

Uncrewed aircraft systems versus motorcycles to deliver laboratory samples in west Africa: a comparative economic study



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Summary

Background Transportation of laboratory samples in low-income and middle-income countries is often constrained by poor road conditions, difficult geographical terrain, and insecurity. These constraints can lead to long turnaround times for laboratory diagnostic tests and hamper epidemic control or patient treatment efforts. Although uncrewed aircraft systems (UAS)—ie, drones—can mitigate some of these transportation constraints, their cost-effectiveness compared with land-based transportation systems is unclear.

Methods We did a comparative economic study of the costs and cost-effectiveness of UAS versus motorcycles in Liberia (west Africa) for transportation of laboratory samples under simulated routine conditions and public health emergency conditions (based on the 2013–16 west African Ebola virus disease epidemic). We modelled three UAS with operational ranges of 30 km, 65 km, and 100 km (UAS30, UAS65, and UAS100) and lifespans of 1000 to 10 000 h, and compared the costs and number of samples transported with an established motorcycle transportation programme (most commonly used by the Liberian Ministry of Health and the charity Riders for Health). Data for UAS were obtained from Skyfire (a UAS consultancy), Vayu (a UAS manufacturer), and Sandia National Laboratories (a private company with UAS research experience). Motorcycle operational data were obtained from Riders for Health. In our model, we included costs for personnel, equipment, maintenance, and training, and did univariate and probabilistic sensitivity analyses for UAS lifespans, range, and accident or failures.

Findings Under the routine scenario, the per sample transport costs were US\$0·65 (95% CI 0·01–2·85) and \$0·82 (0·56–5·05) for motorcycles and UAS65, respectively. Per-sample transport costs under the emergency scenario were \$24·06 (95% CI 21·14–28·20) for motorcycles, \$27·42 (95% CI 19·25–136·75) for an unadjusted UAS model with insufficient geographical coverage, and \$34·09 (95% CI 26·70–127·40) for an adjusted UAS model with complementary motorcycles. Motorcycles were more cost-effective than short-range UAS (ie, UAS30). However, with increasing range and operational lifespans, UAS became increasingly more cost-effective.

Interpretation Given the current level of technology, purchase prices, equipment lifespans, and operational flying ranges, UAS are not a viable option for routine transport of laboratory samples in west Africa. Field studies are required to generate evidence about UAS lifespan, failure rates, and performance under different weather conditions and payloads.

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Introduction

Public health laboratories in low-income and middle-income countries face operational constraints because of poor funding and infrastructure. Transferring patient samples from clinics to reference laboratories often requires costly, unreliable transportation methods across difficult terrain with poor road conditions, traffic congestion, and the requirement for cold-chain methods. These limitations become serious during disease outbreaks when rapid diagnoses are required for timely implementation of effective epidemic control strategies.¹

Uncrewed aircraft systems (UAS)—ie, drones—can mitigate some of these limitations. UAS comprise aircraft and operating equipment that include ground-control consoles and communication systems, with

or without launching apparatus. UAS are classified on the basis of criteria such as flight range, power source, size, operating altitude, and flight mechanism.² In this study, we used the flight mechanism classifications of fixed-wing, rotor-wing, and hybrid (both fixed-wing and rotor-wing mechanisms).³ Fixed-wing UAS have longer operational ranges, large payloads, and better weather tolerance. They are more expensive than rotor-wing systems, usually require dedicated launching and landing apparatus (ie, catapults or runways), and do not have the capability to transport goods on a return trip.³ By contrast, rotor-wing UAS have vertical takeoff and landing capabilities, limited flight range, smaller payloads, and poor weather tolerance, but they are substantially cheaper. Hybrid systems incorporate both

