-of-an-envelope computation outlines this major obstacle to rapid implementation, demonstrated on the over-a-landfill atmospheric cleanup use case.

Consider that the U.S. landfills alone released approximately 119.8×10^6 metric tons of CO₂ equivalent (CO₂e) of methane in 2020, which amounts to 17.1% of total U.S. anthropogenic methane emissions [61]. This makes landfills an attractive cleanup site for such airborne assets as airships, given that landfills are stationary.

There are over 1,250 landfills in the U.S. Let us assume that each landfill emits an equal amount of methane, on average. This yields $109.8 \times 10^6 / 1,250 \approx 95,840$ t CO₂e of CH₄ emission per landfill, per year. (As a reminder, for comparison, consider that the largest, until recently, ground DAC installation can remove approximately 4,000 t of CO₂ per year.) This makes $95,840 / 365 \approx 263$ t CO₂e of CH₄ per landfill per 24 hours. Converting CO₂e to CH₄ yields $263 \text{ t} / 25 \approx 11$ t of CH₄ per 24 hours. (The conversion factor from CO₂e to methane is typically 25-36, i.e., 1 kg of methane is equivalent to 25-36 kg of CO₂e, depending on the source and the specific global warming potential (GWP) used in the calculation; see the explanation of the computation in, e.g., [109]. The back-of-the-envelope computation used the factor of 25. The analysis in Section VIII uses the upper value of 36.)

Assuming that we can capture 50% of persistent emissions per unit time with one scrubbing apparatus per aircraft, with scrubbed gas amounting to 0.5 t, we would require eleven large airships loitering over each landfill. The figure of 0.5 t was taken as the approximate payload considered in a system analysis of electric, long-duration aircraft [62]. The figure does not include the weight of the capture-and-scrub apparatus, which would further increase the number of required carrier aircraft. Even with the extremely generous assumption (according to SMEs) of 50% capture, such a fleet would be impractical. Were it not also unviable due to the expense and paucity of helium, a single airship capable of lifting 0.5 t would be the size of a football field [62]. Moreover, the assumption of 50% capture per unit time is not just generous, it is entirely unrealistic, given the rapid dissipation of gas in the atmosphere. To capture gas at such a rate, the capture mechanism would have to be directly on top of the source, which is impractical, both over landfills, where humans operate, and in such hazardous and safety-critical domains as oil and gas production sites.

Again, should the capture technology become light, miniaturized, and evolve to high throughput capacity in the future, scrubbers can be carried by airborne localization assets and supplement other carbon mitigation efforts.

Given that the target of this activity is *rapid* implementation, the final pivot in the research direction took place after a discussion with a SME team from two oil and gas production firms (Exxon Mobil and Shell Oil). The SME supported the view expressed by the atmospheric science SME: ***the most effective and currently the only scalable way to mitigate methane emissions is to stop them at the source***. Oil and gas production SME claim that localization of the emission sources is an unresolved problem and, should they be informed of the emission locations, the production companies would immediately repair the leaks that cause emissions.

In summary, given the input from the atmospheric science and oil and gas production industry SMEs, the team turned to solving the problem of emission localization. The EPS GHG reporting program, which requires reporting by producers [63], is now supplemented by reporting from third party observers [10, 108]. Third party observation rules provide additional motivation for strengthening the localization technology for use by local communities. Potential methane emission reduction due to localization is described in the sections on the system analysis and feasibility of the concept, with sample numbers also shown in Appendix B.

III. State of the Art: Ground, Airborne, and Satellite Localization

As the present investigation focuses on localization of emissions, in this section, we overview the current approaches to emission localization, as well as their comparative properties.

A. Ground Localization

The following methods are common for ground-based localization of gas emissions:

- Point-in-Space continuous monitoring systems use networks of fixed sensors to monitor wind data and methane concentrations. Point sensors can be very accurate, but they provide information about the gas concentration at a single point. To localize gas emissions, the network is used to triangulate the source of the emissions. The sensors typically measure methane concentrations in and wind speed/direction, which helps to pinpoint the emission source. This method can be expensive and time-consuming, and it may not be practical for large areas or mobile sources of emission [66].
- Laser absorption spectroscopy uses open-path sensors to measure the concentration of a specific gas along a line of sight. These sensors are typically mounted on towers or other elevated structures and use a laser or other energy source to detect the presence of the gas. Open-path sensors can cover a larger area than point sensors, but they may be less accurate and can be affected by interference from other sources of light or atmospheric conditions [66].
- Differential optical absorption spectroscopy uses light to measure the concentration of gases in the atmosphere. By analyzing the absorption spectra of various gases, the method can identify and quantify the presence of multiple gases in a single measurement. The approach can be used to measure gas concentrations over long distances, making it a useful tool for localizing emissions from industrial facilities or other large sources [67].
- Mobile sensors mounted on cars can be used to measure gas concentrations as they move through an area. By comparing the gas concentrations at different locations, mobile sensors can localize emissions sources in real time. However, ground mobile sensors can be affected by interference from other sources of gas or environmental conditions, and they may not be suitable for measuring very low concentrations of gas [68]. We hypothesize that localization from airborne assets would be less affected by environmental

conditions close to the ground, with airborne sensors functioning in a more homogeneous environment than do ground-based sensors.

Overall, ground-based localization can be used in conjunction with airborne localization, should the airborne system have access to ground-based sensor data, such as location and sensor type. For instance, the known availability of ground-based localization in a specific area may reduce the number of required localization flights or legs within a campaign. An investigation of the optimal coupling among ground-based, satellite-based, and airborne-based information, to optimize the resources required for accurate localization of emissions, is relegated to future studies.

B. Airborne Localization

Methane localization via airborne Light Detection and Ranging (LiDAR) instruments is an existing commercial activity; see [8] for instance. Current operations are single campaigns in a inhabited aircraft over a well-defined route, for purchase by customers such as power companies. Data are the product of each campaign. While efficacious for detecting leaks along a pipeline or other infrastructure belonging to a specific company, a single campaign approach is difficult to scale for persistent observation over a large, frequently emitting area, given the high cost of onboard piloted operations. The high cost presents the salient challenge for one of our main objectives: the affordability of persistent localization by the community operators in the affected areas. In addition, the required energy and the emissions produced by flying aircraft with a pilot onboard are, in general, greater than that required for flying the same sensor on an uninhabited aircraft. Ensuring that the emissions from detection campaigns do not outweigh the emissions saved from finding and stopping leaks is important to the feasibility of the airborne localization concept, and uninhabited aircraft provide increased likelihood of feasibility in this sense.

C. Satellite-based Methane Localization

Recent developments in improved resolution of localization from satellites, such as the Carbon Mapper project [9] and MethaneSAT [65], hold a potential for addressing localization from space. Efforts to populate the Earth's orbit with emission-detecting satellites are ongoing [85-94]. Global coverage and the increasingly accurate estimates of emission location will undoubtedly prove beneficial to the analysis of the emission trends and their effects on the climate. Nonetheless, the satellite-based approach has several difficulties.

Observations from satellites are often considered to have lower cost than inhabited airborne observations. However, when viewed from a system perspective, the cost of satellites is high. The approximate total cost of launching and operating a methane monitoring satellite varies. For example, MethaneSAT, developed by the Environmental Defense Fund, costs approximately 88M USD to build and launch [92]. The Tanager-1 and Carbon Mapper satellites together cost approximately 130M USD [92]. A general estimate of cost for construction, launch, and three years of operations is approximately 165M USD [92]. The projected operational life of a methane monitoring satellite typically ranges from five to ten years. Amortizing the 165M USD cost over the generous assumption of a 10-year operational life provides an average cost of over 45,000 USD per day.

Considering that a Beechcraft King Air aircraft can be rented for around 2,000 USD per hour [110] (and other aircraft that are less expensive could also be leveraged), the actual cost of inhabited airborne operations may be less expensive or roughly equivalent to satellites when considering all applicable costs.

The environmental impact of launching a methane-detecting satellite can be significant, particularly in terms of carbon footprint. Rocket launches typically use fuels like RP-1 (a refined form of kerosene) or liquid hydrogen, which produce carbon dioxide and other pollutants. For instance, rocket launches using RP-1 collectively emit around 1,000 metric tons of black carbon (soot) into the stratosphere annually [95]. The carbon footprint of a single launch can vary depending on the rocket type and fuel used. For example, a Falcon 9 rocket launch by SpaceX, which uses RP-1, can emit approximately 336 metric tons of CO₂ per launch [95]. For comparison of emissions, consider that, on average, a Beechcraft King Air aircraft produces approximately 400 kg of CO₂ per landing to take-off (LTO) flight [124], making the CO₂ output of a single satellite launch equivalent to over 670 King Air flights.

Studies have begun to express serious concerns about the environmental effects of massive satellite launches. The released soot absorbs heat and could increase temperatures in the upper atmosphere. When satellites burn on re-entry, the release of aluminum oxides alters the planet's thermal balance as well. Both types of emissions have the potential to destroy ozone. These effects are discussed in ref. [100], which contains references to studies therein.

There is also a growing concern about overpopulating Earth's orbit with satellites, which can lead to several significant risks, such as space debris from defunct satellites [96]. Collisions lead to a conjectured cascading effect known as the Kessler Syndrome, where the density of objects in orbit is high enough that collisions between objects could cause a chain reaction, making space activities increasingly hazardous [97]. Managing and tracking large numbers of satellites becomes more complex, increasing the likelihood of operational errors and collisions [98].

Finally, launch and operation of large satellite constellations can have additional environmental impacts, including the potential for increased atmospheric drag, which can affect satellite lifespans and the dynamics of re-entry [99].

That said, the information from satellites will likely be a valuable contribution to reducing the localization area before airborne assets can be engaged, thus reducing the financial and environmental costs of airborne operations.

Given the uncertainties of data availability, persistence of observation, the permeability of the weather to satellite-based sensors in various areas, and environmental effects, we suggest that to achieve the desired outcomes in methane reduction, a persistent airborne solution should complement the satellite approach.

D. Summary of Current Localization Methods and Their Attributes

Table 1 summarizes the attributes of the three *current* general localization approaches, including their benefits and limitations.

Table 1: Current Localization Method Attributes.

	Ground	Airborne	Satellite
Advantages	Can be in proximity to potential emission sources.	Can provide higher spatial resolution than satellites, making it easier to accurately locate methane sources. Provides broader coverage than ground-based localization.	Can provide global coverage; has potential for observation over large areas.
	Relatively low cost of operation.	Flying at lower altitudes than satellites can improve the sensitivity of methane detection.	Plume detection from difficult-to-access areas, such as remote or protected regions.
		Provides real-time data for quick identification and response to methane emissions.	Data can be combined with other data sources (e.g., weather models and geographic information system (GIS) data) to provide more detailed analysis of methane emissions.
		Given appropriate sensors, can be used for identifying and tracking emission of any material or for observation of any phenomenon.	
Limitations	Extremely limited in the coverage area.	More limited in the coverage area than satellites.	Can be affected by weather conditions, such as clouds and aerosols.
	Can be affected by interference from other sources of gas or environmental conditions.	Can be affected by weather conditions, e.g., sensitive to turbulence.	Data can have longer lag times than air or ground sensing, which can make it difficult to respond to methane emissions in real-time.
	May not be suitable for measuring very low concentrations of gas.		Limited to sensors installed pre-launch.
			Growing concerns over environmental impacts and potential overpopulation of the orbit.

In summary, given current approaches to localization, satellites appear to be appropriate for monitoring methane emissions over large areas and can provide global coverage; airborne assets are better suited for high-resolution, real-time localization of methane sources over smaller areas; and ground localization is suited for emission detection in small, well-known areas, with a relatively homogenous environment. Considering the ongoing developments in remotely piloted and, eventually, autonomous vehicles, the cost of airborne observations is likely to be significantly reduced.

IV. Airborne Methane Localization System Goals

In this section, we describe goals for the proposed concept and motivate the goal of the accessibility of the tools by local communities.

A. System Goals

The concept under development must satisfy the following:

- A system for methane and other emission localization must be amenable to *rapid* practical implementation. By “rapid” we mean two-three years. Ease and rapidity of implementation are necessary to make a meaningful contribution to reducing methane content in the atmosphere because of the impending near-term climate changes, should the current trends in GHG emissions continue.
- The system must be financially viable for operation by local (municipal, county) governments; ideally, by first responders, such as fire services, and, eventually by individual members of the public. Financial viability means affordability within the bounds of the rainy-day portions of average municipal budgets.
- The system must have an interface for ingestion of satellite data and, ideally, information about the available ground localization assets, to enable reduced search areas for airborne assets and efficient operations.
- The total carbon footprint of the system must not exceed a prescribed percent of the projected savings in methane emissions. Specific values of allowable carbon footprint are to be determined in discussions with EPA and atmospheric science SME, for practical operations.
- The localization resolution must be sufficient for determining the source of emissions to initiate repairs and, if needed, to conduct ground-based refinement. Initial estimates are that the resolution must not exceed 10 m, but a final value is to be determined in discussions with SME.
- The system must be equipped with an informative human-machine interface.
- The system must have an actionable interface for reporting to EPA and emission producers.

The goal of rapid implementation requires that the concept be developed in stages: although complete aircraft autonomy is the eventual goal, remotely piloted systems must be feasible at the time of initial implementation. Rapid system integration also affects the choice of vehicles: the initial concept would rely on commercially available uninhabited aircraft systems (UAS). Should the concept enter practical implementation, optimal vehicle design for specific geographical areas and application domains could be considered.

B. Motivation for the Objective of Empowering Communities

The desirability of reducing methane in the atmosphere is unarguable, given that the estimates of actual methane emissions, both anthropogenic and natural, are continually exacerbated by warming and are severely underestimated [1, 120]. Examples of the consequences of warming abound. For instance, the latest findings [69] indicate that the Antarctic Thwaites and Pine Island glaciers are melting faster than at any time in the past 5000 years, due to the previously unknown influx of the salt water beneath the glaciers. The melting of the Thwaites glacier could trigger the collapse of the entire Antarctic Ice Sheet, which would raise sea levels by over ten feet, with enormous effects on the world’s coastal populations. In an illustrative example, the National Oceanic and Atmospheric Administration (NOAA) Sea Level Rise Viewer [70] shows what the ten-foot increase in the sea water level would do to the area that houses the NASA Langley Research Center.



Figure 1: The effects of 10-foot sea level increase in a part of coastal Hampton, VA (screen shot from [70]).

The need to curtail methane emissions is evident and has been known and discussed in the scientific literature for a long time, but the reality is that anthropogenic methane emissions are increasing [1].

In asking why all the available information has not been effective in reducing methane emissions, we have concluded that the hope for change lies in equipping the communities most affected by methane emissions with tools for localization and action, considering the EPA third party reporting programs.

The effects on individual communities in the vicinity of fossil gas leaks is dramatic in addition to the overarching climate effects of global warming. Recent findings by researchers at the North Carolina State University [71] show that venting and flaring by the U.S. oil and gas industry releases pollutants that lead to 710 premature deaths and 73,000 childhood asthma aggravations each year, with a health bill of 7.4 billion USD. When counting air pollution from other parts of the oil and gas lifecycle in the U.S., including production, transportation, and storage, the total impact is estimated at 7,500 excess deaths and a 77 billion USD annual health bill [71].

In a specific example, a grass roots organizer who lives in Eddy County, New Mexico, has reported that at least six gas pipelines run through the back of their family property, a fracking site is located approximately two miles away, and active oil rigs are within sight of the local primary school, health clinic, and senior center. At night, rows of flares burning off excess gas from oil wells are dense enough to light up the horizon. Young families are reported to abstain from having children for fear of health problems because of proximity to the production sites: excessive presence of CH_4 in the atmosphere is linked to respiratory, cardiovascular, carcinogenic, and central nervous system effects, especially with long exposure [71]. Reagan County in West Texas is one of the most affected by CH_4 emissions in the Permian Basin. During the June 2023 heat wave, emissions were reported to be nine times the average for the previous six years, pointing to a clear increase in the emission trends, as well as the increasing risks of negative health impacts.

We conjecture that, given the EPA GHG third party reporting programs and the activism in local communities most affected by proximity to the oil and gas production sites, the local governments and activists can be most effective in curtailing and, ultimately, minimizing methane emissions if they are equipped with user-friendly localization and reporting tools. For the communities directly impacted by the emissions, the issue of excessive methane in the atmosphere is not an abstract number but the immediate reality of every-day existence. Therefore, it is essential to provide communities with the tools and education for localizing emissions.

V. Design Reference Mission: The Permian Basin

Although the proposed concept is applicable to any domain of observation and localization of emissions, both anthropogenic and natural, we chose the Permian Basin as the design reference mission (DRM) because it is representative of general multi-scale observation and localization problems, and because the Permian Basin has been identified as one of the super-emitters of methane by NASA's EMIT project [7].

The site, located in West Texas and the adjoining zone of southeastern New Mexico, covers a region of approximately 86,000 square miles, with the production area of approximately 250 miles by 300 miles as shown in Figure 2 [75]. The basin contains more than 7,000 fields [72]. The production is taking place in more than sixty counties. Recent increased use of enhanced-recovery practices in the Permian Basin has resulted in a substantial increase in the U.S. oil production, accompanied by effects on the ecology [73, 74].

