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Economic Evaluation

Cost-Effectiveness of Aerial Logistics for Immunization: A Model-Based Evaluation of Centralized Storage and Drone Delivery of Vaccines in Ghana Using Empirical Data

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ABSTRACT

Objectives: In mid-2020, the Ghana Health Service introduced Zipline's aerial logistics (centralized storage and delivery by drones) in the Western North Region to enhance health supply chain resilience. This intervention led to improved vaccination coverage in high-utilization districts. This study assessed the cost-effectiveness of aerial logistics as an intervention to improve immunization coverage.

Methods: An attack rate model, adjusted for vaccination coverage and vaccine efficacy, was used to estimate disease incidence among vaccinated and unvaccinated populations, focusing on 17 022 infants. Incremental cost-effectiveness ratios of US dollar per averted disability-adjusted life-year (DALY) were evaluated from societal and government perspectives, using real-world operations data. Probabilistic sensitivity analysis was performed using Monte Carlo simulations.

Results: In 2021, aerial logistics averted 688 disease cases. Incremental cost-effectiveness ratios were $41 and $58 per averted DALY from the societal and government perspectives, respectively. The intervention was cost-saving when at least 20% of vaccines delivered by aerial logistics replaced those that would have been delivered by ground transportation, with potential government savings of up to $250 per averted DALY. Sensitivity analysis confirmed the robustness of these findings.

Conclusions: Under conservative assumptions, aerial logistics was a highly cost-effective intervention to increase immunization coverage. The intervention was cost-saving even with low levels of replacement of traditional last mile delivery. These findings support expanding aerial logistics within the national immunization program and have significant implications for other low- and middle-income countries seeking cost-effective health supply chain solutions.

Keywords: aerial logistics, cost-effectiveness, drones, last mile delivery, vaccines.

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Introduction

Immunization is a key strategy in preventing infectious diseases among children and is universally recognized as a cost-efficient approach to addressing global health challenges.[1] However, the quest for widespread vaccine coverage is fraught with difficulties, particularly in terms of delivery.[2] Governments in low- and middle-income countries (LMICs) often face the daunting task of judiciously allocating limited resources across various immunization programs, each with its own differentiated cost-effectiveness profile.

Extensive research has been undertaken to identify the most cost-effective strategies for boosting immunization coverage. A 2017 systematic review[3] analyzed the cost-effectiveness of diverse interventions aimed at increasing childhood vaccination rates in LMICs. This review encompassed 14 studies, covering approaches ranging from demand generation and modified delivery methods to cash transfer programs, health system improvements, and the application of innovative technologies. The findings, measured in incremental cost-effectiveness ratios (ICERs), varied widely, with costs per additional child vaccinated ranging from as low as $0.66 to as high as $161.95 (in 2017 US dollar). The review highlighted the need for more quantitative evidence to effectively assess the cost-effectiveness of these interventions.

In recent years, drone-based logistics has become a promising solution for overcoming logistical barriers and improving immunization coverage. Research in this field has started to reveal the potential of this technology.[4-6] However, with only a limited number of countries having implemented drone logistics nationally, there remains a notable gap in literature regarding the real-world impact and cost-effectiveness of aerial logistics. To date, only one 2023 study has provided real-world data estimates on the broader programmatic and health outcomes at the population level from using aerial logistics for vaccine distribution.[7] This research specifically focused on operations in Ghana, where medical drones are used for the centralized storage of vaccines and other medical essentials at distribution centers, with on-demand delivery to health facilities using autonomous unmanned aerial vehicles.

The study offers a detailed analysis of the impact of aerial logistics on routine early childhood immunization in Ghana's Western North Region, covering 365 facilities and serving more than 2 million people across 19 districts. This predominantly rural region, which experiences the highest rainfall in Ghana, underwent administrative changes in 2019 aimed at improving access to essential developmental projects and services. As in the rest of rural Ghana, traditional last mile delivery (LMD) in this region typically involves sporadic bulk shipments from the capital by truck, supplemented by health personnel from smaller facilities using smaller vehicles and motorbikes to retrieve vaccines from regional centers. However, ground transportation often faces delays due to poor road infrastructure, heavy rainfall, long travel times, and limited transportation options. These challenges not only lead to vaccine hoarding and increased wastage but also contribute to prolonged stockouts at local health centers. These stockouts can erode community trust in health services, making caregivers less likely to bring their children in for vaccinations, further reducing vaccination coverage.[8]

In contrast, drones provide a reliable and timely delivery system, ensuring smoother ordering behavior, reduced wastage and stockouts, and consequently consistent vaccine availability. This reliability strengthens trust among communities, particularly mothers and caregivers, encouraging them to bring their children for vaccination. In addition, drones can reach remote health facilities more effectively, expanding services at these locations, reducing travel burdens for families, and ultimately increasing overall vaccination rates.