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Research in context

Evidence before this study

We searched the databases PubMed, MEDLINE, Scopus, Google Scholar, EMBASE, CINAHL, Econlit, WHO, and PATH (formerly Program for Appropriate Technology in Health) for studies published between Jan 1, 1990, and June 30, 2019. The search terms included combinations of “drones”, “unmanned aerial vehicles”, “unmanned aerial systems”, “unmanned aircraft”, “economics”, “costs”, “effects”, “benefits”, “utilities”, “motorcycles”, “laboratory”, “specimens”, and “samples”. We mined the references from articles identified during the primary search for related and pertinent articles, dissertations, and programme reports. This study was partly informed by US Centers for Disease Control and Prevention experiences during the west Africa Ebola virus disease epidemic. We therefore included actual programme data from the charity Riders for Health, who transported blood samples during the Ebola virus disease epidemic for the motorcycle comparator. We held a series of telephone and Skype calls with various uncrewed aircraft system (UAS) manufacturers about the limitations of current studies and pointers to other relevant literature including field trial reports. Through this consultative

process, we also obtained access to unpublished and confidential industry operational documents.

Added value of this study

This is the first comprehensive analysis on use of UAS that examined the effect of major factors such as purchase price, operational lifespans, and flight ranges on costs. Previous studies have omitted these factors. Through the use of detailed maps, we also showed the strengths and limitations of different types of UAS, and challenged some of the commonly held assumptions regarding their operations. We also developed a user-friendly Microsoft Excel-based program that can be used by anyone to undertake a UAS-related cost evaluation.

Implications of all the available evidence

Our study showed that additional field performance data are required before UAS can be scaled-up for routine public health use. Future studies should address the major cost drivers of UAS including effective operation ranges, failure rates under various operational conditions, maintenance, weather performance, and actual field implementation.

rotor-wing and fixed-wing components and maximise the advantages of both systems.

Since 2010, use of civilian UAS for public health has increased.⁴ UAS have been used for aerial surveillance of mosquito vector breeding sites,⁵ and for real-time monitoring during major disasters.^{6,7} Pilot tests in Rwanda and Lesotho suggested that substantial savings in time and costs were achieved by the use of UAS for blood-transfusion services.⁸ Samples delivered by UAS have been shown to be of similar quality to samples delivered by road.⁹ Simulation studies suggest that UAS can solve some problems in the vaccine-supply chain by reducing point-of-care inventory holding costs and stock-outs.¹⁰ These studies^{9,10} also showed that UAS are cost-effective compared with traditional land-based transport systems, and recommended their use in health programmes.

However, these studies did not indicate the procurement costs of the systems used or the amortisation factor (ie, operational UAS lifespan in terms of flight hours) used in the cost analyses. Furthermore, they did not account for costs related to UAS training and certification, insurance, personnel, management, preventive maintenance, and accidents or failures.¹¹ The studies also did not investigate UAS operability in inclement weather, extreme temperatures, and arid conditions that might cause dust interference. On the basis of these studies, it remains unclear whether UAS are useful substitutes or complements to traditional land-based transport services.

One costing study has compared the use of UAS with motorcycles for transportation of laboratory specimens

within a 25 km radius of Lilongwe, Malawi, using a single-stop hub-and-spoke strategy.¹² The investigators showed that UAS were less cost-effective than motorcycles in most modelling scenarios. This study, like others referenced here, did not include procurement costs, weather operability, operational lifespan, or maintenance costs in the analysis.¹² Here we present a simulation model for west Africa to identify cost drivers that should be included in future comparative cost analyses for emergency and routine use of UAS for transportation of laboratory specimens. We estimated per-sample costs for each scenario and estimated average cost-effectiveness ratios. The aim of this study was to use these analyses to contribute to the knowledge base and inform the ongoing debate about the use of UAS in public health programmes in developing countries.

Methods

Study design

We did a comparative economic study of the costs and cost-effectiveness of UAS versus motorcycles in Liberia (west Africa) for transportation of laboratory samples under simulated routine conditions and a public health emergency condition (based on the 2013–16 west African Ebola virus disease epidemic). Our unit of effectiveness was the number of specimens transported under both scenarios.