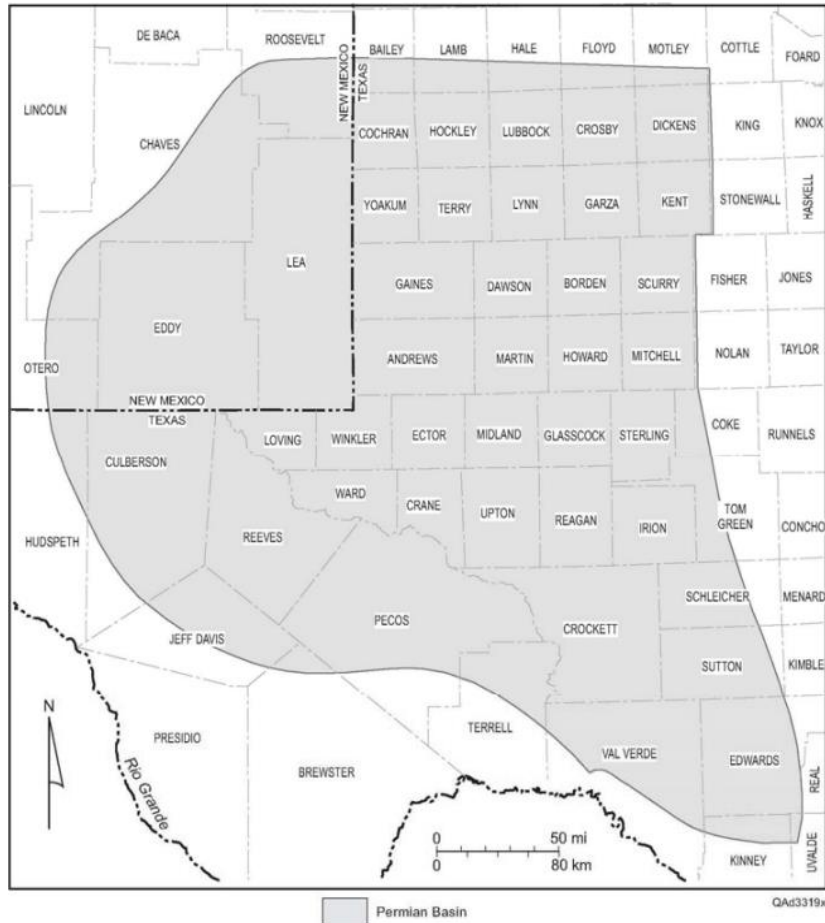


Figure 2: West Texas and Southeast New Mexico Counties in the Permian Basin (courtesy authors of [75], included with permission).

Given its large area and the diversity of producers, from world-known companies to a single well in a private backyard, the Permian Basin presents a challenging use case for the design of persistent airborne monitoring. Concepts for smaller and more homogeneous areas form special cases of the more general concept suitable for the Permian Basin. Moreover, localization over the Permian Basin and similar sites serves as an *actionable* scheme for the rapid prevention of methane emissions. Once informed of an active emission source, an oil producer can conduct repairs quickly and eliminate the emission. This function would be facilitated by the two EPA programs for third-party observation and reporting of emissions. As mentioned earlier, one of the programs [10] requires registration with EPA and is, therefore, more accessible to local community governments, while the other [108] is an online reporting tool open to all.

In contrast to oil and gas production sites, other massive anthropogenic emitters, such as landfills and agricultural sites, are not as amenable to rapid action in response to localization information.

VI. General Concept of Operations

The site of observation is partitioned into units of area (UoA). For the purposes of this analysis, we assume that UoA are counties impacted by oil and gas operations, each county owning a fleet of Uninhabited Aircraft Systems (UAS). In practice, the partition of the areas will depend on the size of the administrative domain, the proximity to the oil fields, and the owner of the fleet. For instance, in a large county, several municipal governments may each employ a fleet. If a large oil and gas production company owns UAS fleets, the observation area may cross county boundaries.

Assumption: Each UoA fleet operator is equipped with a map of current production sites, transport routes, and pipelines within their area. The map is updated periodically. In unmapped, hard to reach areas, observation can proceed

along optimal grid search patterns. However, in known production areas, accessibility to maps will allow the operators of the fleet to minimize the use of resources and expedite localization and, hence, removal of emissions.

For each UoA, operations combine cruise and loiter missions as follows. (In the description of the operations, the term “waypoints” refers to intermediate stops on the search trajectory, where the assets must recharge or refuel.)

Case 1: Localization over Known General Area: Emission Data from Satellites Available Daily

At satellite data comm time:

UoA station: obtain emission data from a designated satellite

If (satellite data indicate emissions) then

 Compute initial optimal asset delivery plan and trajectories with battery re-charging or refueling stops

 For all assets Do

 For all charging/fueling waypoints Do

 Launch asset

 Cruise to edge of general area indicated by satellite

 Asset loiters to localize emission to $O(1\text{ m})$ accuracy

 Record and transmit localization data

 If (sufficient onboard energy)

 Cruise to edge of general area indicated by satellite

 Else

 Recover asset

 Recharge asset

 End If

 Update delivery plan and trajectories subject to local conditions

 End Do

 End Do

Else

 Pause until next satellite data comm time

End If

Case 2: Persistent Monitoring: Satellite Data are Not Available for TBD number of Days

Given history of emission frequency and intensity, compute initial optimal

coverage area plan and trajectories with battery re-charging or refueling stops

For all assets Do

 For all charging/fueling waypoints Do

 Launch asset

 Cruise along pre-determined route

 If (emission detected) then

 Asset loiters to localize emission to $O(1\text{ m})$ accuracy

 Record and transmit localization data

 End If

 If (sufficient onboard energy)

 Continue cruise along pre-determined route

 Else

 Recover asset

 Recharge asset

 End If

 Update delivery plan and trajectories subject to local conditions

 End Do

End Do

The outlined sequences of action are general. Instantiations of operations for various areas would be supplemented with ground localization activities and information. If ground localization in a specific area is known to exist, communication with the ground facilities, if available, will precede the launch of an airborne mission.

We also note that the optimal delivery paths and the locations/times for recharging or refueling will have associated uncertainties. The uncertainties will depend on the environmental parameters, such as the weather, and the atmospheric composition over the areas of interest, potentially requiring longer loitering times to localize the emissions to required

accuracy. Thus, the initial plans for asset delivery trajectories and charging/fueling waypoints may change and will be updated as needed.

VII. Contributing Mission Components

Specific MISTRAL concepts of operations and the satisfaction of mission goals depend on the interplay between the sensors available for airborne operations and the carrier aircraft. In this section we give an overview of a range of sensors and the types of aircraft initially under consideration for the concept.

A. Sensors

The “innermost” design variable in MISTRAL is the airborne sensor. The detection sensitivity and resolution, proximity to a target required for detection, geometry, weight, cost, power required, and robustness to operation in rough weather determine the type of the aircraft optimal for carrying the sensor. The choice of the aircraft, in turn, places constraints on the efficiency and cost of operations. Examples of sensors used for methane detection, along with their typical dimensions, weight, approximate cost, and current availability and deployment are shown in Table 2. We note that in the present preliminary analysis, we have not considered the individual sensor properties, such as the power required for sensor operation, in detail. Practical implementation will require detailed computation.

Table 2: Examples of methane sensors.

Source/Type	Dimensions	Weight	Cost/Availability	Comments
MethaneAIR Imaging Spectrometer [64]	1.2 m x 0.5 m x 0.3 m	25 kg	Deployed on satellites; data are available at no cost to stakeholders.	Data do not appear to be available in real time. Altitude 500-3000 m.
AVIRIS-NG Airborne Visible/Infrared Imaging Spectrometer - Next Generation [26]	1.5 m x 0.6 m x 0.4 m	35 kg	The cost varies; general range: several million USD for full deployment, incl. aircraft operation and data processing.	Not explicitly designed for CH ₄ ; has been used to image high concentrations of methane near point sources.
Kairos Aerospace Methane Sensor [76]	1.0 m x 0.4 m x 0.3 m	20 kg	50,000 USD to 200,000 USD per survey,	Operation on a survey basis.
Compact Quantum Cascade Laser (QCL) Spectrometer [77]	Not specified	2.1 kg, incl. battery	Not publicly listed	Mid-infrared laser absorption spectrometer designed for high-precision methane measurements aboard small UAS. Power efficient and low noise. Altitude up to 500 m.
Lightweight Mid-Infrared Methane Sensor [78]	Not specified	1.5 kg	Not publicly listed	Open-path wavelength modulation spectroscopy for sensitive detection of CH ₄ . Modified to operate on various UAS platforms. Altitude up to 300 m.
NASA Goddard Space Flight Center small, light, graphene-based sensor [125]	TBD	TBD	TBD	
NIST/NOAA Compact Quantum Cascade Laser Spectrometer (CQCLS) [83]	TBD	A few pounds.	TBD	

UC Berkeley Mini-Methane Sensor (MMS) [84]	TBD	Less than 2 pounds	TBD	
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Optical gas imaging cameras (e.g., [101]) may also be used to detect methane from the altitude of several hundred meters for sizable emissions. Of most interest are the compact and lightweight sensor systems in development, as they can be accommodated on relatively small aircraft.

B. Potential Aircraft Alternatives

For the purposes of this analysis, we consider only uninhabited aircraft systems (UAS) that can be piloted remotely or eventually operate autonomously. Although inhabited aircraft could also provide an airborne methane detection platform, we do not consider these due to the higher costs and increased GHG emissions that such larger inhabited aircraft would exhibit in comparison to UAS. All vehicles are geometrically modeled in the OpenVSP (Vehicle Sketch Pad, NASA's open-source parametric geometry platform) [79].

Our preliminary aircraft database includes three vehicles, shown in Figure 3, that are based on commercial-off-the-shelf (COTS) aircraft that could address different mission needs at varying performance levels. First is a long-endurance vertical takeoff and landing (VTOL) UAS with either a fully electric or hybrid-electric propulsion system, capable of operations at up to approximately 12,000 ft (3.7 km). We refer to this aircraft as COTS-I, and a representative aircraft based on the JOUAV CW-25 E/H [80] is shown in Figure 3a. The second and third aircraft are electric vertical takeoff and landing (eVTOL) small UAS (sUAS) intended exclusively for low-altitude operations at up to 400 ft (121 m). The second aircraft, termed COTS-II and depicted in Figure 3b, is a multi-tiltrotor eVTOL sUAS, such as Wingcopter 198 [81]. The final aircraft, shown in Figure 3c, is a lift-plus-cruise eVTOL UAS termed COTS-III, such as T-Drone VA23 [82]. The COTS-III aircraft is the focus of this initial study on the viability of UAS for methane detection and localization.

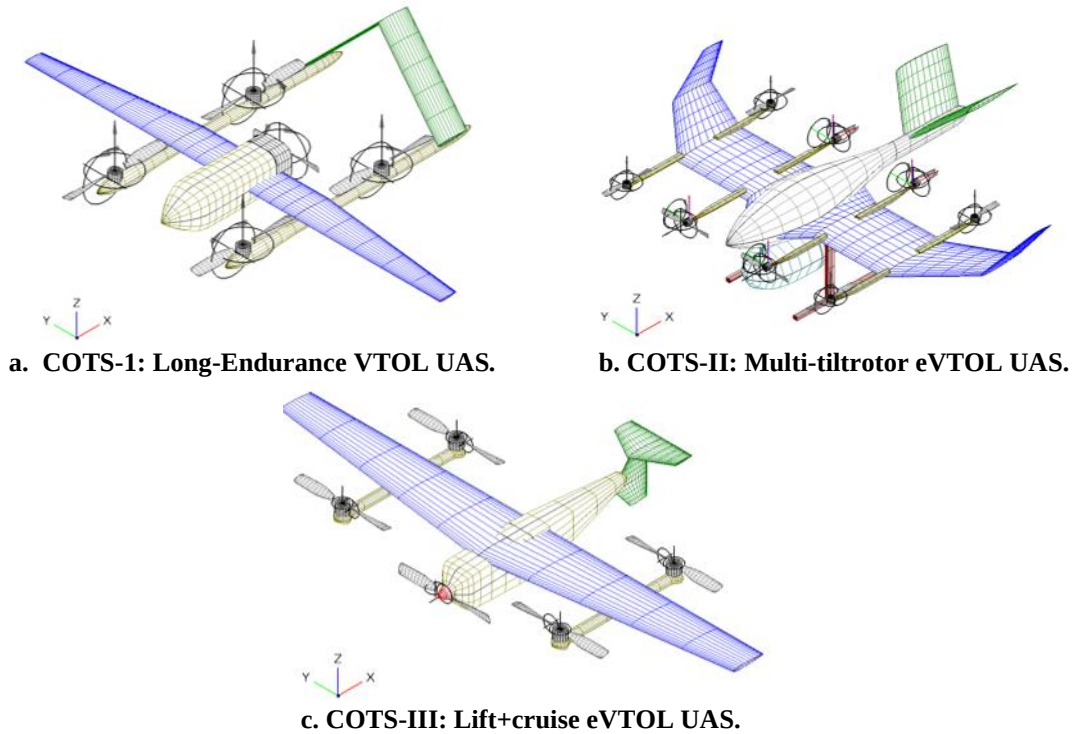


Figure 3: OpenVSP models of three commercial-off-the-shelf aircraft.

The COTS-III aircraft has a maximum payload capacity of 1.6 kg (3.3 lb), a cruise speed of 20 m/s (44.7 mph), a loiter speed of 10m/s (22.3 mph), and a range of 195 km (121 mi) [82]. For our simulations, we assume that the 257 Wh/kg batteries [82] can be recharged for 300 cycles with a depth of discharge of 90%. The associated efficiencies assumptions to match the manufacturer-specified performance for the battery, motor, speed controller, and propeller

are assumed to be 90%, 90%, 99%, and 75%, respectively, which are roughly based on typical values for these components.

We modeled the aircraft with a simple drag polar based on VSPAERO analysis [122] at the stated cruise speed from the manufacturer. We estimated the parasite drag via the component drag buildup method within VSPAERO, which uses flat plate skin friction coefficients modified by form factors and interference factors to estimate the drag on each aircraft component (i.e., wing, fuselage, etc.). VSPAERO provides multiple form factor options that can be chosen for the aircraft components, and we selected the form factors from “Hoerner” within VSPAERO. The interference factors and the percentage of laminar flow over components were estimated with engineering judgment. We iterated in our estimates of interference and percentage laminar flow assumptions along with an overall propulsive efficiency to achieve the stated range performance of the aircraft from the manufacturer when analyzing the aircraft with the electric version of the Breguet range equation [123]. Ultimately, we estimated the drag at cruise and loiter as $C_D = 0.0822 + 0.1 C_L^2$ and $C_D = 0.0925 + 0.1 C_L^2$, respectively, and a propulsive efficiency of 67%.

C. Operations for the Purposes of Analysis

To facilitate rapid implementation of localization, the initial concept of operations (CONOPS) includes remotely piloted aircraft, with a single operator controlling one aircraft. Although this CONOPS could eventually be performed with one remote pilot controlling multiple aircraft—see current m:N operation research [11]—we analyze the missions assuming one remote pilot is assigned to a single aircraft to provide a conservative estimate of the required resources.

We assume that each county within the Permian Basin will be responsible for observing the necessary areas within the county for methane emissions and that the county surveys the required areas within a 24-hour time window. For the purposes of preliminary analysis, we choose a simplified concept of operations for each county as follows:

1. Determine which areas to survey for emissions within the county.
 - The entire county will be surveyed via a pattern search to identify potential emission locations.
 - Other data sources, such as satellite observations, provide the locations of emission sites that need to be observed to localize the actual emission location.
2. Select between a cruise or loiter mission.
 - A cruise mission conducts a pattern search over a large area without any knowledge of where emissions may be generated. In our analysis, we assume cruise missions are performed over the entire county, and we assume the aircraft is capable of flying its maximum range for each leg of a cruise mission.
 - A loiter mission is conducted when other data sources provide a small area over which it is desired to search to localize the emissions source. In our analysis, we estimate the number of these missions for each county by assuming that the total number of sites that require more detailed surveying within the Permian Basin are divided among the counties in proportion to the area of the Basin that lies within the county. Based on emission data from Carbon Mapper [9], we assume there are a total of 577 specific sites to survey with loiter missions within the Permian Basin. Furthermore, we assume that loiter missions survey the 1 mi² area around a potential emitter along with 2-mile ingress and egress legs.
3. Launch a single aircraft or a fleet of aircraft.
 - A single aircraft is launched if one aircraft can survey the total required area within the 24-hour period.
 - If one aircraft cannot survey the entire area within 24 hours, the smallest number of aircraft required to survey the required area within 24 hours are launched.
4. Each aircraft completes a single mission profile and is recovered.
 - For cruise missions, the aircraft is recovered at the max range location. We assume that the aircraft flies its full range in these observations without accounting for any wind or reserves beyond the 90% depth of discharge assumption for the battery. We acknowledge that this is a somewhat non-conservative assumption, but it is within the margin of error of the analysis.
 - For loiter missions, the aircraft is recovered at its launch point.
5. Repeat after battery recharge until the needed areas have been observed.

For practical operations, the CONOPS would be refined in collaboration with local communities and accounting for higher-fidelity information on potential emission sites. Here, we are interested in developing a parametric tool that will enable a system analysis, given specific operations. For the purposes of this preliminary analysis, we make exceedingly conservative assumptions, including the cruise and loiter mission profiles shown in Table 3. This leads

to a pessimistic assessment of the required resources. We comment on more realistic assumptions when discussing the results.

Table 3: Mission Profiles.

Mission Profiles	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6
Cruise Mission	30 sec VTOL @ Max Power	5 sec Hover Transition @ Max Power of both cruise propeller and VTOL rotor	Climb @ Best Rate of Climb and Max Power	Cruise @ 400ft AGL* and Best Cruise Velocity	5 sec Hover Transition @ Max Power of both cruise propeller and VTOL rotor	No range credit descent VTOL @ Max Power to ground level
Loiter Mission	30 sec VTOL @ Max Power	5 sec Hover Transition @ Max Power of both cruise propeller and VTOL rotor	Climb @ Best Rate of Climb and Max Power	Loiter @ 400ft AGL* and Best Loiter Velocity	5 sec Hover Transition @ Max Power of both cruise propeller and VTOL rotor	No range credit descent VTOL @ Max Power to ground level

*AGL = above ground level

VIII. Preliminary Results: Aircraft Performance for Localization of Methane

In this section we summarize the modeling parameters and assumptions that make up our analysis and present the initial modeling results. The analysis is intentionally performed with coarse assumptions as detailed below to provide a rough estimate of the potential costs and emission savings that could be realized from aerial methane sensing missions. This high-level analysis will not yield perfectly accurate results; rather, it is intended as an initial examination to verify whether there may be an economically viable pathway to detecting methane with sUAS over a relatively large area.