The findings from this study showed that aerial logistics in LMD increased satisfaction with access to vaccines, likely through these combined effects. Using a difference-in-differences model to assess the impact of aerial logistics on vaccination coverage, the research revealed a significant improvement in pre- and post-intervention vaccination coverage, with gains ranging from 13.1 to 37.5 percentage points for most vaccines compared with the counterfactual (no-intervention) scenario.

Building on these findings, our study explored the field of aerial logistics for health commodity supply chains, focusing specifically on vaccine distribution. We aimed to evaluate the cost-effectiveness of aerial logistics as an intervention that has improved immunization coverage in Ghana's Western North Region. By providing comprehensive data on the cost-effectiveness of this method compared with traditional LMD, our research contributes to the decision-making process regarding public health interventions in LMICs. It offers a critical analysis of the viability and impact of innovative logistic solutions in healthcare, providing valuable insights for policy makers and healthcare practitioners.

Methods

Our study used an attack rate model, adjusted for vaccination coverage and efficacy, to estimate disease incidence separately in vaccinated and unvaccinated populations. Following established immunization cost-effectiveness methodologies,[9,10] the model assumes that the observed incidence reflects a weighted average of these 2 groups, with lower incidence in the vaccinated due to their partial or full protection.

Building on documented impacts of aerial logistics on vaccination rates,[7] the model evaluates the averted burden of disease by shifting more individuals into the vaccinated group.

The health impact assessment is limited to the intervention year, focusing on acute disease episodes that would have occurred within that period. We also accounted for lifelong sequelae from these acute cases, using a 1-year time horizon for averted healthcare costs and a lifetime horizon for averted disability-adjusted life-years (DALYs), with a 3% discount rate. This approach improves the reliability of our estimates by avoiding assumptions about future vaccination scenarios, although it likely underestimates the long-term impact, particularly for diseases such as hepatitis B, which can develop later and have significant health consequences. The target population for this study corresponds to the 2020 to 2021 national birth cohort in 4 Ghanaian districts with high exposure to aerial logistics—Suaman, Aowin, Sefwi Akontombra, and Bodi—as studied previously,[7] encompassing an estimated 17 022 infants. Vaccines included correspond to the full immunization vaccination schemes, namely Pentavalent3, PCV3, MR2, and BCG. The diseases associated with each vaccine are listed below:

- BCG: tuberculosis
- MR2: measles
- PCV3: acute otitis media, lower respiratory infections, and bacterial meningitis
- Pentavalent3: diphtheria, tetanus, acute hepatitis B, lower respiratory infections, and bacterial meningitis

We assessed the incremental cost-effectiveness of aerial LMD of vaccines in the Western North Region of Ghana during 2021 from both government and societal perspectives. The aerial logistics scenario was compared with traditional LMD methods, representing the status quo or no-intervention scenario. The effectiveness measures incorporated in the ICERs include cost per averted DALY and cost per additional fully immunized child (FIC). Univariate and probabilistic sensitivity analyses were performed using Monte Carlo simulations to construct acceptability curves and cost-effectiveness planes. The analysis was performed using R statistical software (version 4.3.2), developed by the R foundation for Statistical Computing, Vienna, Austria.

Input sources used in the costing and impact methodology are presented in Appendix A, Tables 1-4 (see Appendix A in Supplemental Materials found at https://doi.org/10.1016/j.vhri.2024.101066).