Our baseline model assumed kerosene-powered hybrid UAS that have an operational range of 65 km (UAS65), an optimal flight speed of 65 km/h, and a lifespan of 3000 flight hours. We did sensitivity analyses with 30 km (UAS30) and 100 km (UAS100) operational radii, and

lifespans of 1000 to 10 000 flight hours. The motorcycle transport system assumptions were based on the Yamaha AG-200—a two-stroke engine motorcycle most commonly used by the Liberian Ministry of Health and the international charity, Riders for Health.

The analysis was done from a health system perspective and included costs for procurement, personnel, training, maintenance, and replacement. We included direct costs of treatment for motorcycle-related injuries but omitted costs for community sensitisation and post-crash recovery operations of UAS. We used 2014 as our base year and used a discount rate of 3%¹³ for the analyses over a 3-year horizon. Liberia is a US dollarised economy, therefore all local costs were collected in US\$.¹⁴ Table 1 lists the main assumptions used in this paper.

Data sources

We obtained motorcycle operational data from Riders for Health, a non-profit charity that was contracted to transport samples in Liberia during the Ebola virus

disease epidemic. The Riders for Health motorcycles are fitted with global positioning system (GPS) devices linked to a specialised fleet management application called Fulcrum that captures detailed operational data including distances travelled, fuel consumption, accident rates, breakdowns, and maintenance.

We obtained UAS data inputs from three qualified expert sources: Skyfire (Atlanta, GA, USA), a UAS consultancy specialising in emergency response; Vayu (Ann Arbor, MI, USA), a UAS manufacturer that has done studies across Africa; and Sandia National Laboratories (Albuquerque, NM, USA), a federally-funded private enterprise with civilian and military UAS research experience. Each of these has generated data that cover operational performance, training needs, and putative prices.

Geography

Liberia is an equatorial country in west Africa covering 111 369 km² with a population of 4·7 million. A quarter of

	Values	Distribution	Estimated parameters	Source
Motorcycle				
Price	US\$5000	Point estimate		Riders for Health
Maximum range	300 km	Point estimate	..	Yamaha manufacturer manual
Daily distance covered	150 km	Beta PERT	Min: 75, max: 200	Riders for Health
Fuel tank capacity	11 L	Point estimate	..	Yamaha manufacturer manual
Effective fuel consumption	22·1 km/L	Gamma	$\alpha=0\cdot381$, $\beta=9\cdot38$	Riders for Health
Effective operating speed	40 km/h	Beta PERT	Min: 28 km/h, max: 70 km/h	Google: Riders for Health
Terrain impassability	33%	Gamma	..	Riders for Health
Average replacement km	55 000	Beta PERT	Min: 30 000, max: 70 000	Riders for Health
Breakdowns	0·6:10 000 km	Point estimate	..	Riders for Health
Motorbike lifespan	1·2 years	Beta PERT	Min: 0·8 years, max: 2·0 years	Riders for Health
Minor accident rate	1·65: 100 000 km	Point estimate	..	Riders for Health
Major accident rate	0·43: 100 000 km	Point estimate	..	Riders for Health
Mortality rate	0%	Point estimate	..	Riders for Health
Motorbike breakdown rate	20%	Point estimate	..	Riders for Health
Maximum payload	60 kg	Point estimate	..	Yamaha manufacturer manual
Total distance (70 bikes)	1 881 408 km	Point estimate	1 302 292 km	Riders for Health
UAS (hybrid)				
Effective operating radius	65 km	Beta PERT	$\alpha=30$ km, $\beta=100$ km	Sandia National Laboratories, Skyfire
Maximum payload	20 kg	Point estimate	..	Sandia National Laboratories, Skyfire
Effective operating speed	65 km/h	Point estimate	..	Skyfire
Lifespan	3000 hours	Beta PERT	$\alpha=1000$ h, $\beta=10\,000$ h	Sandia National Laboratories
Weather inoperability	10%	Point estimate	..	Liberian Hydrological Service
Flight restrictions	2%	Point estimate	..	Internal estimates
UAS loss rates	0%	Point estimate	Max: 7%	WeRobotics
UAS price	US\$15 000	Beta PERT	10 000: 120 000	Vayu
Console lifespan	5 years	Point estimate	..	Vayu
Samples				
Emergency	40 264	Beta PERT	$\alpha=10\,268$, $\beta=74\,000$	Riders for Health Internal data
Routine	1·8 million	Beta PERT	$\alpha=1\,350\,000$, $\beta=2\,250\,000$	Internal estimates
UAS=uncrewed aircraft systems.				
Table 1: Technical assumptions				