A. Assumptions and Simplifications

We assume a “clean sheet” search of an area, without access to a map of potential emission sites. This is the worst-case assumption for the purposes of localization over well-known infrastructure areas, such as Permian Basin, but is a normal assumption for observations over unknown areas or in the case of science data collection, where uniform coverage of the area is needed.

We assume up to 24-hour remotely piloted operations over idealized counties. To simplify calculations, we convert the portions of each county that are to be monitored for emissions into rectangles with a length equal to the range that the aircraft can fly for the cruise mission. The areas of the idealized counties are computed as depicted in **Error! Reference source not found.**, where the variables are defined as follows in Table 4.

Table 4: Idealized county simplification parameters.

Parameter	Description
$Range_{ac}$	Range of the aircraft, assuming the cruise mission profile outlined above.
$Area_{county}$	Area of the county that is to be observed for potential emissions.
$Width_{ideal}$	Width of a rectangle with an area of $Area_{county}$ and a length of $Range_{ac}$.
$n_{flights}$	Number of flights with distance $Range_{ac}$ required to fully monitor the idealized county for emissions. We refer to each of these flights as a “leg.”
$Spacing_{flight}$	Distance between flight legs in the grid search pattern. This parameter will be determined in practice from a combination of the aircraft capabilities, flight altitude, and sensor characteristics; most notably, the field of view

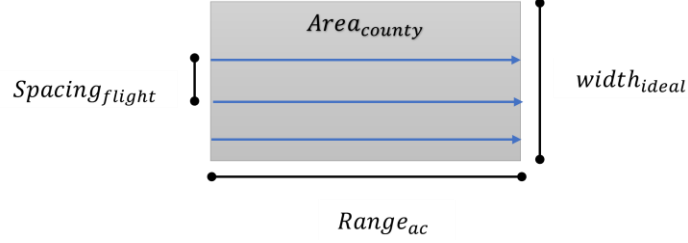


Figure 4: Idealized county diagram.

Estimates of the required missions for vehicles to complete observations depends on the size of the area of interest, vehicle performance, and assumptions on vehicle spacing during operations. The size of the area is approximated using the square milage attribute from the U.S. Census Annual Geographic Information Table data [111] and assumptions about how much of a county is contained within the Permian Basin using Figure 2. This assumption characterizes the operation as a column of n flights of length equal to the range of the aircraft separated across a pre-defined distance to capture the desired ground resolution parametrized as $Spacing_flight$.

$$Area_{county} = Sq.Milage_{county} \times AreaPct_{county}$$

Equation 1: County area estimate.

$$width_{ideal} = \frac{Area_{county}}{Range_{ac}}$$

Equation 2: Idealized county width estimate with vehicle range performance.

$$width_{ideal} = Spacing_{flight} \times n_{flights}$$

Equation 3: Idealized county width estimate with parameterized ground solution.

$$Missions\ Required, n_{flights} \cong \frac{Area_{county}}{Range_{ac} \times Spacing_{flight}}$$

Equation 4: Missions / flight legs required.

Together with the vehicle range and endurance estimated with the vehicle and aerodynamics modeling, estimating the number of required flights for observation operations is expressed in Equation 4. The time required for “hot swaps,” i.e., battery changes, is neglected. Two types of hot swaps are analyzed, each of which requires some form of ground support personnel. First, an idealistic “distributed battery hot swap” scenario in which personnel and charged batteries are distributed along the flight paths to change battery packs at the end of each flight leg. Second, a “chase vehicle battery hot swap” scenario in which personnel follow the aircraft along the flight paths with a ground vehicle to change the battery packs at the end of each flight leg.

B. Key Parameters for Analysis

For our analysis, we select the CONOPS, economics, and emissions parameters listed in Table 5 to analyze the campaign operations for this study.

Table 5: Study Parameters.

	Parameter	Value	Justification	Source
CONOPS	$Spacing_{flight}$	0.17 miles (900 ft)	Goal for useful ground resolution in data	-
Economics	Remote Pilot Wage	63 USD/hour	Industry average for a Part 107 remote pilot	[112]
	Aircraft Acquisition Cost	7,900 USD/unit	COTS-III platform	[82]

	Battery Pack Acquisition Cost	709 USD/unit	COTS-III equipment	[82]
	Ground Support Personnel Wage	20 USD/hour	Industry average for a Part 107 observer	[113]
	Aircraft Average Useful Life	500 hours	Conservative estimate based on a conversation with a sUAS manufacturer ²	-
	Electricity Rates	0.1477, 0.1539 USD/kWh	Electricity cost for charging aircraft batteries in Texas and New Mexico counties based on state-wide, residential averages	[114]
	Ground Vehicle Lease Rate	6.97 USD/day + 0.25 USD/mile	Estimated cost to operate chase vehicle that includes insurance and maintenance	[115]
Emissions	Electricity Grid emissions rate	0.4, 0.5 gCO ₂ /kWh	Conservative grid emissions rate for generating electricity in Texas and New Mexico counties	[116]
	Ground Vehicle CO ₂ Emissions Rate	400 gCO ₂ /mile	Conservative estimates of ground vehicle emissions	[117]
	CO ₂ to CH ₄ Equivalence	36:1	Upper bound of international assessment for CO ₂ to CH ₄ equivalence	[118]

The analysis assumes remotely piloted operations by including pilot rates for cost estimations. This is a conservative assumption because, in practice, we anticipate that trained county or municipal personnel, such as first responders (e.g., the fire services), would be engaged in remote piloting of the aircraft. In addition, if autonomous capabilities and beyond-line-of-sight (BVLOS) Part 108 operations are established, it is conceivable that no additional personnel costs above existing staffing could be required, yielding zero additional cost for piloting. Similarly, with the ground support personnel, it is possible that in the limit, no additional cost could be required if existing county or municipal personnel can carry out these duties.

In the chase vehicle scenario, a ground vehicle follows the aircraft wherever it flies. The notional ground vehicle assumed is a conventionally fueled, full size, four-by-four crew cab pickup truck with a 6700 lb gross vehicle weight rating per the U.S. General Services Administration [115] expending roughly 400 gCO₂ per mile [117]. In addition, the analysis assumes that ground-miles traveled by the chase vehicle are equal to the air-miles traveled by the aircraft.

To understand the potential net environmental benefit of the operations, the CO₂ to CH₄ equivalence is used to compare the amount of equivalent CH₄ generated from the mission campaigns with a notional representative day of CH₄ emissions assessed using Carbon Mapper data dashboard [9]. In 2023, the Carbon Mapper initiative assessed 4365.6 mega-kilograms of CH₄ per day among the 577 emitter sources detected in the Permian Basin throughout that year on days of sensing. Because Carbon Mapper operates both satellite and piloted operations with general aviation sized aircraft at intermittent frequencies, the daily emission figure is not representative of all emissions found, but rather the emissions sensed throughout the sensing intervals. The number of emitters per day is unknown, given the aggregate level of the data. The Carbon Mapper data dashboard has the capability to isolate the number of daily emitters and CH₄ detected. However, an average daily emission figure is sufficient to understand the general tradeoff in emissions produced by the sensing campaigns vs. the potential methane emissions that could be mitigated, without assessing which day is the best representative day for analysis.

C. Preliminary Assessment Results

² Fredericks, W.J., personal correspondence, September 30, 2024

We developed parametric analysis tools that allowed us to rapidly estimate the cost of operations and their anticipated environmental impact under multiple sets of assumptions. Analysis results depend on the size of the area of interest, vehicle performance, and assumptions on vehicle spacing during operations. The areas of interest in this work are counties within Texas and New Mexico located in the Permian Basin, and we perform analysis on a county-by-county basis. The size of the area within a county to be surveyed is approximated using the square mileage numbers from the U.S. Census Annual Geographic Information Table data [111] and the assumptions on the portion of a county contained within the Permian Basin, using Figure 2**Error! Reference source not found..** Because not all county boundaries align perfectly, each county was simplified to an “idealized” rectangular county normalized by the range of the aircraft. This assumption characterizes the operation as a column of n flights of length equal to the range of the aircraft separated by a predefined distance that is determined by the field of view of the methane sensor and altitude of operation assumed to capture the desired ground resolution.

In this section, we focus on the results with the relatively pessimistic assumptions outlined above, as well as the aggregated results. More detailed results of the analysis are summarized in eleven plots shown in Appendix A. Here, we show the results aggregated by county via “violin plots”, where the y-axis shows the output of interest, such as the cost associated with a specific function. The plot itself shows how the parameter on the y-axis varies across the 55 counties analyzed within the Permian Basin, with the minimum, median, mean, and maximum values denoted by horizontal lines. The light blue shading shows the relative number of counties at each given y-axis value.

Figure 5 shows the number of flight legs required to cover each county in a single campaign. Due to different sizes of the counties and the areas of land required to be surveyed, the number of flight legs varies from eight to 214 with a mean of 63. The long tail of the distribution on the high end in Figure 5 and all the following figures except for Figure 8 is due to the considerably greater areas of nine (9) of the counties, which require more than 2600 mi² to be surveyed and make up approximately 40% of all land area within the Permian Basin. For comparison, the mean required survey area of all counties is 1278 mi² and the median area is 902 mi². For most counties, a single aircraft would require approximately 44 travel legs to completely survey the area of the county, and the nine largest counties require 129 to 214 flight legs. In practice, because the energy production and transportation infrastructure are known, the number of flight legs and all the attendant metrics would be significantly lower.

Figure 6 shows the number of flight hours associated with surveying the county area. The plot shows the same distribution shape as that in Figure 5, since the aircraft is assumed to cruise at a constant velocity. Estimates of the number of flight hours per campaign per county is expressed as the number of flight legs required, multiplied by the estimated vehicle endurance. Total times are shown in hours and vary from 24 to 642 hours with a median of 132 hours. The nine largest counties require between 387 and 642 hours.

It may be desirable to survey the entire Permian Basin at regular intervals to routinely monitor for leaks. Due to the large area of many counties and the relatively slow aircraft speeds, multiple aircraft are required to operate simultaneously to complete a single observation campaign over the full county in a relatively short period of time. We assume that a campaign is to be completed within 24 hours of operation, which could enable observation every day or, more practically, every few days. We determine the number of aircraft required by dividing the total required flight hours by 24. Figure 7 shows the number of aircraft required per county, which range from one to 27 with a mean of eight, and most counties require approximately six aircraft. The nine largest counties require 17 to 27 aircraft.

Figure 8 shows both the number of mission legs and flight hours per campaign per vehicle to illustrate how the total mission legs and flight hours are notionally distributed across the number of vehicles required. The mission legs per campaign per vehicle range from five to eight with a median and mean around eight; and the flight hours per campaign per vehicle range from 18 to 24 hours with a mean of 23 hours with most counties, including the nine largest, operating vehicles for 24 hours. With the assumption of a 500-hour airframe, several campaigns per vehicle are possible for each county.

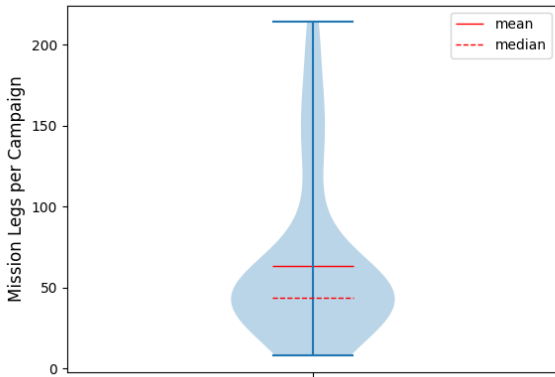


Figure 5: Distribution of mission legs required to survey the counties in the Permian Basin.

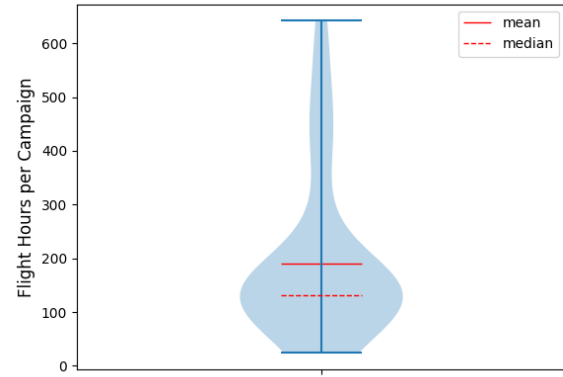


Figure 6: Distribution of flight hours required to survey the counties in the Permian Basin.

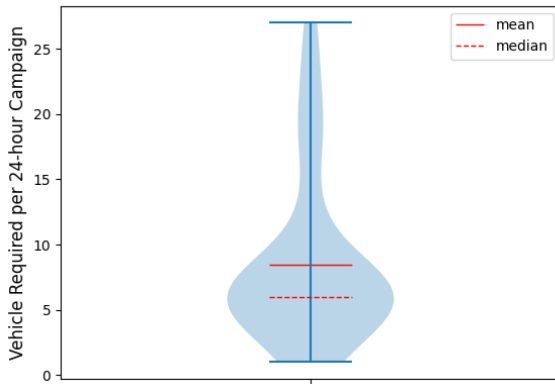


Figure 7: Distribution of the number of aircraft required to survey the counties in the Permian Basin in a 24-hour period.

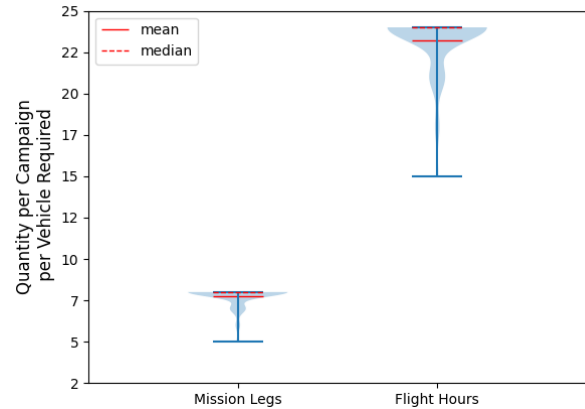


Figure 8: Distribution of the mission legs and flight hours per campaign per vehicle required to survey the counties in the Permian Basin in a 24-hour period.

Two distributions of acquisition cost per flight hour for all 55 counties are shown in Figure 9. First, an overly conservative approach in which an aircraft and associated equipment (including batteries) are purchased each time the county is to be surveyed. Second, another conservative approach in which the aircraft and associated equipment costs are amortized over an average lifespan of 500 hours. In the first case, costs range approximately from 390 USD per flight hour to 620 USD per flight hour. Most counties see costs around 420 USD per flight hour, and the nine largest counties have costs between 390 and 410 USD per flight hour. The largest acquisition cost per flight hour of 620 USD corresponds to one of the smallest counties (Floyd County, Texas) with the smallest of area to service the Permian Basin. Because Floyd County was determined to require 30 flight hours per campaign given the estimated COTS-III performance, the cost of two aircraft to perform the mission is driving the cost per flight hour up in the acquisition per campaign cost-scenario. However, with the 500-hour aircraft and equipment lifespan, smaller counties or counties that have smaller areas within the Permian Basin are no longer outliers and the cost begins to scale with the size of the counties. In addition, with a 500-hour aircraft and equipment lifespan, these costs are significantly reduced in many cases, though the distribution of costs is considerably more varied among counties due to their relative sizes. In this case, costs per flight hour range from approximately 75 USD to just under 500 USD per flight hour, with most counties requiring around 200 USD per flight hour or less. The costs for the nine largest counties range from 330 to 490 USD per flight hour. Since the lifespan for an aircraft is more realistic, from this point forward we will only show results under the assumption that the aircraft and associated equipment have 500-hour lifespans.

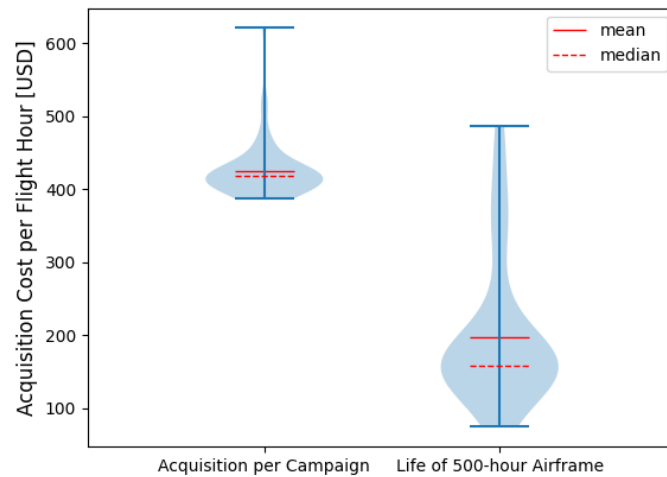


Figure 9: Distribution of acquisition costs for all counties assuming either new acquisitions for each campaign or amortizing aircraft over 500 hours of useful life.

Figure 10 shows the distribution of various cost-per-flight-hour metrics for two different operational concepts. In the case of the chase vehicle, costs are higher due to paying ground support personnel to constantly follow the aircraft and incurring ground vehicle operating costs along with supporting maintenance activities. In the distributed hot swap scenario, ground support personnel are observers and provide support maintenance. An electric ground vehicle may incur reduced operational costs compared to that shown in the figure. In practice, some level of ground support will likely be required, so that costs would fall between the two bounds. However, if flight operations become autonomous, pilot wages could be essentially eliminated, leading to even lower operating costs than indicated in the figure. (Acquisition costs would likely increase with autonomous aircraft, but the degree to which they would increase is unclear.) In addition, the cost to operate the distributed hot-swap concept includes only the electricity used to charge the batteries. As can be seen in Figure 10, these electricity costs are negligibly small when compared to all other costs.

Ultimately, the acquisition cost is a major portion of the costs per flight hour, and, in the chase vehicle scenario, the chase vehicle operational costs form the largest single component of the costs.