Health Impact

The model estimates the underlying incidence rates for both vaccinated and unvaccinated groups (*Iunvaccinated* and *Ivaccinated*), using baseline incidence (*Iobserved*), vaccine efficacy (*ve*), and immunization coverage (*vc*), as depicted in Eq. (1) and Eq. (2).

$$I_{unvaccinated} = \frac{I_{observed}}{1-(\mathrm{ve} \ast \mathrm{vc})} \quad (1)$$

$$I_{vaccinated} = (1 - \mathrm{ve}) \ast \mathrm{I_{unvaccinated}} \quad (2)$$

Data sources used for each variable in these equations in the intervention districts are presented in Appendix A, Table 1 (see Appendix A in Supplemental Materials found at https://doi.org/10.1016/j.vhri.2024.101066). Using these incidences and drawing on previously documented impacts of aerial logistics over vaccination rates, we were able to estimate the number of cases of disease that were averted in the intervention scenario.

Using country-specific case fatality rates and DALY weights from the Institute for Health Metrics and Evaluation–Global Burden of Disease data for 2019, we estimated the averted premature deaths and DALYs derived from acute episodes of disease and lifelong disabilities acquired in the intervention year.

Costs

The analysis was conducted from both societal and government perspectives. Although Ghana's health system includes both public and private sectors, the public sector, led by the Ghana Health Service (GHS), is the primary healthcare provider, particularly in rural and underserved areas such as the Western North and most districts where Zipline's services are extensively used. The GHS manages healthcare delivery at regional, district, and subdistrict levels and oversees the Expanded Program on Immunization, which targets 13 vaccine-preventable diseases and ensures free treatment at the point of delivery for these diseases. Given the GHS's dominant role, the government perspective in this analysis included healthcare treatment costs and incremental LMD costs. The societal perspective also accounted for externalities such as caregivers' wage loss and transport costs.[11]

To calculate the total cost for aerial LMD of vaccines, we analyzed Zipline's monthly operational costs and the depreciation of capital expenditures for the GH4 distribution center in the Western North Region. These were adjusted to 2023 US dollar values, and the corresponding portion attributed to vaccine delivery was determined, resulting in a cost per dose of $0.27. This was later multiplied by the total number of vaccines distributed in 2021 to the intervention districts.

To estimate the incremental cost of the intervention, we took into account that the impact of aerial logistics on vaccination rates can be explained through either a pure expansion of access (ie, health facilities receiving vaccine doses that they otherwise would not have) or more efficient access (ie, health facilities receiving the same number of vaccine doses they would have otherwise received but in a more timely manner, leading to fewer missed opportunities of vaccination). Anecdotal evidence suggests that the impact is likely a combination of both factors. The distinction is significant when computing costs in an ICER: in the former, aerial logistics LMD cost is an additional expense to the existing supply chain cost for the government, whereas, in the latter, aerial logistics LMD replaces the traditional supply chain cost for transporting those vaccines.

This rationale for the incremental cost is summarized in the following equation:

$$\text{Incremental LMD cost} = \text{CPD}_{\text{ZL}} \times \text{Incremental Doses} + (CPD_{\text{ZL}} - CPD_{\text{trad}}) \times \text{Replaced Doses} \quad (3)$$

where CPD_{ZL} and CPD_{trad} correspond to aerial logistics LMD cost per dose and traditional LMD cost per dose, respectively; *Incremental Doses* would be the doses that correspond to purely increased access; and *Replaced Doses* correspond to the doses that would have been delivered in both scenarios but in the intervention scenario were delivered using aerial logistics instead of traditional delivery. The sum of these 2 equals the total number of doses delivered with aerial logistics. Due to the absence of detailed data on traditional LMD, we were unable to differentiate between incremental and replaced doses within the number of doses delivered with aerial logistics during the intervention period. To mitigate the impact of this uncertainty on our estimations, for our primary ICER calculation, we proceeded with the conservative assumption that all doses delivered by aerial logistics during this period were incremental. This approach may inflate our incremental cost estimates but ensures the solidity of our findings amid the well-known ambiguous quality and high variance of the traditional LMD data that were used for illustrative purposes in the sensitivity analysis.