the population lives in the capital, Monrovia. Tropical and mangrove forests cover approximately 29% of the country. Liberia is subdivided into 15 counties, each with a county referral hospital and health administrative structure.¹⁵ The annual precipitation ranges from 2200 mm in the interior to 5000 mm in the capital, Monrovia. Following a protracted civil war, road conditions are poor and few are paved. Some roads, especially in the southeast and northwest of the country, become impassable during the May to October rainy season. The heavy forest cover and poor road infrastructure in Liberia are ostensibly ideal for UAS services.¹⁵

There are approximately 789 government and missionary health facilities in Liberia. These facilities have substantial resource constraints, including understaffing, with little equipment, electricity, and running water. Figure 1 shows the Liberia road network and clinic distribution. Facilities in the southeast and northwest of the country are isolated since there are few roadways, whereas facilities in the central part of the country are more accessible because of denser road networks that offer alternative land routes when some roads are impassable.

Models

We used the actual road distances covered by Riders for Health, who operated a fleet of 70 motorcycles, for our base analysis. These motorcycles collected 40 624 laboratory samples across 302 collection points over 14 months covering 1·88 million km (appendix p 1). We used the peak Ebola virus reference laboratory capacity in Liberia as the baseline and assumed that the UAS would be operated and maintained in those laboratories.¹⁶ In our public health emergency simulation scenarios, for areas with insufficient UAS geographical coverage, we added motorcycles to ensure that all patient samples were collected.

See Online for appendix

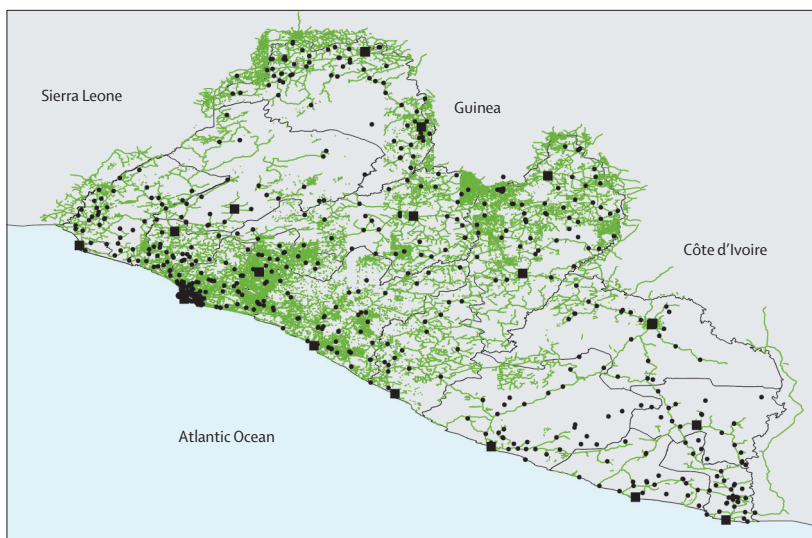


Figure 1: Road networks and distribution of clinics in Liberia

Black squares indicate the county hospitals where the reference laboratories were located. Black dots indicate clinics.

We envisaged a well defined weekly sample collection schedule under the routine transportation model and assumed that these systems were solely dedicated to laboratory sample transport. We assumed a spoke-hub transport topology where transportation services are located at county hospitals (hubs) with radiating connections (road and air) to peripheral clinics (spokes).¹⁶ Our model followed the Liberian health strategic plan assuming that each county would in future have its own well staffed, well equipped, referral laboratory service.^{17,18} We estimated round-trip Euclidean (straight-line) distances from county referral laboratories to each peripheral clinic within a county. We also estimated road distances between each clinic and the county laboratories (appendix pp 1,4). The combined average road and Euclidean distances (appendix pp 1–2) between each county laboratory and the peripheral clinics are in the appendix (pp 1–3). These distances were used to calculate the minimum number of motorcycles and UAS needed per county per year (appendix pp 4–9).