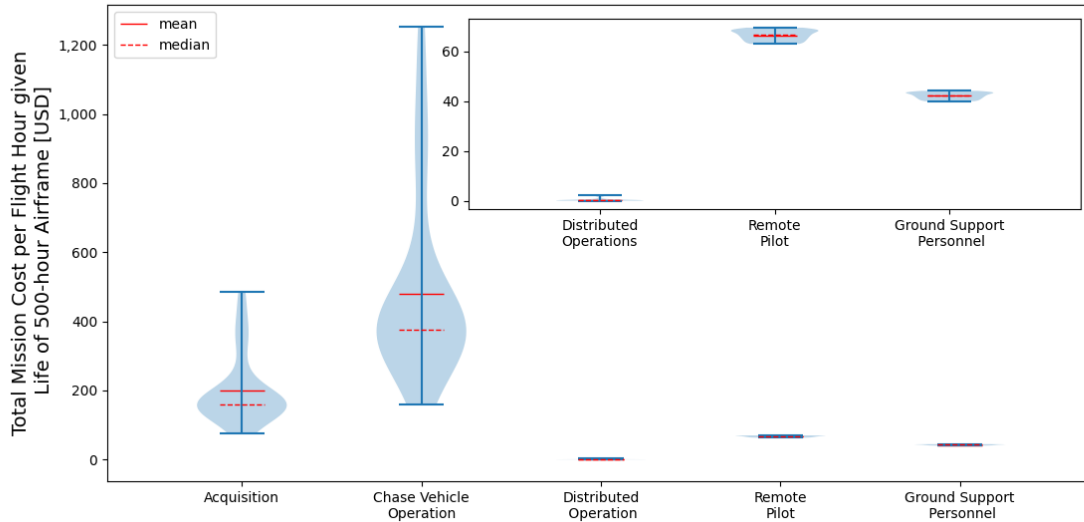


Figure 10: Distribution of acquisition costs, operating costs, remote pilot costs, and ground support personnel costs per flight hour for the distributed hot swap and chase vehicle concept of operations.

Figure 11 shows the estimated total mission cost, including acquisition and operations, to completely survey each county. We believe this cost is higher than could be realized in practice for the reasons already outlined. The costs range widely across counties due to the vastly different sizes of some of the counties. However, most counties would require less than 31,000 USD to survey the entire county with a chase vehicle or less than 25,000 USD in the case of distributed battery swapping.

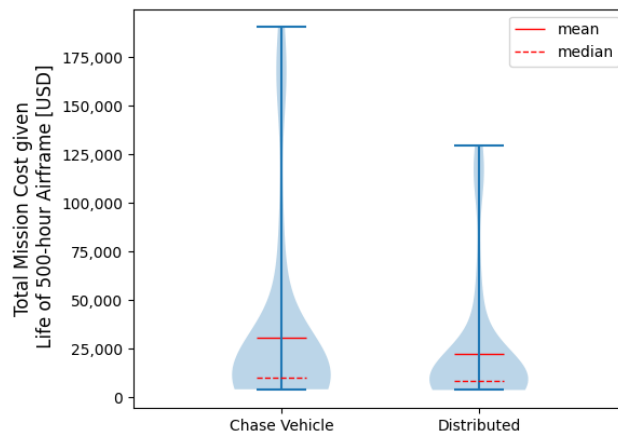


Figure 11: Distribution of total mission cost for all counties for the distributed hot swap and chase vehicle scenarios amortizing aircraft over 500-hours of useful life.

The affordability of the missions as outlined is not immediately clear from the results presented in the preceding figures. If we assume that the county government will perform these operations, one means of normalizing the results to indicate the affordability of the missions is to divide the total costs by the number of individuals in the county. The distribution of this per-capita cost is given in Figure 12. Most counties have costs of approximately 2 USD per capita

per mission; however, there are a few outliers in the data with considerably higher costs, which are counties with large areas and low populations.

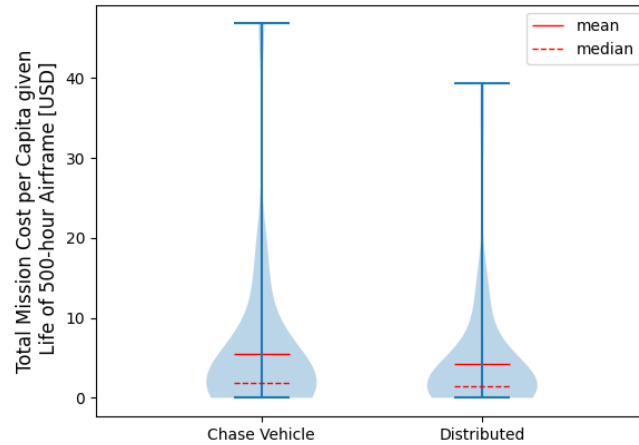


Figure 12: Distribution of total mission cost per capita for all counties, including both distributed battery hot-swapping and chase vehicle scenarios.

Another means of analyzing the costs is on a per-flight-hour basis. These costs, assuming a 500-hour lifetime for the aircraft, are shown in Figure 13 for both the optimistic distributed battery hot-swap scenario and the chase vehicle scenario. For the smaller counties, costs per flight hour do not vary much between these two scenarios, but for the larger counties, there is a significant per-flight-hour cost increase with the chase vehicle scenario. These higher costs are due to the large distances the chase vehicle travels and long timeframes required to pay personnel driving those vehicles. Estimated costs for the distributed battery hot-swap case range from approximately 178 to 592 USD/hr across counties, with most counties seeing less than about 310 USD/hr. With a chase vehicle, there is a wider range of costs from 188 to 870 USD/hr, with the cost for most counties less than 330 USD/hr.

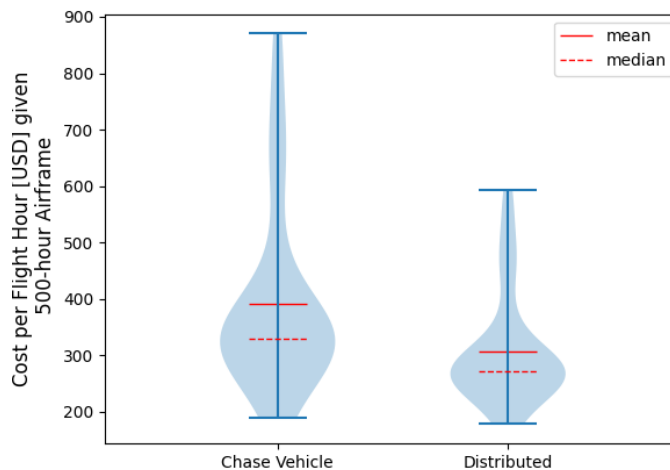


Figure 13: Distribution of total mission cost per flight hour for all counties for the distributed hot swap and chase vehicle scenario.

In addition to economic considerations, the environmental impacts of sensing for methane must be analyzed. If the amount of methane detected and mitigated does not outweigh the emissions from the operations to detect that methane, then the airborne detection concept is not a logical pathway to pursue. Estimates of the total CO₂ emissions are provided in Figure 14 for both the battery hot-swap scenario (left) and the chase vehicle scenario (right). Both

scenarios include emissions from aircraft battery charging. The plot on the right also includes emissions from the operation of a fuel-burning chase vehicle.

The general shape of the distributions is similar for the two scenarios. However, the magnitude of the emissions is vastly different, with the chase vehicle scenario having multiple orders of magnitude greater emissions than the distributed battery hot-swapping scenario. The distributed battery hot-swapping scenario represents a reasonable lower bound on anticipated emissions in practice (barring changes in the electricity grid emissions index), while the chase vehicle scenario is likely near the upper bound on anticipated emissions. The chase vehicle scenario emissions could be reduced with a hybrid-electric or fully electric ground chase vehicle.

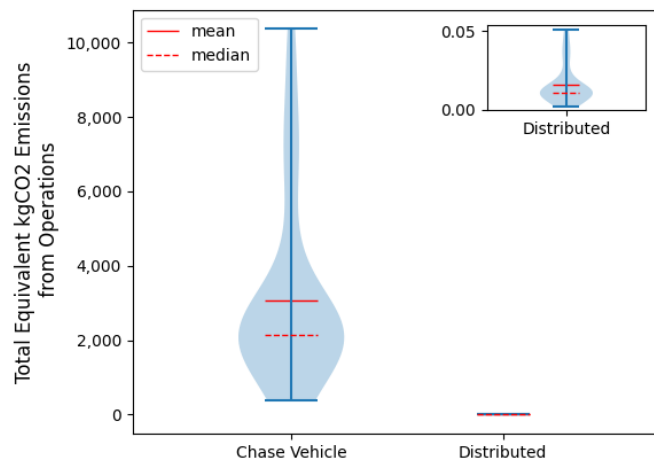


Figure 14: Distribution of estimated equivalent CO₂ emissions from methane-detecting operations for all counties with the distributed battery hot-swapping scenario on the right and the chase vehicle scenario on the left.

To evaluate the efficacy of methane localization, it is useful to convert the anticipated operational emissions from CO₂ emissions to equivalent CH₄ emissions. If more equivalent methane is released in attempting to detect methane than is saved from being emitted after sensing a leak, then there would be no environmental benefit to the methane sensing operations. Figure 15 shows the amount of equivalent methane emissions from the distributed battery hot-swapping and chase vehicle scenarios, assuming that 36 kg of CO₂ is equivalent to 1 kg of CH₄. The emissions from charging the batteries to power the aircraft, as indicated in the distributed battery hot-swapping scenario on the left, are very small: less than 0.0015 kg of CH₄ equivalent in all counties. Although the chase vehicle scenario exhibits considerably higher emissions—on the order of 100 kg of CH₄ equivalent—typical methane leaks detected by Carbon Mapper in the Permian basin generally were estimated to release thousands of kilograms of CH₄, which indicates that there is likely a net environmental benefit from even the most pessimistic scenario studied for the airborne sensing concept.

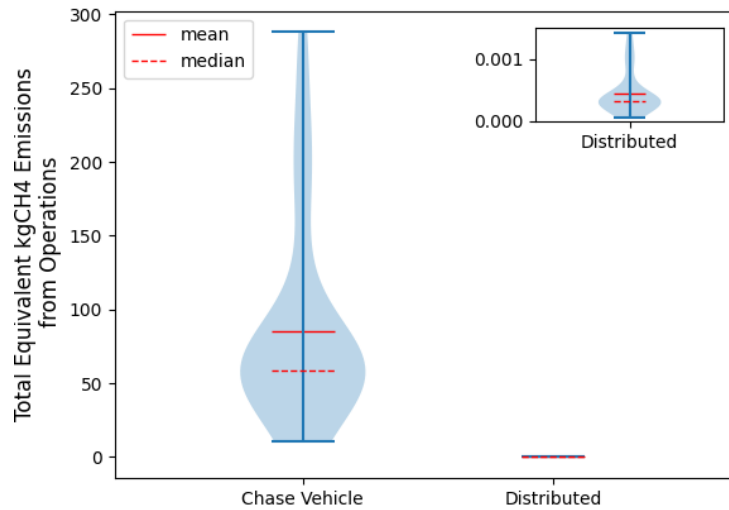


Figure 15: Distribution of estimated equivalent CO₂ emissions from methane-detecting operations for all counties with the distributed battery hot-swapping scenario on the right and the chase vehicle scenario on the left.

As a means of estimating a “break even” point at which the emissions from the airborne sensing missions would emit an equivalent amount of methane as that emitted in the Permian Basin, we pull data from Carbon Mapper, which estimated methane emissions in the Permian Basin. Over the course of a year, Carbon Mapper collected data via satellites and inhabited aircraft flights and estimated $4,365,600 \text{ kg CH}_4 \pm 52,800 \text{ kg}$ were emitted. If airborne sensing operations were to occur every day with the pessimistic chase vehicle scenario, it would take approximately 2.5 years for the airborne sensing operations to produce as much equivalent methane as is estimated to have been released in a single year. Therefore, routine airborne sensing for methane leaks can provide a net environmental benefit. These preliminary data, under the conservative assumptions (no site map, continual observation of the entire county, relatively high-cost vehicle, remote pilots, and ground support paid by hour), indicate that routine airborne detection of methane may be both affordable and a net benefit to the environment. We address the affordability as one of the DVF components in the next section.

IX. DVF Assessment of the Concept Space

A. Desirability

The desirability of MISTRAL’s overarching goal—curtailing methane emissions—is unarguable. The desirability of MISTRAL operations is a multi-part question:

Is it desirable to empower local communities with low-cost localization tools? We believe that empowering local community to localize methane emissions is not only desirable but is a necessary step toward preventing methane emissions. Communities that are directly impacted by GHG emissions are most likely to take advantage of the EPA reporting programs [10, 108] if they are equipped with affordable localization technology.

Is it desirable to conduct airborne operations in terms of localization efficacy? The efficacy of airborne localization of methane has been demonstrated commercially. We seek to develop a low-cost, persistent observation complement to efficacious but high cost, campaign-based, inhabited airborne commercial efforts, and satellite-based observations.

Is it desirable to conduct persistent airborne operations in terms of the environmental impact?

- Carbon footprint: Preliminary analysis indicates a relatively low carbon footprint of operating airborne localization (see Section VIII), even under exceedingly pessimistic assumptions. In practice, the number of flights and flight legs would be significantly lower than estimated in the analysis, because localization areas would be minimized based on satellite data, and the clean-slate search areas would focus around potential emission sites, given known locations of the infrastructure.

- Noise: Unfortunately, the high-pitched noise of drone operation is known for its annoying properties. However, we anticipate that operations over densely populated areas will not be continuous, as they will be informed by the presence of methane plumes detected from satellites and many potential emitter sites are not in densely populated areas. The localization efforts should decrease the frequency of emissions over time, this reducing the frequency of flights. We also conjecture that the benefit of curtailing methane emissions will outweigh an occasional annoyance of drone noise. Moreover, active research in drone noise reduction is ongoing [102].

B. Viability

We view the viability of persistent airborne operations from two perspectives: those of the local communities and the oil and gas productions companies.

Given our main target of empowering local communities with the ability to localize and report emissions, “viability” for this solution space means affordability of operations by municipal governments. Although affordability for specific communities will have to be established in meetings with community stakeholders, we claim general affordability based on existing average numbers, as follows.

The average municipal budget for small towns with populations under 50,000 in the U.S. typically ranges from 10 million USD to 50 million USD. For medium-sized towns with populations between 50,000 and 200,000, the budgets typically range from 50 million USD to 200 million USD [103].

On average, municipal governments maintain rainy-day funds, in addition to general fund balances, to ensure financial stability and manage unexpected expenses. The general fund balance for municipal governments can vary widely, but many aim to maintain a balance that is approximately 15-20% of the annual operating expenditures [104]. Rainy-day funds typically range from 5% to 15% of the general fund [105, 106]. These funds are critical for municipalities to handle economic downturns, unexpected costs, and revenue shortfalls, ensuring that they can continue to provide essential services without undue disruptions.

Assuming that the aircraft are autonomous or remotely piloted by salaried municipal employees, the acquisition of the aircraft that carries the localization equipment is a major expense of the airborne operations. We anticipate that the cost of the initial purchase would be supported via the rainy-day funds.

The largest potential expense in the above analysis is an automobile under the chase vehicle scenario; however, we anticipate that these cost estimates are considerably greater than would be realized in practice. Chase vehicle costs could be significantly reduced through detailed mission planning at the municipal and/or county level and through a variety of strategies, including reducing search areas to focus only on those around potential emitter sites; purchasing additional aircraft to be stationed at facilities throughout the county to allow aircraft to return to the base during each sensing campaign to recharge or change batteries; and leveraging existing ground vehicles owned by the county/municipality and routes already driven routinely, such as police patrol routes, to perform the chase vehicle function.

We anticipate that maintaining persistent airborne localization via uninhabited UAS is also economically viable for medium and large oil and gas production companies. See Appendix B for approximate estimates of direct gas recovery values and carbon credit values. Additional benefits would include avoided fines, reduced reporting costs, and simplified compliance.

C. Feasibility

Technical feasibility of airborne localization has been demonstrated for conventional inhabited aircraft. Because rapid implementation of operations is essential in reducing methane emissions, initial operations would be conducted via remotely piloted aircraft, which are supported by feasible technology as well. The development of autonomous operations that coexist with other airspace participants—the eventual goal of the concept—would leverage the ongoing developments in UAS Traffic Management (UTM), in particular, the anticipated beyond visual line of sight operations rules that are planned for 14 CFR § 108.

Feasibility in the context of this concept also includes the overall efficacy of the approach for methane emissions reduction. While any computation of this nature involves a degree of uncertainty, an approximate computation of the potential savings is given in Appendix B.

X. ROI Risks and Risk Mitigation

The proposed work involves several groups of risk. In this section, we address the risks, based on the stakeholders relevant to the effort. The barriers and risks are summarized in Table 6. “D” refers to desirability, “V” to viability, and “F” to feasibility.

Table 6: Summary of barriers and risks.

Barrier	Category	Advantage	Limitation	Mitigation
Safety in proximity to hazard-sensitive sites	D, F	Lower sensor cost.	Potential regulatory difficulty.	Optimize fleet and task allocation based on multiple sources of data.
Fleet autonomy	F, V	Radical operational cost reduction compared to piloted vehicles; more persistent presence.	FAA permission required for autonomous operations.	Staged implementation with remote piloting; leverage m:N operations research; optimal fleet allocation and scheduling.
Completing solutions (satellites)	F, V	Hybrid approach minimizes search area.	Likely none.	Use satellite data for large-scale monitoring, combine with high accuracy local observations; dynamic reallocation of fleet as emission reduces.
Cost of operations	V	No need for expensive ground infrastructure; autonomous operations require limited human participation.	Autonomy may not be immediately supported by FAA.	Dynamic and optimal fleet allocation. Multiple use: • Science data collection • Medical first response • Wildfire observation • Other emission and spill tracking
Coexistence in airspace	F, V	Multi-modal, flexible fleet	Potential limits in areas of observation.	Leverage UTM developments.
Net GHG savings	F	Real-time actionable localization prevents emissions.	Net reduction in emissions depends on effectiveness of reporting.	Early collaboration with EPA and communities.