ICERs

ICER calculations were based on the following equations:

$$\text{ICER DALY}_{\text{healthcare perspective}} = \frac{\text{Incremental LMD cost} - \text{AHTC}}{\text{Averted DALYs}} \quad (4)$$

$$\text{ICER DALY}_{\text{societal perspective}} = \frac{\text{Incremental LMD cost} - \text{AHTC} - \text{ATC} - \text{ALW}}{\text{Averted DALYs}} \quad (5)$$

$$\text{ICER per incremental FIC} = \frac{\text{Incremental LMD cost} - \text{AHTC}}{\text{Additional complete immunization schemes}} \quad (6)$$

In these equations, *AHTC* represents the averted healthcare treatment cost; *ATC* and *ALW* correspond to the averted transport costs and averted lost wages, respectively, related to the averted burden of disease in the intervention scenario; *Incremental LMD Cost* is the LMD cost that would have occurred in the counterfactual scenario (if part or all the doses had been delivered through traditional means); *Averted DALYs* denotes the DALYs averted due to the increased immunization coverage in the intervention districts; *Incremental LMD cost* follows equation 3 specified before; and *ICER per incremental FIC* is the ICER per incremental FIC.

Sensitivity Analysis

For the probabilistic sensitivity analysis, cost parameters were sampled from gamma distributions to accurately reflect the right skew of observed costing data, whereas noncost parameters were sampled from normal distributions. The lower and upper ranges of these distributions were derived from published literature. Our analysis involved 10 000 Monte Carlo simulations to assess the robustness of our results under varied assumptions.

In the univariate sensitivity analysis, we focused on the variance and uncertainty around the incremental LMD cost. Despite having had access to extensive operations data from aerial logistics, there is still a noticeable gap in data and research regarding traditional LMD, which are required for constructing counterfactual scenarios. To tackle this, we have developed various scenarios to evaluate the potential impact on the cost-effectiveness of aerial logistics as an LMD solution. In addition, in Appendix B, Figures 1-3 (see Appendix B in Supplemental Materials found at https://doi.org/10.1016/j.vhri.2024.101066), we have used the available operations data from aerial logistics to explore how economies of scale play a role in enhancing the cost-effectiveness of aerial logistics.

For estimating traditional LMD costs, applicable to scenarios with any level of replacement doses, we used the logistic component of published data on the delivery cost per dose for Ghana.[12] In the absence of specific LMD percentage data for Ghana, we adopted, for analytical purposes, the Zambian

Table 1. Results from the disease cost analysis.

Disease	Averted treatment costs	Averted transport costs	Averted loss of caregiver wages
Acute hepatitis b	$348 ($253-$489)	$42 ($31-$59)	$8 ($6-$11)
Acute otitis media	$490 ($257-$842)	$3 ($2-$4)	$83 ($44-$143)
Lower respiratory infections	$12 686 ($9990-$16 057)	$56 ($44-$71)	$1247 ($982-$1578)
Measles	$3 307 ($1121-$7012)	$186 ($63-$393)	$251 ($85-$531)
Meningitis	$3043 ($2310-$3989)	$42 ($32-$55)	$762 ($578-$999)
Tuberculosis	$453 ($318-$629)	$106 ($74-$147)	$38 ($27-$53)
Total	$20 324 ($14 246-$29 016)	$432 ($244-$727)	$2387 ($1721-$3313)

Note. Total averted treatment and transport costs and averted loss of caregiver wages with the intervention in 2021. 95% CIs in parentheses (all values in 2023 USD). USD indicates US dollar.

percentage as reported in previous literature,[13] which led to an estimated cost of $0.47 per dose.

We also assessed how the ICERs change from both the government and societal perspectives for each percentage of doses delivered with aerial logistics being replacement doses.

Results

Base Case

Drawing from previous findings on the impact of aerial logistics,[7] we calculated that aerial logistics facilitated the completion of an additional 14 979 full immunization courses, including BCG, MR, PCV, and Pentavalent vaccines, in 2021 for the specified population of 17 022 infants in 4 districts of the Western North Region in Ghana. Focusing solely on the health outcomes for that year, our analysis suggests that aerial logistics prevented 688 episodes of disease (95% CI 446–1041). We estimated that 4 children's lives (95% CI 2–7) were saved in these districts during 2021. We also found that, between the averted episodes of acute disease and long disabilities that would have been acquired in the year of the intervention, aerial logistics averted more than 170 discounted DALYs. In terms of costs related to the burden of disease, we estimated that the intervention averted a total of $20 324 in treatment costs and $2819 for caregivers between lost wages and transport. Total costs are presented in Table 1.