Number of UAS needed per year

The minimum number of aircraft needed per county was estimated as a function of total return distances travelled (based on the collections schedule), operational speed, daily working hours, and operational lifespan in flight hours. In the base case, we assumed minimal time for preflight checks, and route programming, and no accidents or failures, but undertook sensitivity analyses around these conditions. We assumed that both motorcycles and UAS were dedicated to laboratory transport during the public health emergency and were subsequently reallocated to other services once the emergency was contained. We amortised the procurement costs of all equipment across their useful lifespan.

Costs

Motorcycle training cost estimates were based on the Riders for Health curriculum that includes defensive riding, motorcycle self-inspection and performance checks, biosafety, specimen identification, infection prevention and control, and data entry into the Fulcrum app. UAS training costs included didactic, simulator-based, and supervised practicum. We added a one-off post-training UAS certification check to our estimates, and assumed that all trainings were done in-country to minimise international travel costs. We assumed that the logistical costs of setting up UAS training sites were trivial and omitted in-country pilot licensing costs, since these are unknown. We omitted curriculum development, post-accident training, and recertification costs. We assumed that peripheral clinic staff attended a half-day training to learn about proper procedures for loading and off-loading specimens from the UAS.

We used Riders for Health salaries and benefits for riders, project managers, mechanics, and support staff.

We prorated managerial costs for the UAS models based on the overall number of personnel needed for operations. Since UAS operator salaries are unknown, we used salaries for Liberian air traffic controllers (\$800 per month) as a proxy wage. We assumed that one loader would assist each UAS operator.

We included costs for cold-chain equipment at relay points, and for rider gear in the motorcycle system model. Since most African countries waive licensing costs for equipment and vehicles used for dedicated public health programmes, we did not include import duty and licensing costs for UAS in our model. All maintenance work for UAS and motorcycles were assumed to be performed in-house at no additional logistical personnel costs but include costs of replacement parts. We assumed that all maintenance work did not interfere with regular working hours and that there was no need for backup aircraft.

Sample estimates and analyses

We used the actual number of samples transported by Riders for Health for the public health emergency models. For the routine scenario, we projected sample transport needs as a function of outpatient and inpatient attendance. We assumed that half the samples would be from referral hospitals and would not need to be transported. We also assumed that half the remaining samples would need to be transported or roughly 1·8 million samples per year.^{17,19} We assumed there was no deterioration of samples under either transport method because UAS transfers were rapid, while cold-chain relay systems were used in the motorcycle scenario.⁹

We did univariate and probabilistic sensitivity analyses by varying the purchase price, estimated lifespan, range, and number of samples. For every reported scenario, we used 10 000 Monte Carlo simulations and presented the results in cost-effectiveness analyses planes. We entered data into Microsoft Excel (v 16.0) but did our analyses and visualisations in Stata (v 14.2).

Role of the funding source

There was no funding source for this study. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

In the public health emergency scenario, 357 (45·2%), 104 (13·2%), and 50 (6·3%) of the clinics were outside the aircraft operational collection ranges of UAS30, UAS65, and UAS100 (figure 2). The geographical coverage under routine programming was 92% (UAS65), 62% (UAS30), and 100% (UAS100) (figure 3).