An important consideration is that, regardless of the specific airborne concept, one of its benefits is that the approach does not require the construction of massive ground infrastructure, as opposed to the DAC ground approach. The lack of permanent infrastructure reduces the cost of operations and, most importantly, enables a rapid deployment capability. Moreover, given appropriate sensors, an autonomous airborne fleet can be used for other observations; for instance, in support of science missions, wildfire fighting, tracking toxic emissions following a railroad disaster, and providing situational awareness and medical deliveries in the aftermaths of natural disasters. A fleet can also be used to deliver autonomous robots to repair methane and other gas leaks should they be detected in remote, difficult to reach geographical areas. Thus, if or when methane emissions at oil and gas production sites are sufficiently reduced, we conjecture that the cost of redeploying the operations will be minimal, as it would not require discarding the airborne fleet or control strategies.

Finally, we anticipate that the relatively low cost of operations and the EPA regulatory guidelines for third-party observation and reporting will enable the use of the fleet by local governments of the areas most affected by methane emissions, thus reducing the risk that localization information may be less actionable than anticipated.

A. Stakeholder: The Environment / the Public

Risk: The airborne concept *adds* minimal risk to the environment because the concept of operations relies on existing COTS UAS and on support from existing satellite input. Should the concept be successful, the additional infrastructure, such as stationary charging networks, is optional.

The major risk is the ability to enforce the repair of leaks and infrastructure malfunctions.

Risk if Effort Not Attempted: Not involving the local communities in observation and localization of emissions threatens to indefinitely delay meaningful actions to curtail emissions and, thus, threatens to speed up irreversible and

possibly catastrophic climate changes. Attempts to rely on satellite localization alone, by increasing the numbers of satellites carries an environmental risk, both in satellite construction and deployment, with increased carbon footprint and effects on the ozone layer.

Risk Mitigation: Empowering the local affected communities increases the probability of reducing and extinguishing emissions. The EPA reporting programs allow for direct communications between local communities and EPA to enforce the cessation of emissions.

B. Stakeholder: The Fleet Operators (Municipal Governments and Oil and Gas Industry)

Risk: We anticipate that the only risk in conducting persistent airborne operations is the investment in the equipment purchase and operation.

Risk if Effort Not Attempted: As municipal governments represent their communities, the risks of not attempting persistent localization are the same as outlined in the Subsection A. For the oil and gas industry, the risks are in the loss of product, avoided fines, reporting costs, and assuring compliance with regulations.

Risk Mitigation: To reduce financial risk, the implementation may be conducted in stages: high-risk area coverage first, followed by full area (e.g., full county). Integration with other sources of monitoring (ground-based and satellite-based) reduces the financial risk significantly, by reducing the localization area.

To optimize both the environmental and economic outcomes, the initial efforts would focus on large and medium emissions, gradually expanding operations to smaller leaks. Frequent re-assessment of the state of the art in sensors and the state of regulations for autonomous flight would support operational optimization.

C. Overall Research Investment

Risk: Enabling persistent airborne localization involves research in the areas of autonomous planning and trajectory management, as well as establishing interfaces between satellite data and trajectory planning for the airborne fleet. The financial risk of investment in research related to an airborne localization system is very low, given a broad range of applications for sUAS and increasingly autonomous multiagent fleets. The risk that the concept “will not work” is related to the risk that, even given the localization information, the oil and gas producers will refuse to repair the leaks.

Risk if Effort Not Attempted: Not attempting to empower local communities with affordable localization systems will be a missed opportunity for making a significant, long-term contribution to public and planetary wellbeing.

Risk Mitigation:

Multi-agent autonomous or remotely controlled fleets are broadly applicable, and the developments in airborne localization of GHG should leverage and support other activities, such as science missions, wildfire observations, and assistance to medical first responders. Dual missions, such as localization and scientific data gathering at low altitudes, can increase the viability of the operations. An additional use case is the delivery of robotic repair systems for temporary repairs, should the emissions occur in difficult to reach areas. Autonomous multiagent operations are also applicable in space and planetary exploration and operation domains.

XI. Continued Work

We believe that the current preliminary analysis indicates the desirability, technical feasibility, and financial viability of the solution space for airborne localization of methane and other emissions, supported by satellite and ground-based information. Since participation by local community governments and activists is critical to the efficacy of methane reduction, the first future step in this activity would be the establishment of contacts with local communities, specifically with the county and municipality governments of the affected areas, such as Reagan County, TX. Meeting with community representatives would be crucial for fine tuning the requirements for cost ceilings on vehicles and equipment, as well as training and operations.

Another important step is to down select low-weight and low-cost sensors optimal for inclusion on airborne assets, as well as the parameters of accessing satellite data daily. An in-depth analysis of oil-and-gas production and transportation distribution would be required to develop initial maps for trajectory computation.

This information collection effort would result in detailed requirements for the path analysis and planning tool for engaging the fleet in observation and localization of emissions. A successful effort would produce the following software tools for local communities to enable observation and localization by counties, townships, municipalities, and individuals: interface and input from satellite observations; potential emitter maps; optimal trajectory planning for airborne observation and localization; training and education materials to accompany tools. The tools would be

demonstrated in simulation and flights, accompanied by safety analysis. The concept would be further strengthened via an architecture for multi-use of the airborne assets, in coordination with science, medical, and wildfire use cases, as well as an architecture for autonomous operations.

XII. Concluding Remarks: Impact

The general concept of combining satellite, airborne, and ground methane localization methods is desirable, viable, and feasible: it leverages the strengths of all platforms and provides a flexible, relatively low-cost approach to actionable localization of methane emissions.

sUAS-based localization has clear benefits in the flexibility of operations, given the capacity for adjustable flight paths, multiple sensor options, and scalable coverage; in data quality, given high-resolution imaging and access to multiple data types; and operational control, given local management, rapid deployment, and custom planning.

While satellites and airborne assets operating independently can yield valuable information about emissions, the combined application optimizes operational resources and enables the use of information by communities. Combining data from all platforms allows for a more robust analysis. Satellite data can guide airborne missions, ensuring that they focus on the most relevant areas. This integrated approach enhances the accuracy and reliability of methane emission estimates.

The goal of empowering the affected communities with affordable tools to act directly in response to emission localization information is supported by the EPA's programs on third-party GHG observation and reporting.

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Appendix A: Concept Analysis Data

This appendix contains additional details of the analysis results on a county-by-county basis.

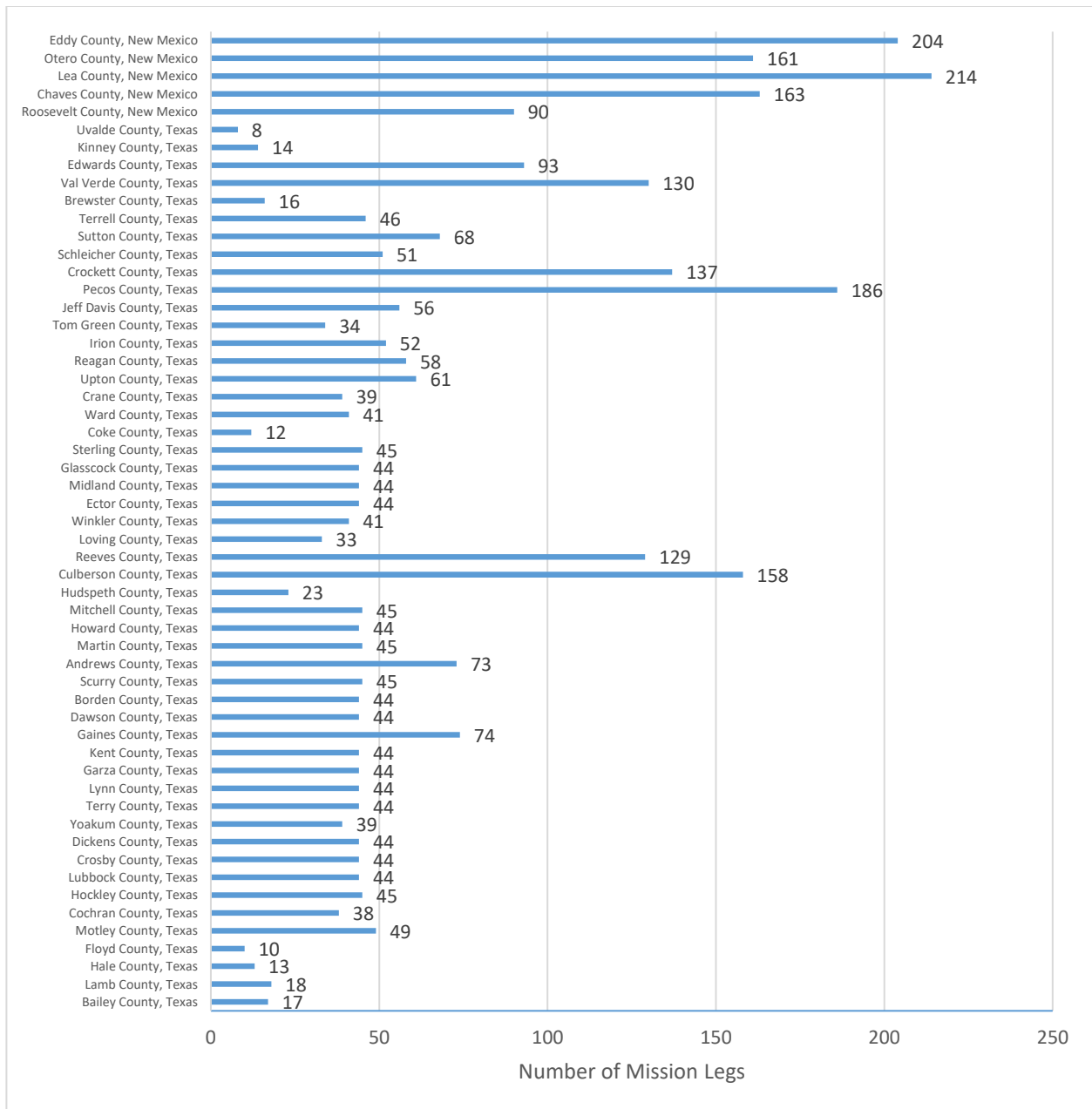


Figure 19: Mission legs per campaign by county.

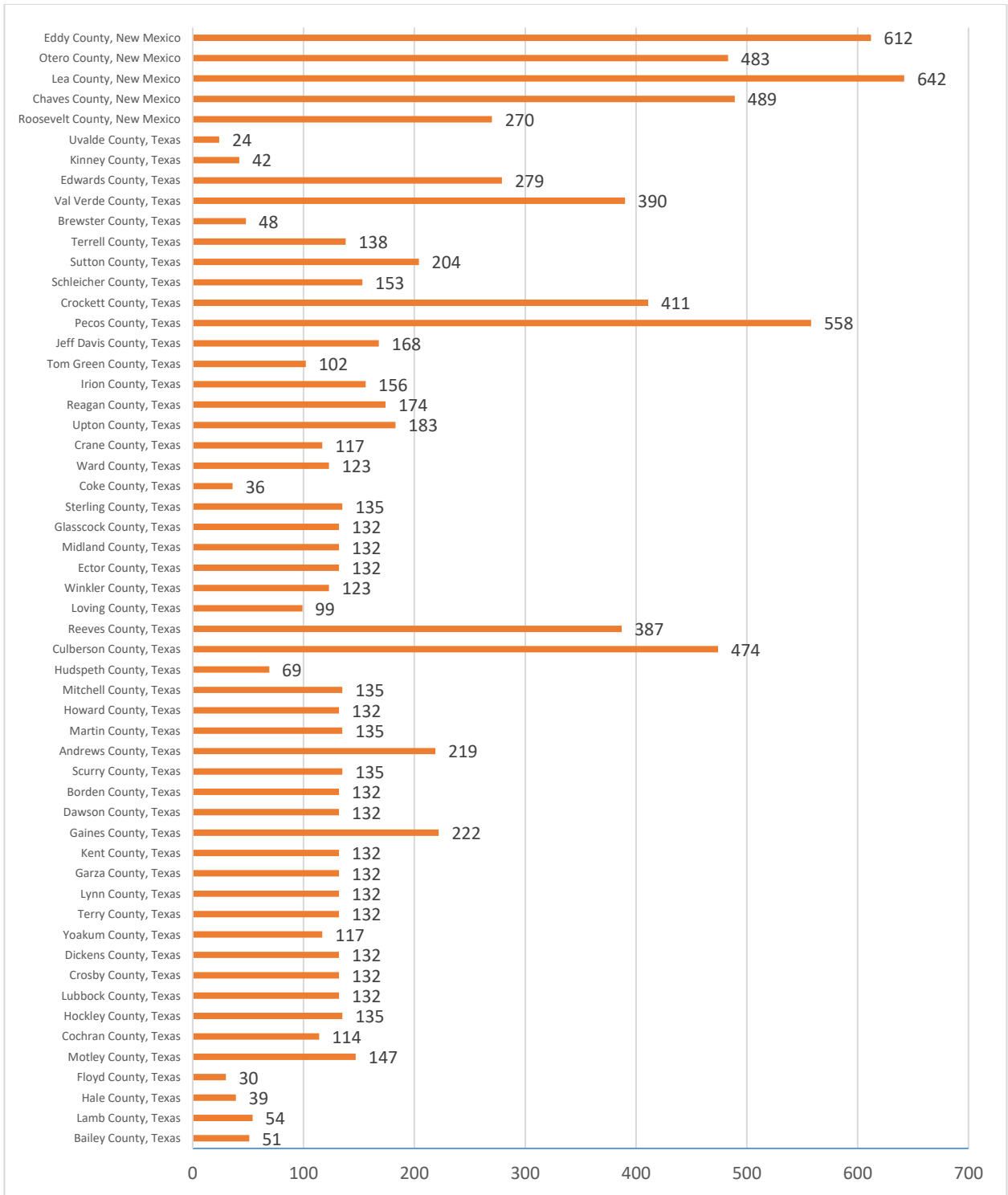


Figure 20: Flight hours per campaign by county.

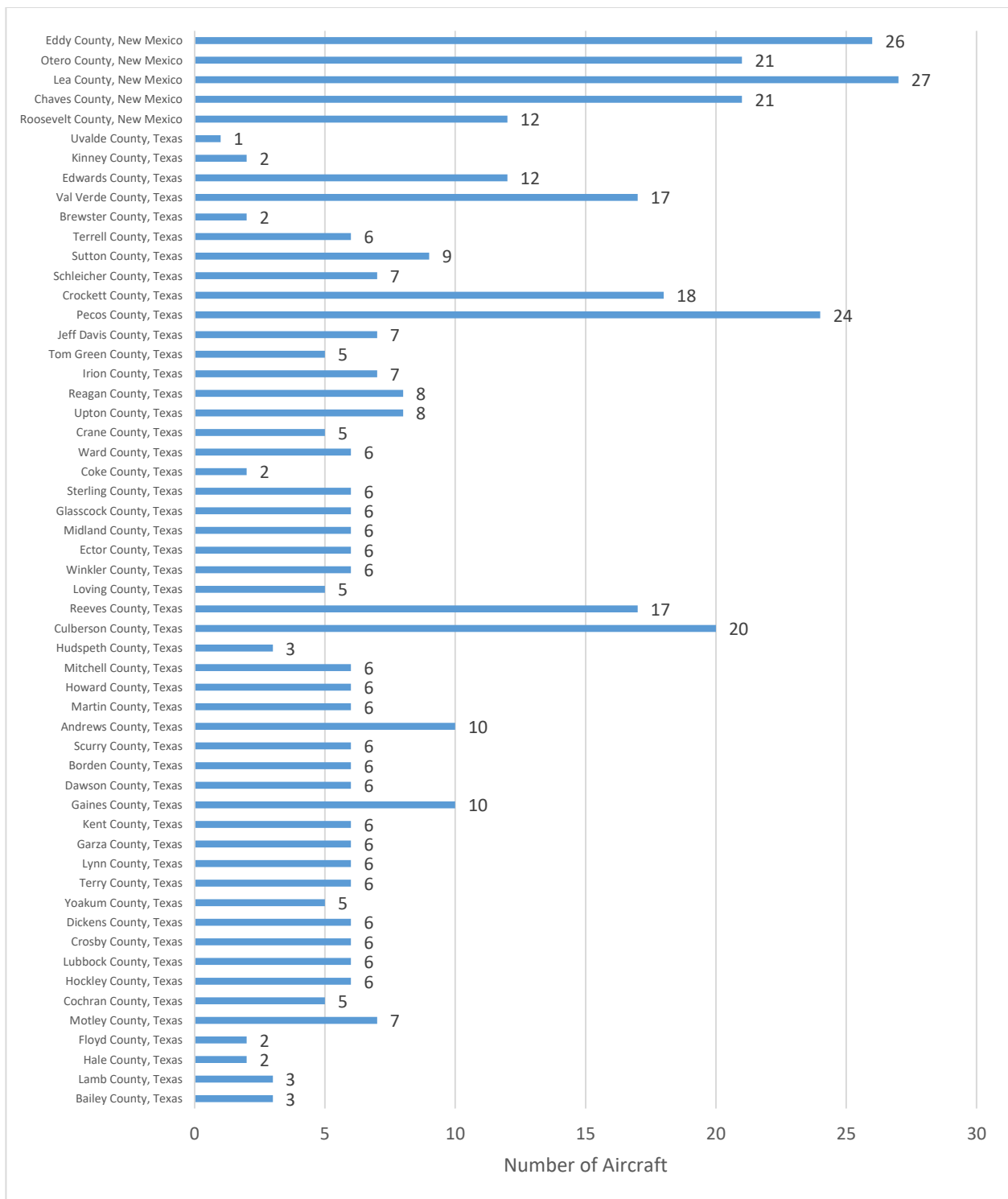


Figure 21: Number of vehicles required to survey the entire county within a 24-hr period.