In our base-case analysis, we operated under the assumption that all vaccine doses delivered via aerial logistics were incremental doses. This means that doses delivered with aerial logistics would not have been covered by traditional LMD methods in the no-intervention scenario. This represents the most conservative, yet improbable, scenario where all doses delivered are incremental doses corresponding purely to an expansion of access. To address the implications of this assumption, a detailed univariate sensitivity analysis is presented in the subsequent chapter.

All these parameters, including the ICERs and their corresponding CIs, are presented in Table 2. We estimated that, from the government's perspective, the ICER for aerial logistics is $58 per averted DALY. From a societal perspective, this cost-effectiveness improves to $41 per averted DALY. Notably, both ICERs fall well below the standard willingness-to-pay (WTP) threshold, which is 1× Ghana's per capita gross domestic product per averted DALY (approximately $2100 for 2023).

Another key metric we reported is the incremental cost of aerial logistics per FIC, calculated at $0.66. This metric is gaining attention in immunization literature as a comparative tool for public health interventions aimed at improving immunization coverage.[3] Acknowledging the challenges in standardizing costing methodologies, our discussion section explores how this figure suggests that aerial logistics is more cost-effective than other interventions targeting the delivery aspect of immunization.

Probabilistic Sensitivity Analysis

The simulations of the probabilistic sensitivity analysis produced 2 key outcomes: a cost-effectiveness plane and acceptability curves. The cost-effectiveness plane in Figure 1 demonstrates that the intervention is cost-effective in more than 99.9% of iterations for the traditional World Health Organization–recommended WTP threshold of 1× Ghana's gross domestic product per capita. Acceptability curves in Figure 2 show that aerial logistics is a cost-effective intervention from the government and societal perspective with a confidence of 95% at a WTP threshold of $150 and $120, respectively.

Univariate Sensitivity Analysis

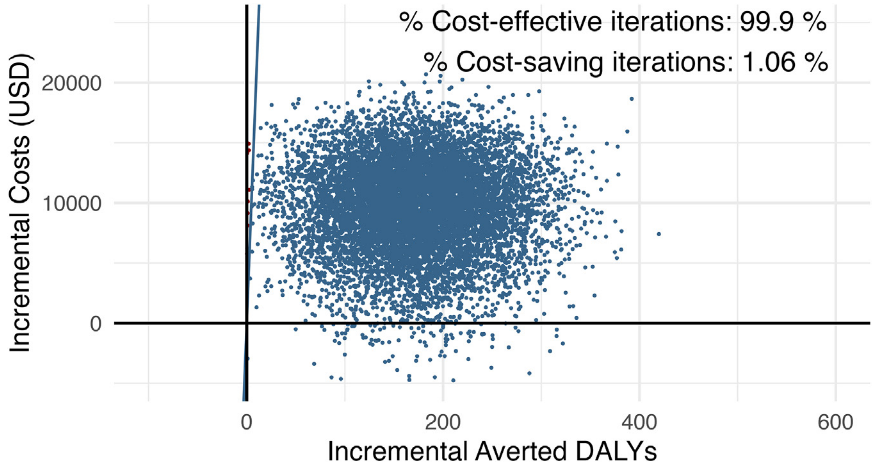
Figure 3 shows the total 2021 incremental aerial logistics LMD immunization costs for the 4 selected districts, for all possible degrees of traditional LMD replacement by aerial logistics—0% to 100% of doses delivered being replacement doses. The red vertical

Table 2. Inputs and resulting ICERs from the government and societal perspective.

Variable	Value
Averted DALYs	172 (106-295)
Averted loss of caregiver wages	$2387 ($1721-$3313)
Averted transport costs	$432 ($244-$727)
Averted treatment costs	$20 324 ($14 246-$29 016)
Total averted costs	$23 143 ($16 211-$33 056)
Aerial logistics additional fully immunized children	14 979 (6199-23 526)
Aerial logistics incremental LMD cost	$30 251
ICER: USD per averted DALYs government perspective	$58 ($4-$167)
ICER: USD per averted DALYs societal perspective	$41 ($9-$146)
ICER: USD per incremental fully immunized child	$0.66

Note. 95% CIs, when applicable, in parentheses (all values in 2023 USD). DALY indicates disability-adjusted life-year; ICER, incremental cost-effectiveness ratio; USD, US dollar.