The total number of vehicles needed was a function of total return distances travelled, lifespan, operational range, operating speed, base station location, transportation

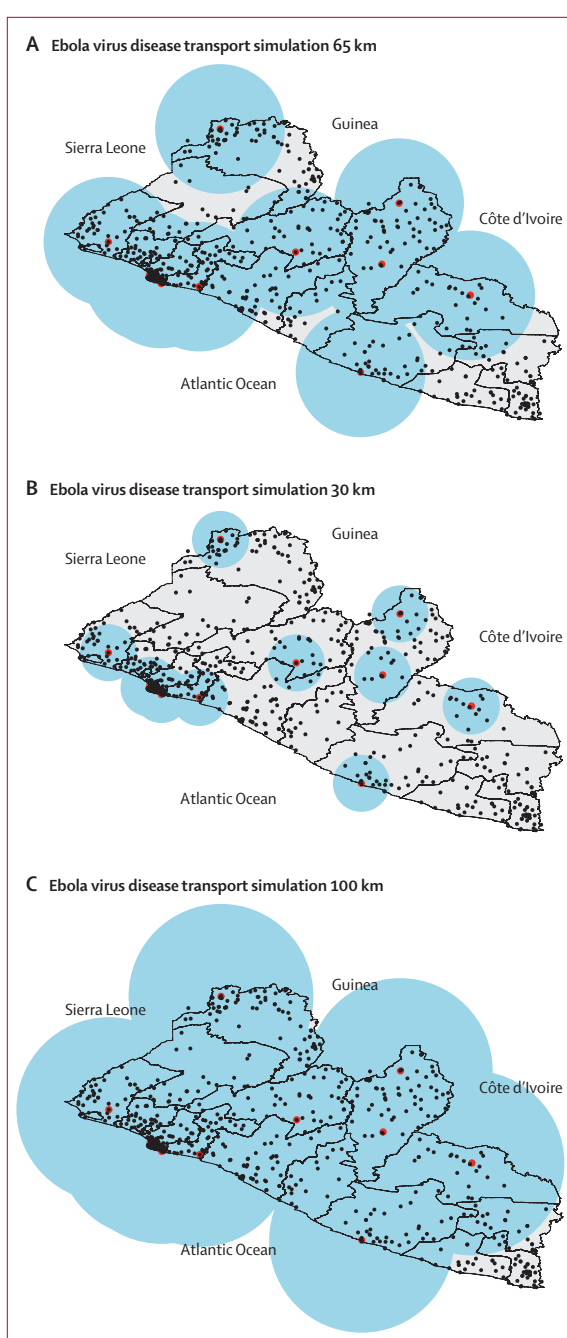


Figure 2: Emergency transport simulations

Figure shows emergency transport simulations for Ebola virus disease in the aircraft operational collection ranges of 65 km (uncrewed aircraft systems [UAS] 65), 30 km (UAS30), and 100 km (UAS100). Black dots represent peripheral clinics. Red dots indicate an Ebola virus disease laboratory site. Blue circular areas represent the operational radius using the reference laboratory as the origin.

schedule, and equipment lifespan. The total number of aircraft needed per annum is in the appendix (p 9), assuming average UAS operating speeds of 65 km/h, with 10 operating h per day. For example, under a daily operating schedule, Lofa County, which has a total