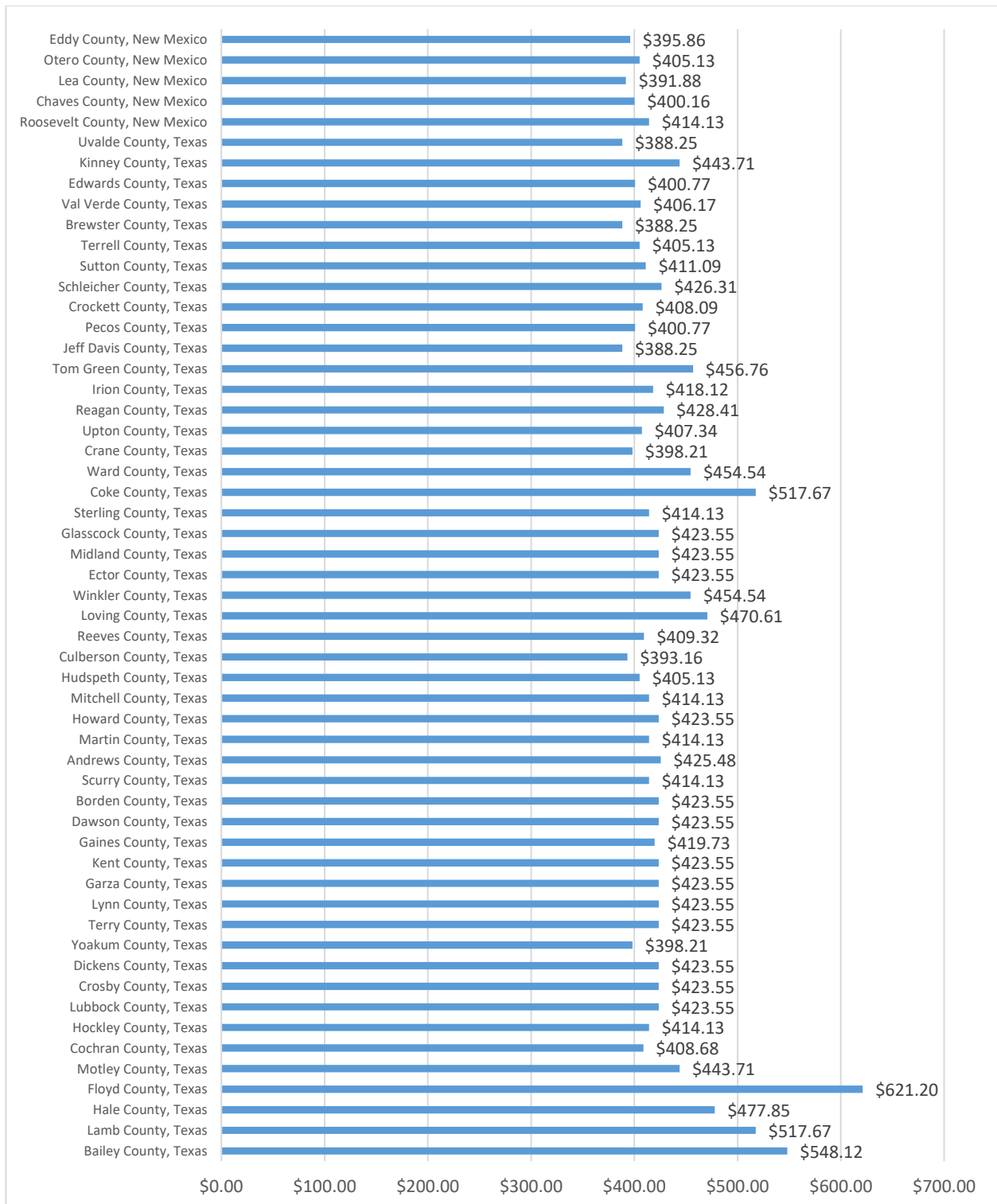


Figure 22: Aircraft acquisition Cost per Flight Hour given an acquisition per campaign [USD]

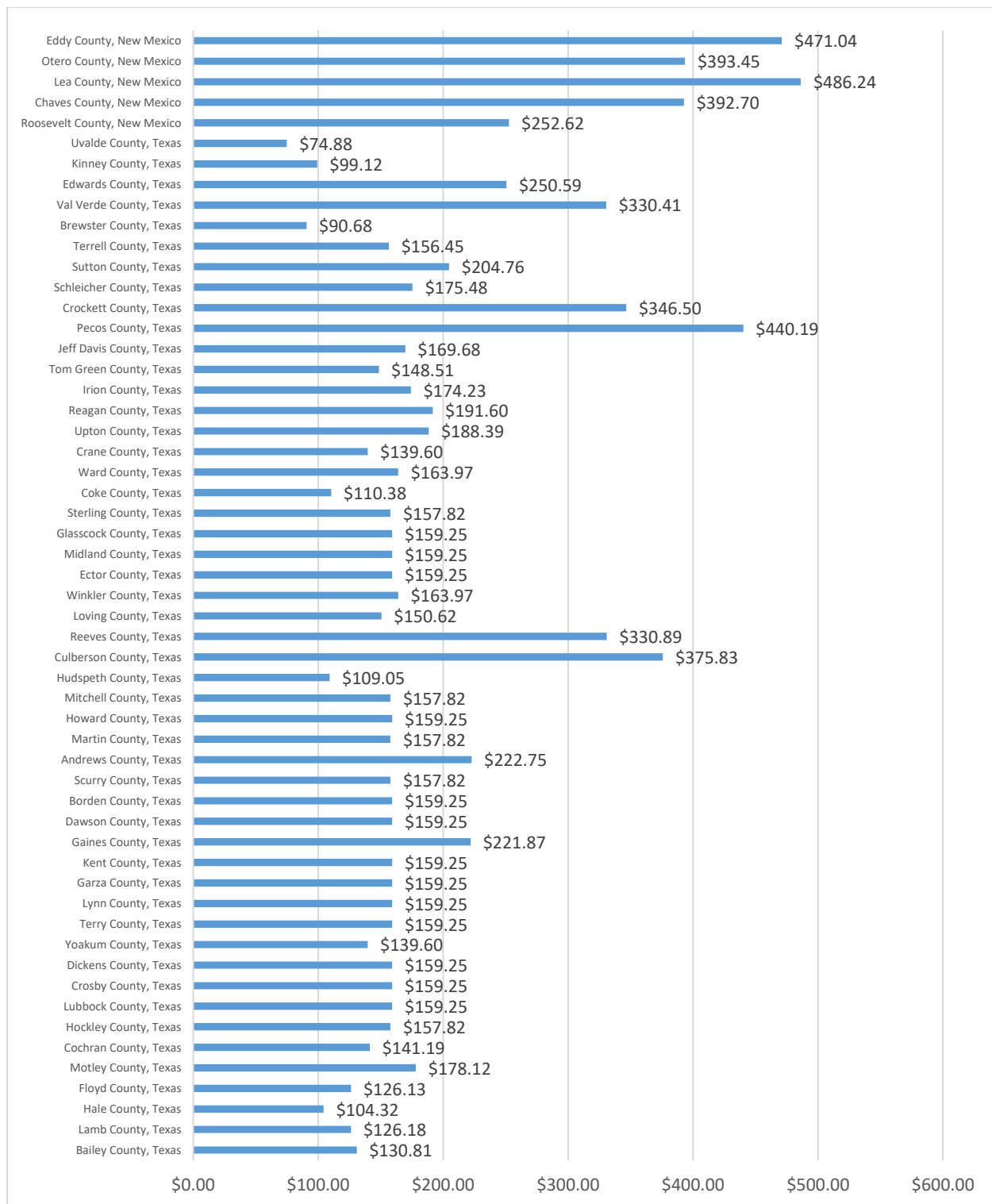


Figure 23: Aircraft acquisition cost per flight hour given an average 500-hour airframe useful life [USD].

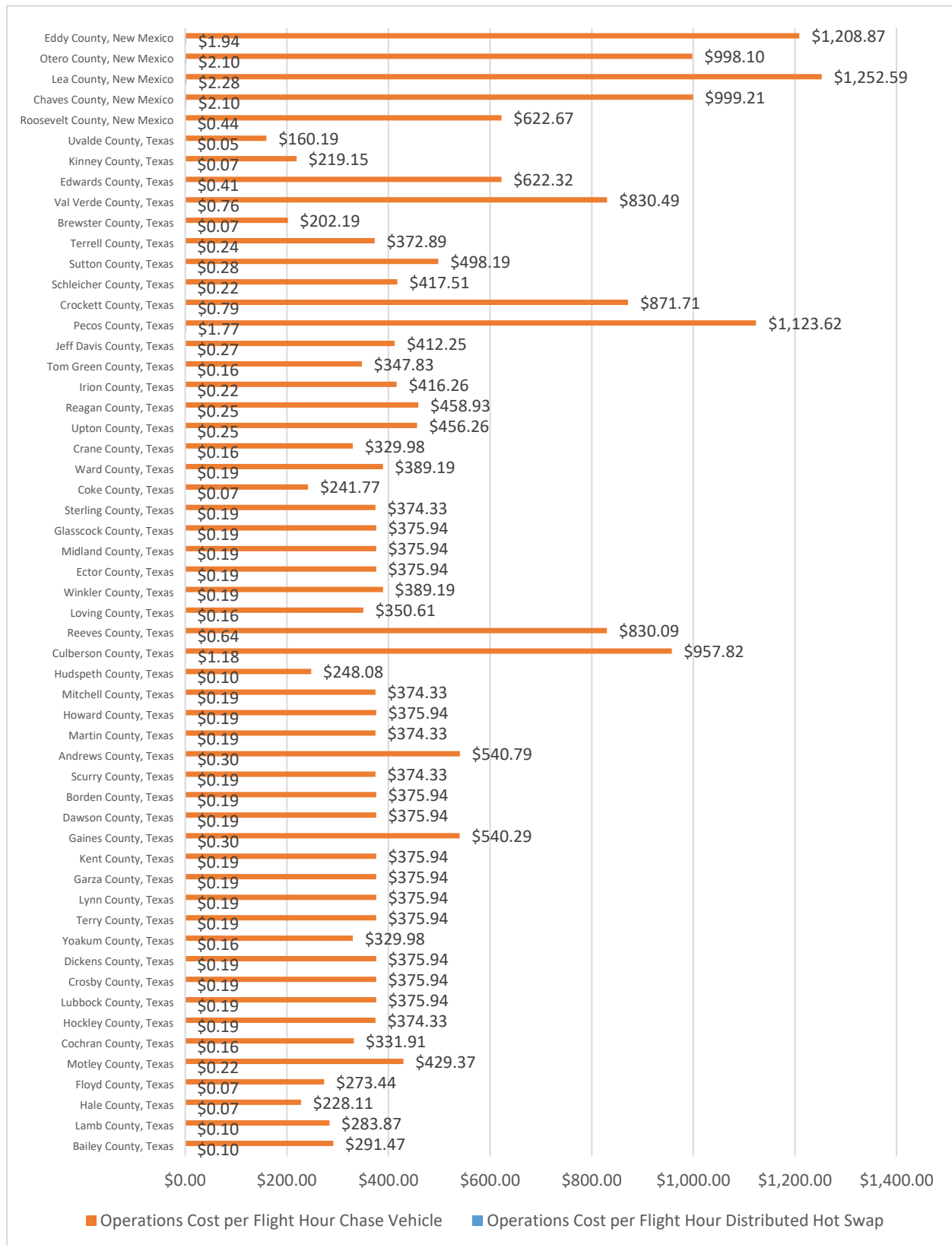


Figure 24: Operations cost per flight hour [USD]

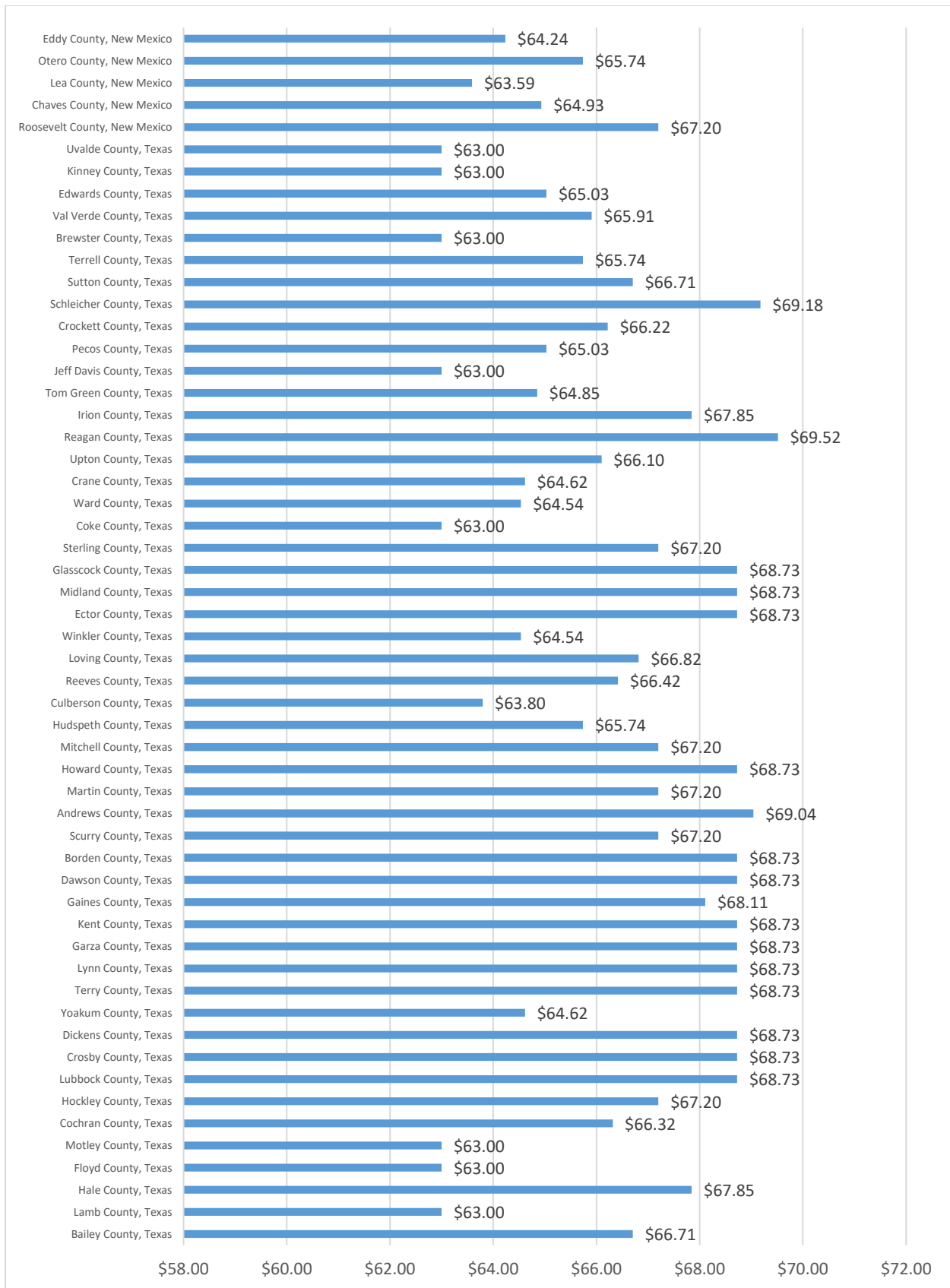


Figure 25: Remote Pilot cost per flight hour [USD]

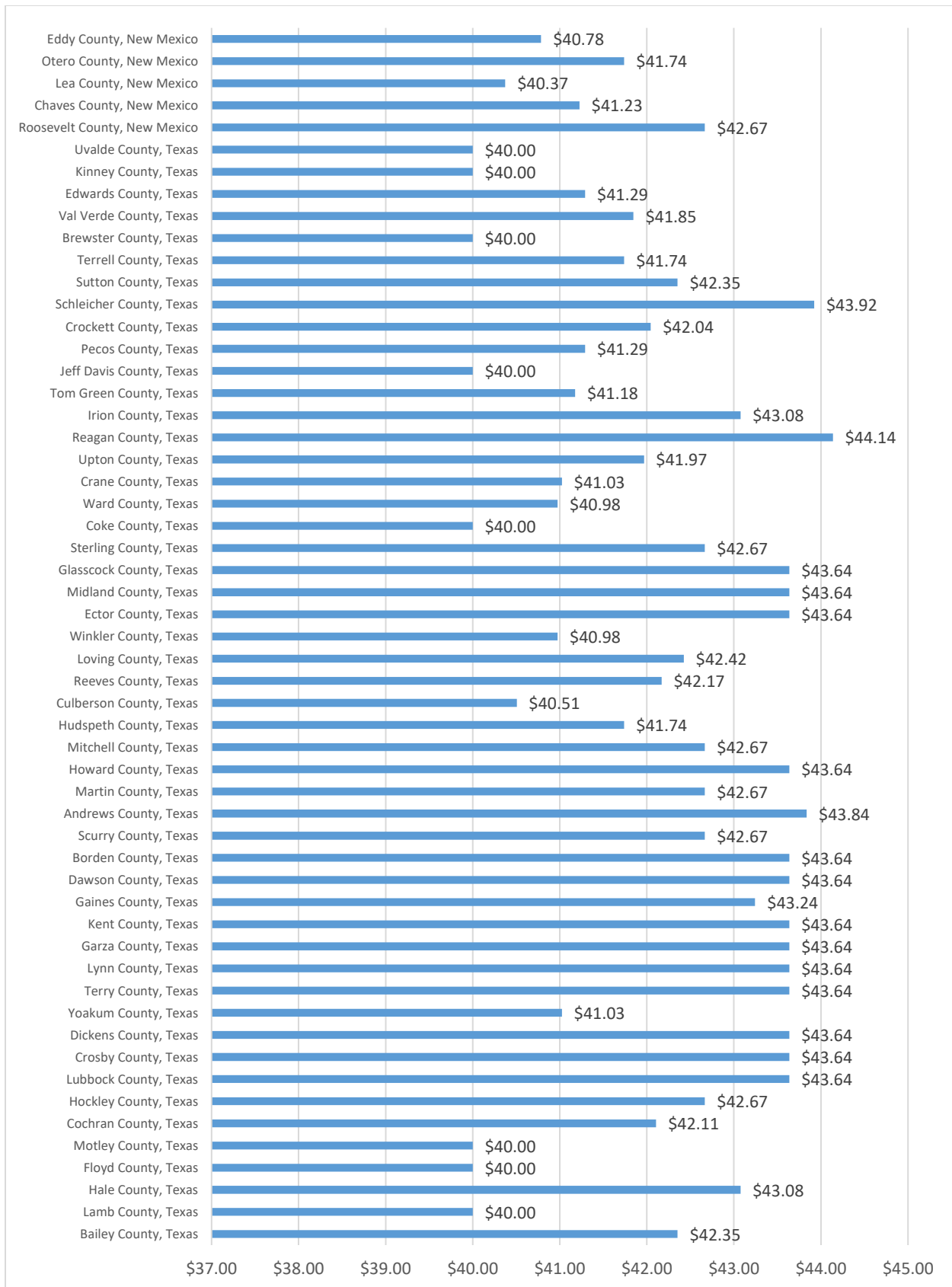


Figure 26: Ground Support Personnel cost per flight hour [USD]