Figure 1. Cost-effectiveness plane for the aerial LMD of vaccines (government perspective).



LMD indicates last mile delivery.

line represents the number of replacement doses at which these costs become negative (ie, become savings): the 63 307 doses represent approximately 50% of the doses delivered with aerial logistics as part of the intervention.

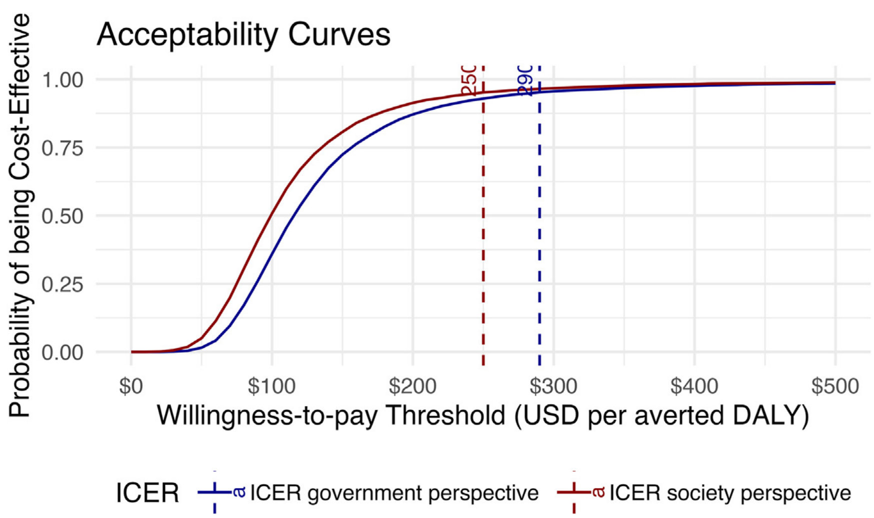
Figure 4 demonstrates that the cost-effectiveness of the intervention increases as the number of replacement doses rises. This trend aligns with expectations given that aerial logistics' cost per dose is lower than the estimated cost per dose for traditional delivery methods.

Notably, the intervention becomes cost-saving from the government's perspective once it reaches 20 807 replacement doses, which is less than 20% of the total doses delivered with aerial logistics during the intervention year. From the societal perspective, the cost-saving threshold is expectedly lower, at 14 907 replacement doses. In the scenario in which all doses delivered with aerial logistics are replacement doses, the intervention could have saved the government more than $250 per averted DALY.

Discussion

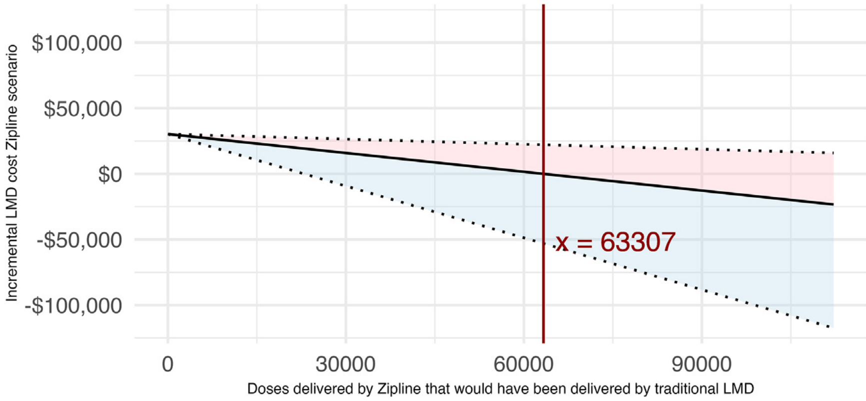
Our analysis yielded 2 key findings. First, at-scale aerial logistics for vaccine delivery is highly cost-effective, providing significant health benefits at a cost substantially lower than the WTP threshold, from both governmental and societal perspectives. Even with a conservative approach that considers only the financial benefits within the intervention year, the cost-effectiveness of this method is evident. This conclusion remained robust even after a probabilistic sensitivity analysis and considering a scenario that includes the initial ramp-up costs.

Figure 2. Acceptability curves for aerial LMD of vaccines. The vertical red line and vertical blue line correspond to the WTP thresholds at which the intervention has a probability of 0.95 of being cost-effective, from the society perspective and government perspective, respectively.