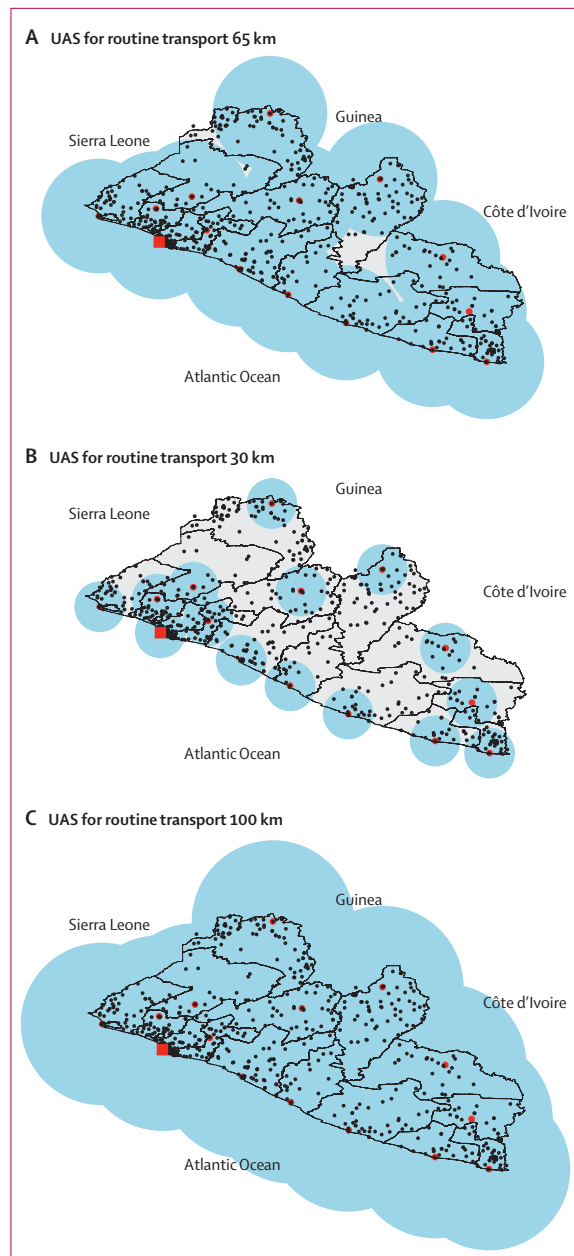


Figure 3: Routine transport
Figure shows geographical coverage under routine programming in the aircraft operational collection ranges of 65 km (uncrewed aircraft systems [UAS] 65), 30 km (UAS30), and 100 km (UAS100). Black dots represent peripheral clinics. Red dots indicate a county referral hospital. Blue circular areas represent the operational radius.

Euclidean return distance of 86500 km between the country referral hospital and all health facilities, would need a minimum of 11 aircraft under a pure UAS transport scenario. The minimum number of UAS needed increase with increasing operational radii because a greater number of facilities are covered and longer average distances travelled. The number of motorcycles needed to cover clinics outside the UAS's operating range decreased with

	Routine (\$)	PHE pure UAS (\$)	PHE UAS plus motorcycle (\$)
Motorcycle			
1.1 years lifespan	0.65 (0.01–2.85)	24.06 (21.14–28.2)	..
UAS30			
1000 flight h lifespan	1.11 (0.82–2.82)	46.32 (34.75–115.81)	47.04 (41.31–81.47)
3000 flight h lifespan	0.78 (0.65–1.51)	30.89 (26.76–55.48)	39.40 (37.35–51.58)
10 000 flight h lifespan	0.66 (0.61–1.05)	25.38 (23.95–33.95)	36.67 (35.96–40.91)
UAS65			
1000 flight h lifespan	1.37 (0.94–4.00)	46.15 (32.31–129.14)	49.20 (38.03–116.13)
3000 flight h lifespan	0.82 (0.66–1.80)	27.42 (22.66–55.96)	34.09 (30.25–57.11)
10 000 flight h lifespan	0.63 (0.56–1.03)	20.81 (19.25–37.59)	28.75 (27.50–42.29)
UAS100			
1000 flight h lifespan	1.68 (1.11–5.05)	48.05 (33.27–136.75)	51.36 (38.69–127.40)
3000 flight h lifespan	0.96 (0.75–2.18)	28.19 (23.03–59.14)	34.33 (29.91–60.87)
10 000 flight h lifespan	0.71 (0.63–1.17)	20.92 (19.29–30.73)	28.10 (26.70–36.51)

PHE=public health emergency. UAS=uncrewed aircraft systems.

Table 2: Selected per-sample costs with different transport methods

increasing UAS range (appendix p 7). The geographical coverage of UAS30 was limited to urban and periurban areas with a high concentration of clinics.

If UAS were to substitute motorcycles under a weekly collection schedule (figure 3), between 19 and 38 aircraft would be required per year based on their operational lifespans. Aircraft with 1000-h lifespans would need to be replaced every 4 months, while 3000-h aircraft would need to be replaced annually. Changing the sample collection schedule from weekly to daily will triple the number of requisite aircraft (appendix pp 5–6).