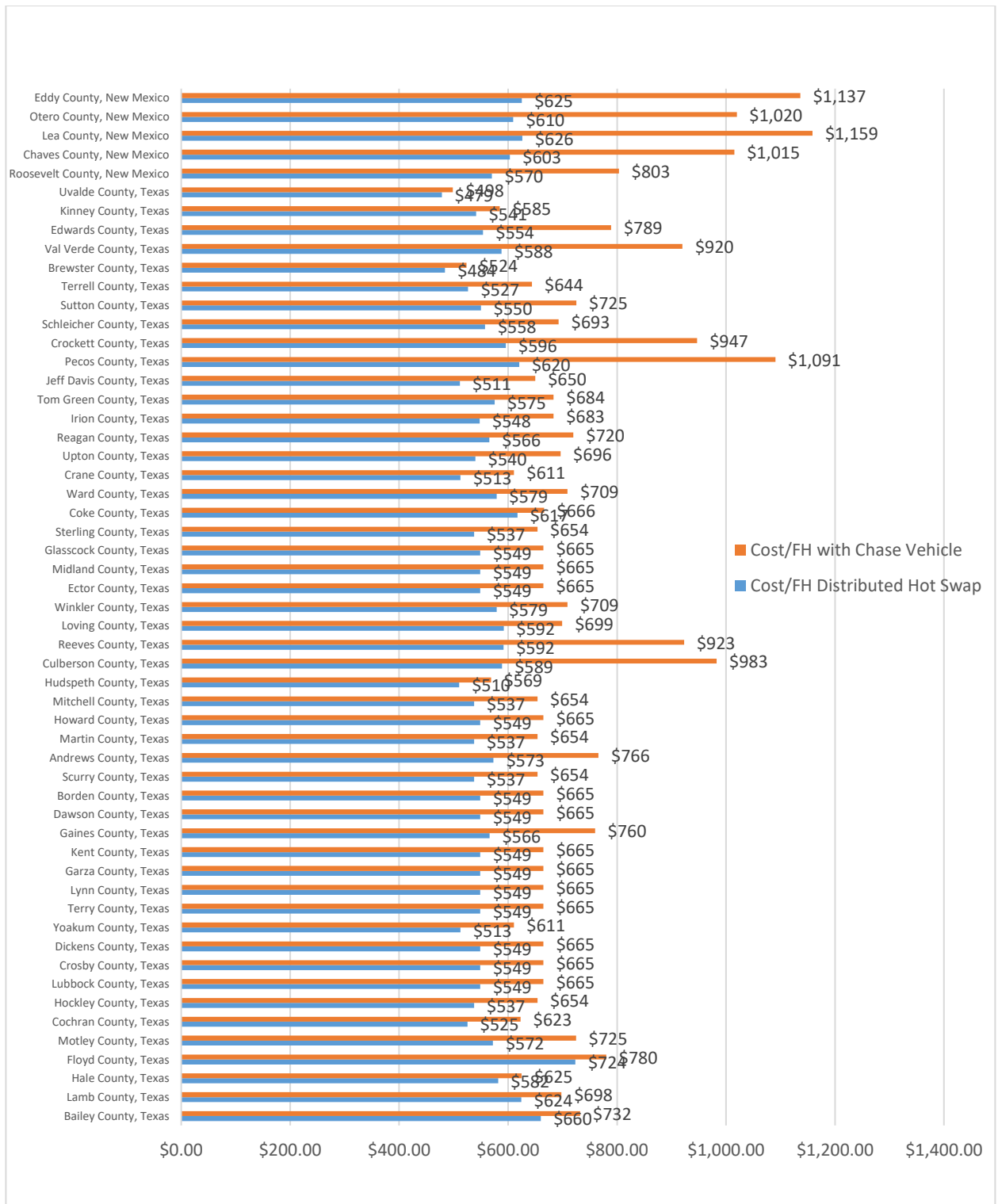


Figure 27: Estimated Total Mission Cost (Acquisition + Operations) per Flight Hour an acquisition per campaign [USD].

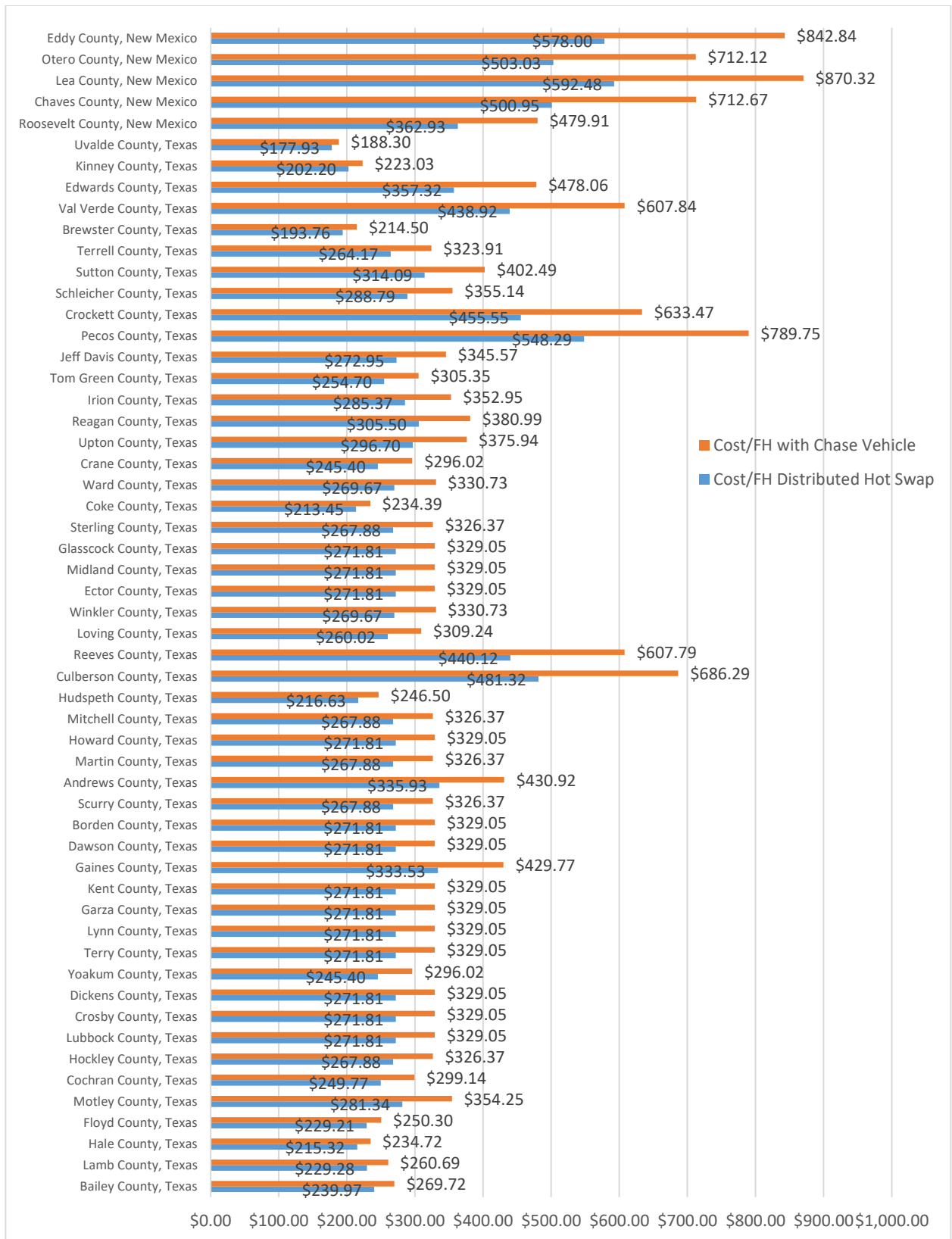


Figure 28: Estimated Total Mission Cost (Acquisition + Operations) per Flight Hour given an average airframe useful life of 500 hours [USD].

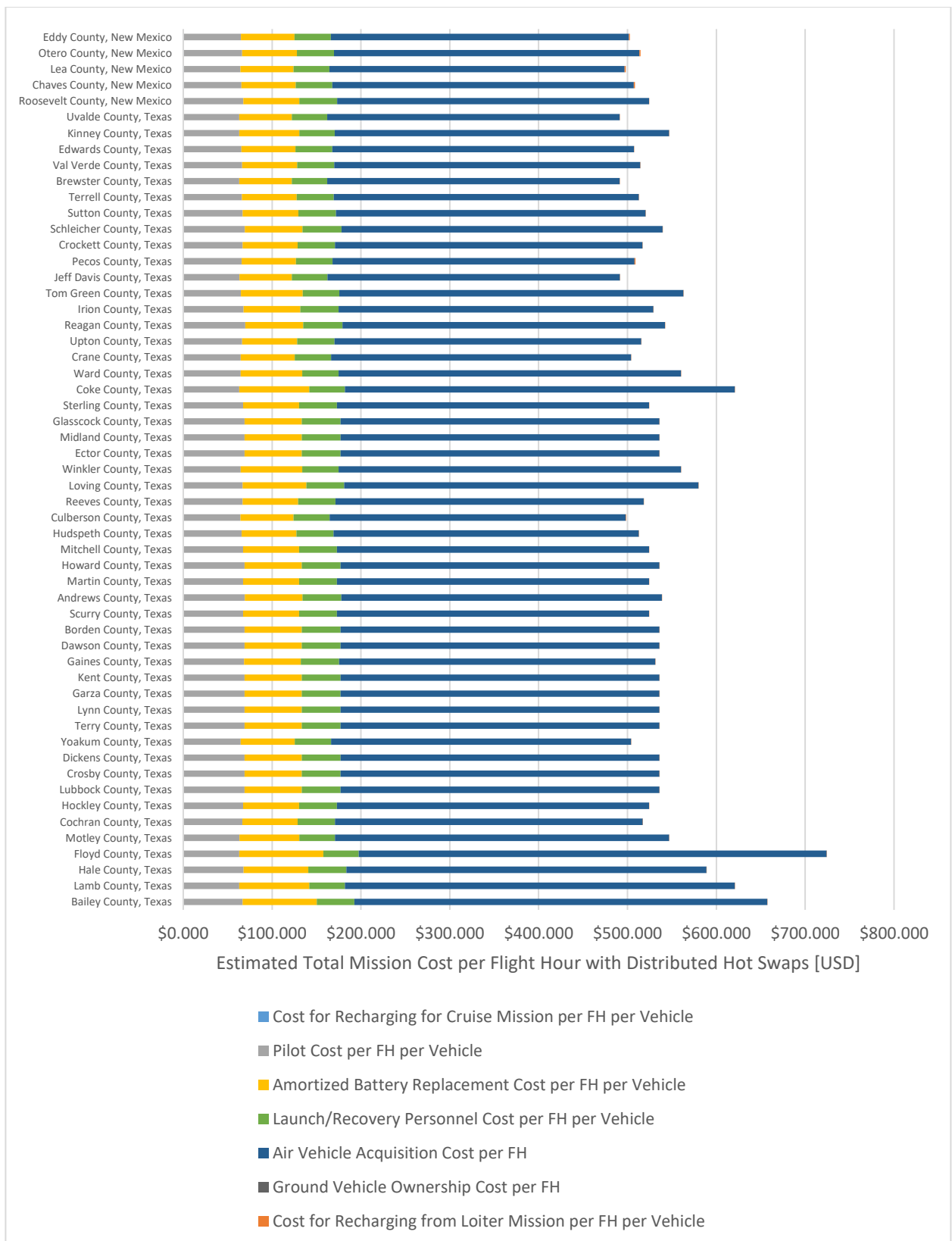


Figure 29: Itemized total mission cost per flight hour of the distributed hot swap concept of operations given an acquisition per campaign basis.

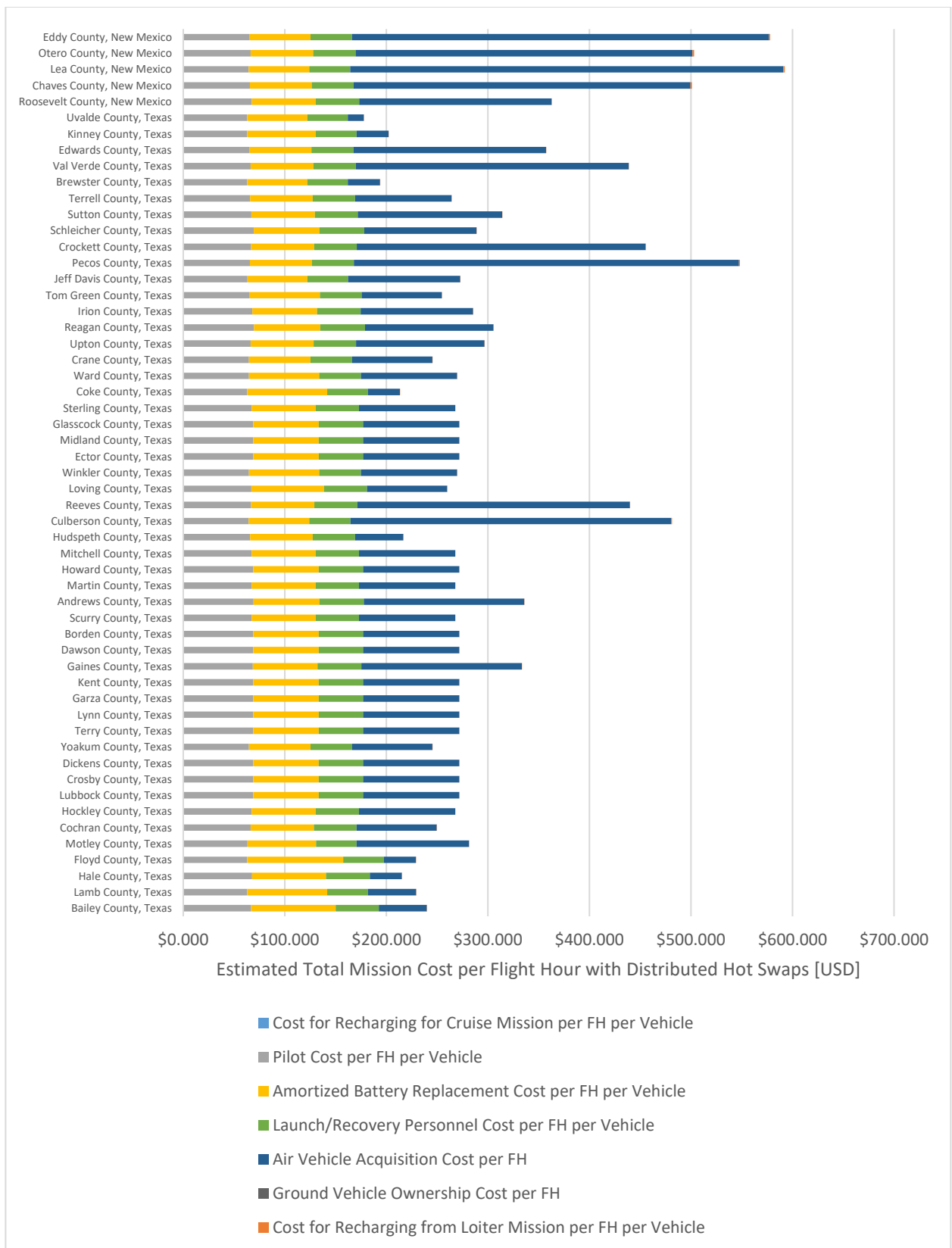


Figure 30: Itemized total mission cost per flight hour of the distributed hot swap concept of operations given an average airframe useful life of 500 hours.