LMD indicates last mile delivery; WTP, willingness to pay.

Figure 3. Incremental LMD cost for each possible number of replacement doses from aerial logistics. Pink and blue areas reflect the CI around the central estimated value for the total cost for traditional LMD, with cost per dose at $0.47 (95% CI 0.12–1.31). The vertical red line corresponds to the number of replacement doses at which incremental LMD cost in the aerial logistics scenario becomes negative.

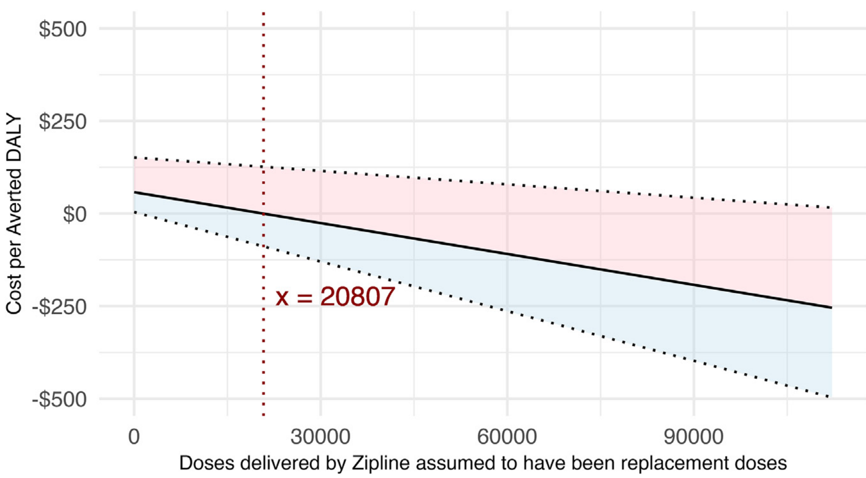


LMD indicates last mile delivery.

Second, we shed light on the influence of integrating aerial logistics with traditional LMD on the savings and overall cost-effectiveness of the intervention. Our primary calculations used a conservative scenario where all doses delivered via aerial logistics were considered incremental. Although the notion of zero replacement doses is improbable, the unique circumstances of 2021 render a scenario with relatively fewer replacement doses plausible. The disruptions induced by the COVID-19 pandemic within the healthcare supply chain, coupled with interruptions to routine vaccination protocols, suggest that a substantial number of vaccines would not have reached their intended remote facilities without aerial logistics. When we examined the effect of including replacement doses, we found that the incremental costs of the intervention decreased through 2 mechanisms: aerial logistics LMD was not strictly additional to baseline LMD, and the cost per dose for aerial logistics was lower than the estimated benchmark for traditional LMD. Consequently, as aerial logistics expand and become the primary means of distribution for more health facilities, the cost-effectiveness of replacing traditional supply chains with aerial logistics is likely greater than our early estimates suggest.

Our research also adds valuable insights to the existing literature on strategies to enhance vaccination uptake. Building upon a systematic review on this topic,[3] our findings establish for the first time the cost-effectiveness of aerial logistics in increasing immunization coverage. At a cost of $0.66 per incremental FIC, this approach outperforms other delivery methods analyzed in the review, including the most cost-effective category of interventions identified, namely “Delivery Approach” interventions, such as monthly immunization by mobile teams in villages and the enhancement of satellite clinic immunization practices.[14,15]

Figure 4. ICERs for different LMD replacement scenarios (government perspective). Pink and blue areas reflect the CI around the central estimated value for the total cost for traditional LMD. The vertical line corresponds to the minimum number of replacement doses required for aerial logistics to become a cost-saving intervention.



ICER indicates incremental cost-effectiveness ratio; LMD, last mile delivery.

A key strength of this research is that it marks a pioneering effort in conducting a cost-effectiveness analysis of centralized storage and drone delivery of vaccines based on empirical data, distinguishing it from previous studies that relied on a combination of hypothetical inputs.[4,5] These studies did not incorporate real-world data elements such as operational costs, health facility usage patterns, and the direct impact on population health. Our research fills this gap by presenting data-driven insights into the practical application and cost-effectiveness of drone-based logistics in vaccine distribution, thereby offering a more grounded and comprehensive understanding of its potential as a public health intervention.