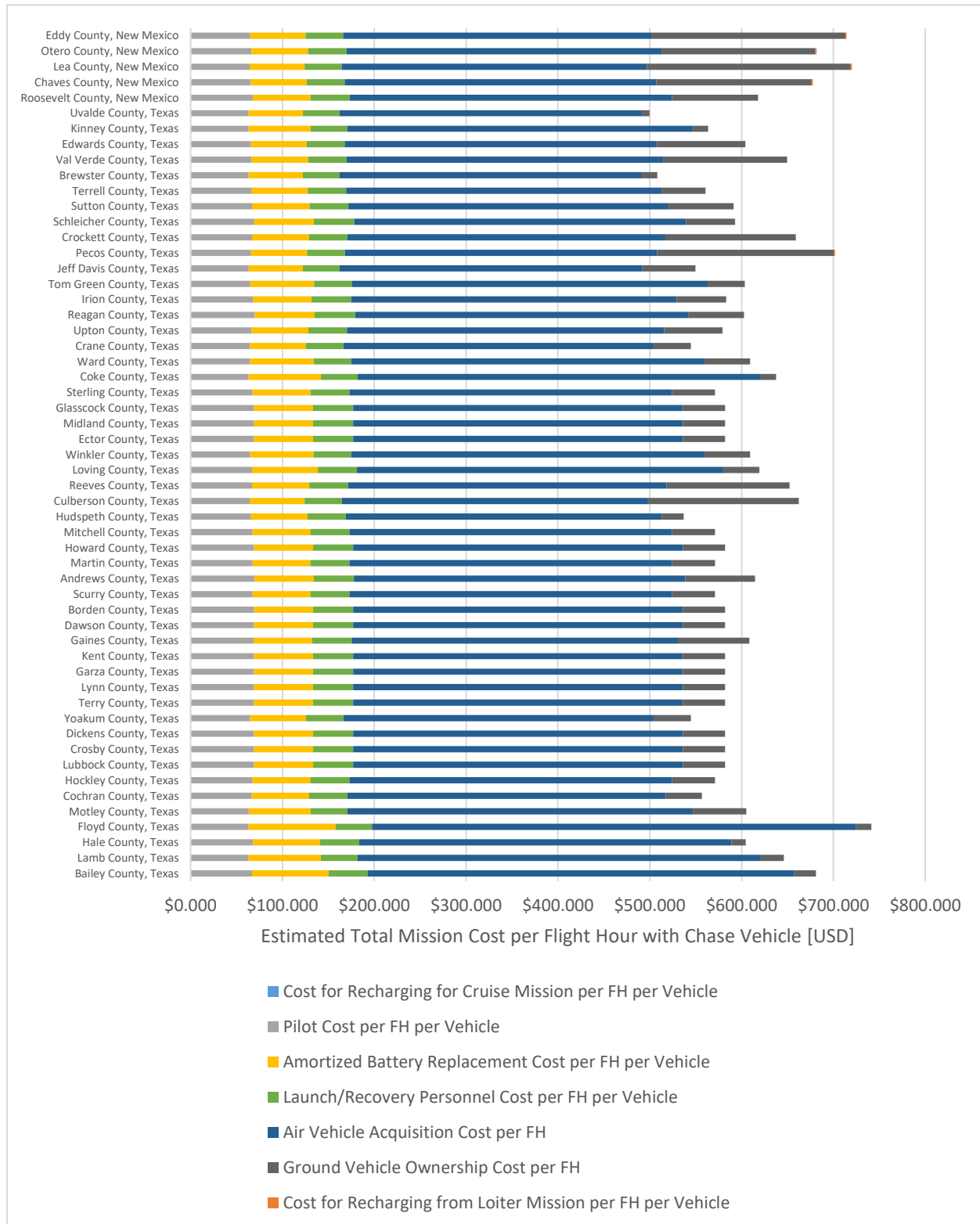


Figure 31: Itemized total mission cost per flight hour of the chase vehicle concept of operations given an acquisition per campaign basis

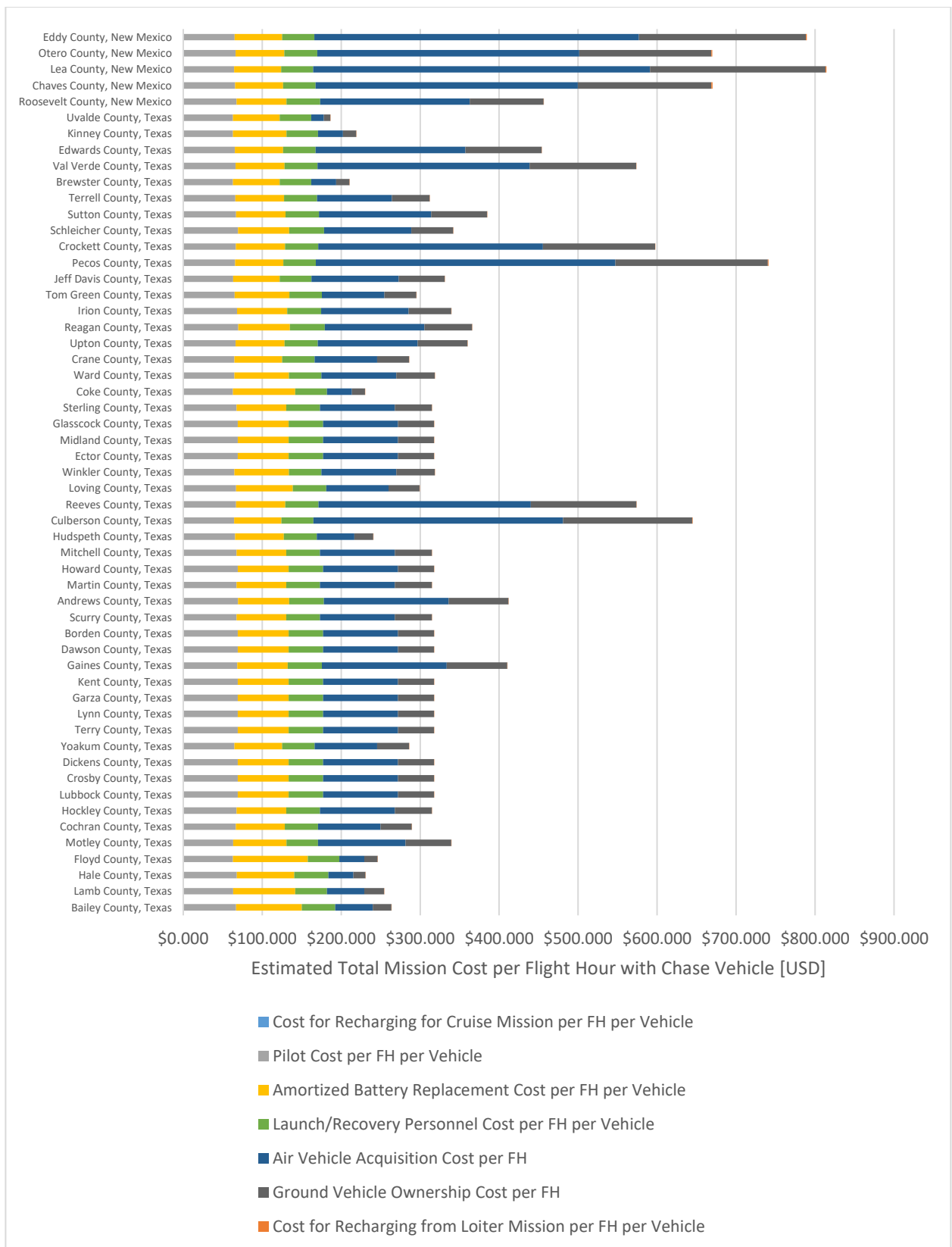


Figure 32: Itemized total mission cost per flight hour of the chase vehicle concept of operations given an airframe average useful life of 500 hours.

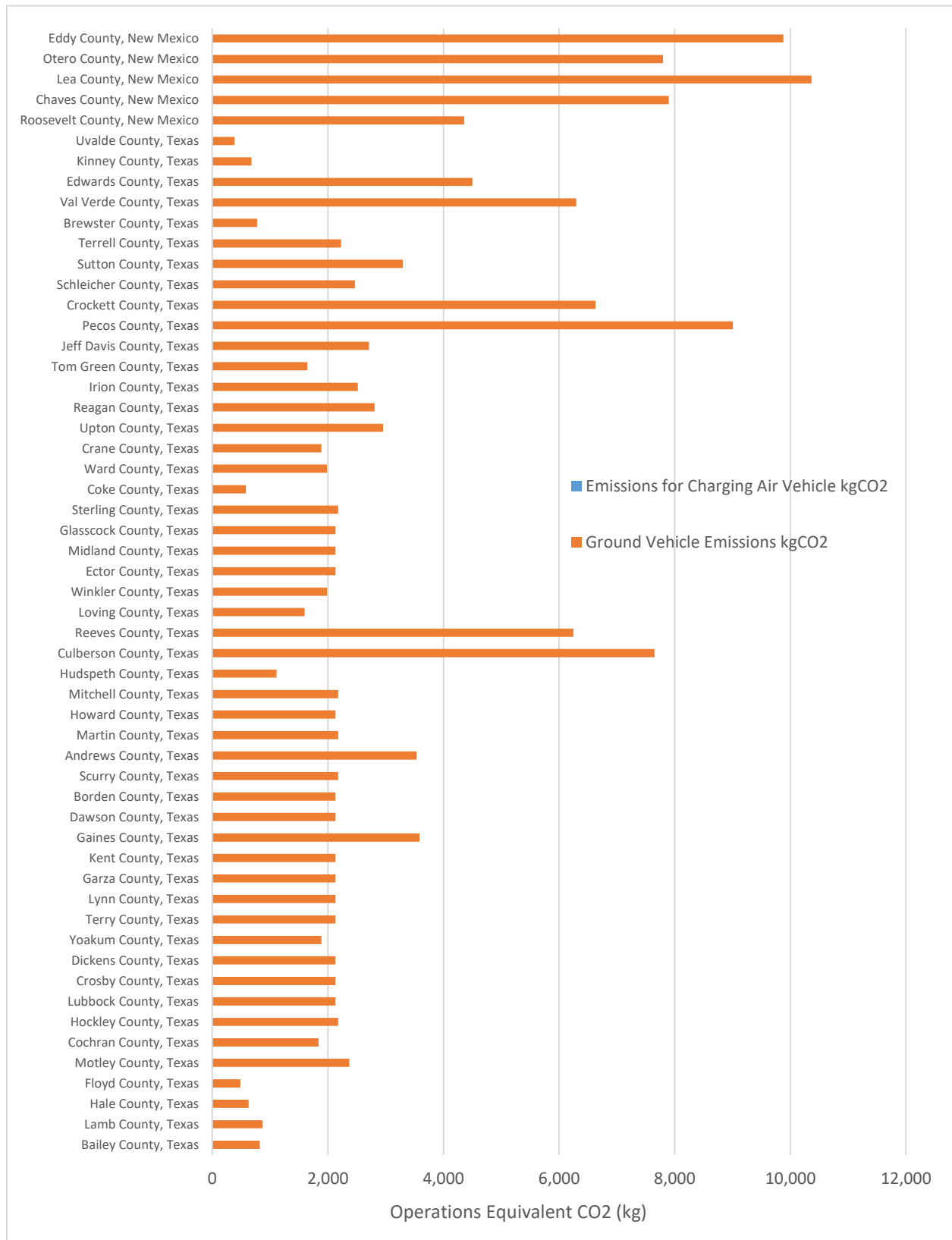


Figure 33: Estimated CO₂ emissions for the chase vehicle concept of operations.

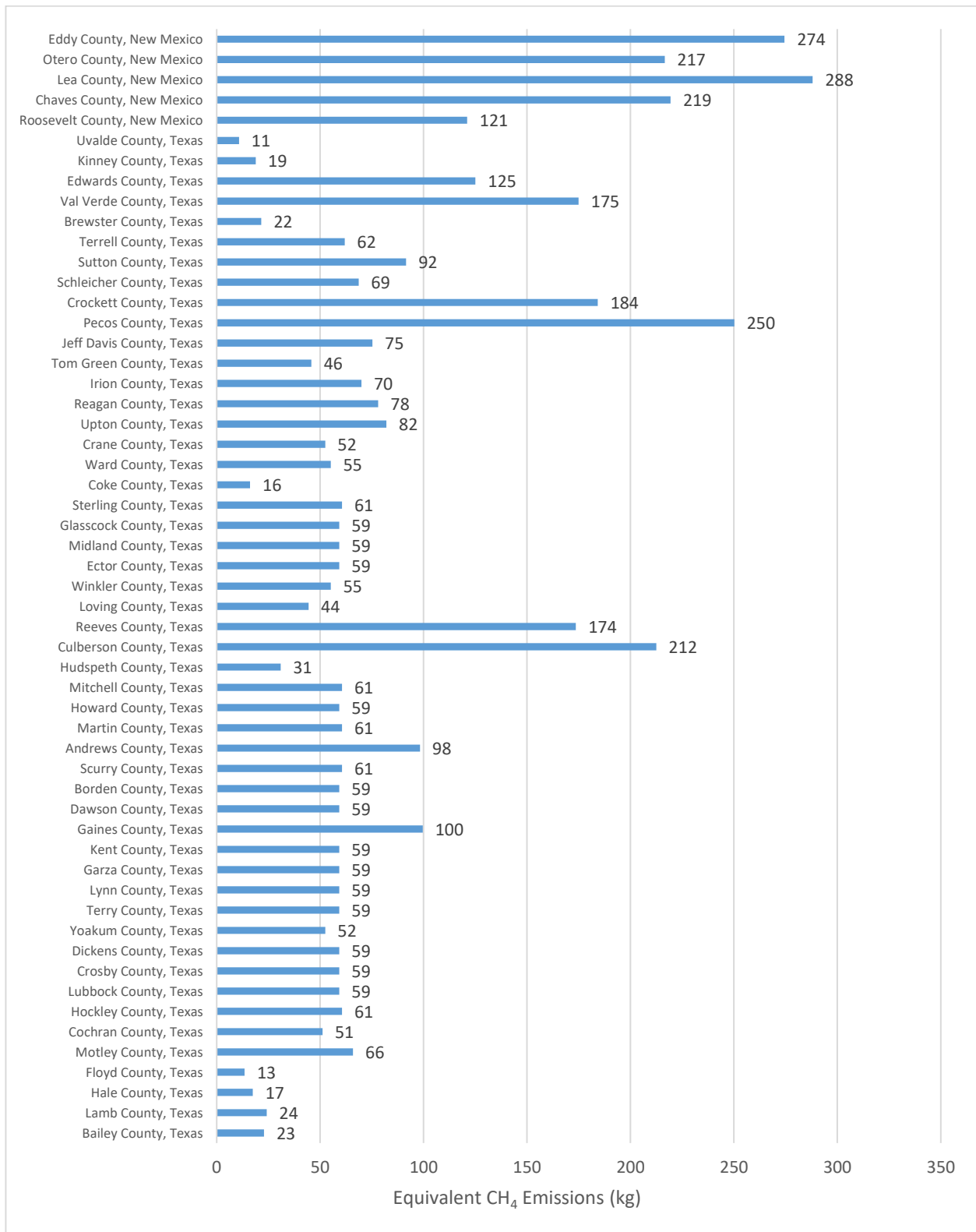


Figure 34: Total equivalent emissions of CH₄ per daily mission under the chase vehicle concepts of operations.

Appendix B

General Feasibility: Emission Reduction of Permian Basin Methane

We show the details of the overall feasibility analysis in terms of potential reduction in methane emissions from the Permian Basin, under several general assumptions and estimates, which are based on the materials in [118] and [119]. Values, such as well density, can vary considerably based on geology, production history, and economic conditions in a specific area. Moreover, recent studies indicate that methane emissions from the Permian Basin significantly exceed EPA estimates [120]. The presented potential outcomes are approximate computations. The actual numbers for a local analysis would vary, depending on the conditions in the county areas where operations would take place. We also include several financial viability considerations as part of the general feasibility estimates. Although the Permian Basin numbers cover 60 counties, we multiply per-county estimates by 55 for the totals, to match the 55 counties used in the preceding analysis.

Baseline Assumptions

- County characteristics:
 - Average size of a county in the Permian Basin: $\approx 1,645 \text{ mi}^2$, computed as arithmetic average of the areas of twenty top Permian Basin counties by population size.
 - Typical well density: 5 wells per mi^2 .
 - Average total number of wells per county: $\approx 8,225$ active wells, computed as average county size times typical well density.
- Sample emission rates, based on satellite data:
 - Average methane leakage rate: 3.7% of gas production.
 - Average daily production per county: $\approx 500 \text{ MMcf}$.
 - Daily methane emissions per county: $\approx 18.5 \text{ MMcf}$ (3.7% of production).
 - Annual methane emissions per county: $\approx 6,752.5 \text{ MMcf}$ (daily $\times 365$).
- Detection and repair efficiency
 1. Drone-based detection sensitivity: 0.1-1 kg/hour.
 2. Typical response time: 24-48 hours.
 3. Repair success rate: 90%.
 4. Coverage capability: 15-20 wells per day.
 5. Full county coverage cycle: ≈ 2 months.

Computation of Emission Reduction

- Detectable leaks
 1. Large: $>100 \text{ kg/hr}$:
 - 10% of total emissions
 - Most easily detected
 - Potential annual savings: 675.25 MMcf
 2. Medium: 10-100 kg/hr:
 - 30% of total emissions
 - Good detection rate
 - Potential annual savings: 2,025.75 MMcf
 3. Small: $<10 \text{ kg/hr}$:
 - 60% of total emissions
 - More difficult to detect
 - Potential annual savings: 4,051.5 MMcf
- Detection and repair success rate per leak type:
 1. Large: 95% detection, 90% repair = 85.5% reduction
 2. Medium: 80% detection, 90% repair = 72.0% reduction

3. Small: 50% detection, 90% repair = 45.0% reduction
- Potential for annual emission reduction:
 - Large leaks: 577.3 MMcf
 - Medium leaks: 1,458.5 MMcf
 - Small leaks: 1,823.2 MMcf
 - **Total annual reduction per county: 3,859 MMcf (≈57% of total emissions)**
 - **Total annual reduction: 3,859 x 55 (counties) = 212,245 MMcf**
 - Total environmental impact of methane reduction (over 55 counties)
 - Methane 20-year GWP: 84-87 times of carbon dioxide
 - CO₂ equivalent reduction: $\approx 323,156 \times 55 = 17,773,580$ metric tons CO₂e per year
 - **Equivalent to removing $\approx 70,251 \times 55 = 3,863,805$ cars from the road annually**
 - Economic value
 - Average natural gas price: 3 USD/MMBtu
 - Value of recovered gas: $\approx 11.6\text{M USD} \times 55 = 638\text{M USD}$ annually
 - Carbon credit value (25 USD/ton CO₂e): $\approx 8.1\text{M USD} \times 55 = 445.5\text{M USD}$ annually
 - Societal value
 - Environmental (global), with all the attendant consequences (climate, health, economy, quality of life).
 - Confidence Factors
 - High
 - Basin-wide emission rates.
 - Large leak detection capabilities.
 - Repair success rates.
 - Medium
 - Medium leak detection rates.
 - Coverage timing.
 - Economic valuations.
 - Lower
 - Small leak detection rates.
 - Weather impact on operations.
 - Future gas prices.
 - Key Limitations
 - Weather conditions affect drone operations.
 - Equipment maintenance downtime.
 - Variable leak sizes and durations.
 - Access restrictions to certain areas.
 - Seasonal variations in emissions.
 - Notes
 - Conservative estimates used where uncertainty exists.
 - Actual results may vary based on specific county characteristics.
 - Continuous monitoring may improve detection rates over time.