The methodology used in this study is distinguished by its context-specific approach, using a model that estimates the averted burden of disease based on actual vaccine coverage at the district level. This approach ensures a more accurate and localized understanding of the public health impact. In addition, the study's focus on the immediate effects of the intervention within the same year eliminates the need for speculative assumptions about future vaccination scenarios. This is particularly valuable in contexts where data scarcity challenges long-term forecasting.

The study acknowledges several limitations, including the need for an enhanced understanding of how aerial logistics integrate with traditional LMD. A related challenge is the difficulty in achieving transparency of the cost per dose for traditional LMD compared with newer LMD methods. Although previous research has improved our understanding of immunization logistics costs in Ghana,[11,16] the specific expenses associated with traditional LMD remain largely unavailable. This data gap, common across many LMICs, stems from the considerable variability in traditional LMD systems, which depends on factors such as geography, accessibility, and cold chain capabilities of health facilities.[17,18] The findings of our primary scenario, which assumes no replacement of traditional LMD, allow the cost-effectiveness of aerial logistics to be assessed independently of these uncertainties. However, the lack of clarity in LMD cost specifics can impede the ability of governments to make fully informed decisions when considering various delivery technologies. This highlights the importance of further research to bridge these knowledge gaps, enabling more effective decision making in public health logistics.

Another area where data were insufficient concerns the impact of vaccine wastage in both traditional and aerial logistics LMDs. Previous research highlights wastage as a key weakness in traditional LMD of vaccines in Ghana.[19] Emerging evidence suggests that aerial logistics may reduce wastage of blood and other medical supplies,[20,21] but focused research on its effect on vaccine wastage is lacking. A deeper understanding of wastage rates in the context of aerial logistics could illuminate additional dimensions of its cost-effectiveness.

For policy makers, our study's results suggest that at-scale aerial logistics could be a highly cost-effective strategy for enhancing early childhood immunization coverage. Although it is important to exercise caution in broadly applying these findings to other contexts, it is worth noting that the effectiveness of this intervention was demonstrated during a period marked by significant disruptions in the health supply chain due to the COVID-19 pandemic.[22,23] This context underscores the additional value of aerial logistics not only in improving immunization rates cost-effectively but also in bolstering the resilience of the supply chain in challenging situations.

As the body of empirical data on at-scale aerial logistics for public health interventions expands, the methodology used in our study offers a framework for adaptation in diverse contexts. This capability to tailor the approach to different environments is crucial for a more comprehensive understanding of the variables that contribute to the success of such interventions. This ongoing research will enable the development of more cost-effective approaches to increase immunization coverage and fortify healthcare systems.

Conclusions

This article presents evidence on the cost-effectiveness of using aerial logistics for LMD of vaccines as a public health intervention to improve immunization coverage. Our analysis confirms that at-scale aerial logistics for vaccine delivery is highly cost-effective, providing significant health benefits at a cost substantially lower than the WTP threshold from both governmental and societal perspectives. Even with a conservative approach that considers only the financial benefits within the intervention year, the cost-effectiveness of this method is evident, remaining robust after a probabilistic sensitivity analysis and considering a scenario that includes the initial ramp-up costs.

Moreover, the integration of aerial logistics with traditional LMD influences both savings and overall cost-effectiveness. In our extremely conservative scenario where all doses delivered by aerial logistics were considered incremental, the intervention's cost-effectiveness was still apparent. As aerial logistics expand and replace traditional supply chains in more health facilities, the cost-effectiveness of this approach is likely to exceed our early estimates.

A back-of-the-envelope calculation indicates that in 2021, had aerial logistics been extended to encompass all Ghanaian children under 2 living in rural areas, this intervention could have potentially prevented 27 716 cases of vaccine-preventable diseases and saved 198 lives in this specific age group within that year alone.

In conclusion, at-scale aerial logistics represents a promising and cost-effective strategy for enhancing early childhood immunization coverage, particularly in regions facing logistical challenges. The findings underscore the potential for broader applications of this technology in public health logistics, contributing to more resilient and efficient healthcare delivery systems.

Author Disclosures

Author disclosure forms can be accessed below in the Supplemental Material section.

Supplemental Material

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.vhri.2024.101066.

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