The effective flying time—ie, projected time in air plus time on ground to reprogramme the UAS for a new destination, change the battery or refuel, check flight path weather conditions, alert the receiving clinic, do pre-flight checks, and launch is also crucial.¹¹ The number of aircraft needed increased by 40% when pre-flight time checks were considered.

The average cost per sample transported under routine conditions was \$0.65 (95% CI 0.01–2.85) with the motorcycle transport system and \$0.82 (0.56–5.05) with UAS65 (table 2; figure 4). The cost-effectiveness planes in the appendix (pp 2,3) show the sensitivity analysis results of 10000 Monte Carlo simulations of different UAS scenarios compared with motorcycles. Motorcycles dominated—ie, were more cost-effective than—UAS30 (left upper quadrant) under all scenarios that we modelled. The probability of UAS being cost-effective increased

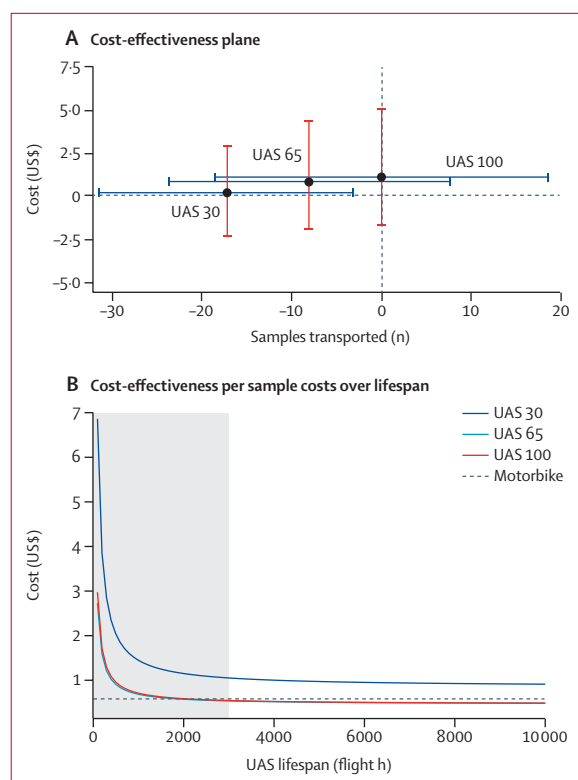


Figure 4: Cost-effectiveness plane (A) and per-sample costs over lifespan (B) under routine scenario

Values shown for the aircraft operational collection ranges of 30 km (UAS30), 65 km (UAS65), 100 km (UAS100), and for motorbikes. Scenario based on a UAS lifespan of 3000 h and cost of US\$10 000. Error bars show 95% CIs based on 10 000 simulations. Shaded area represents plausible lifespan. UAS=uncrewed aircraft systems.

with increasing UAS ranges, lifespans over 1000 h, and prices less than \$15 000 (appendix pp 16–18). The incremental cost-effectiveness ratios varied by scenario: -0.1 (-0.4 to -0.003) for UAS65, -0.03 (-0.05 to -0.01) for UAS30, and -1.67 (-77.88 to -0.01) for UAS100.

The mean per-sample cost for motorbikes in the emergency scenario was \$24.06 (95% CI 21.14–28.20; table 2, figure 5). Per-sample costs were \$27.42 (95% CI 19.25–136.75) for the unadjusted UAS scenario, and \$34.09 (26.70–127.40) when motorcycles were added to maximise geographical coverage (table 2). Using UAS65, 75% of the simulation fall in the left upper and left lower quadrants—ie, would cost more to implement than motorbikes and would transport fewer samples under most conditions (figures 3, 4; appendix pp 14–15). The UAS30 scenarios were dominated by the motorcycle transport system (figure 5). 30% of the simulated incremental cost-effectiveness ratios in the UAS100 scenario were more cost-effective than motorcycles in 30% of the simulated scenarios.

The major cost categories for both systems were capital, maintenance, and personnel. In sensitivity analyses, purchase price, lifespan, and failure rates were the main

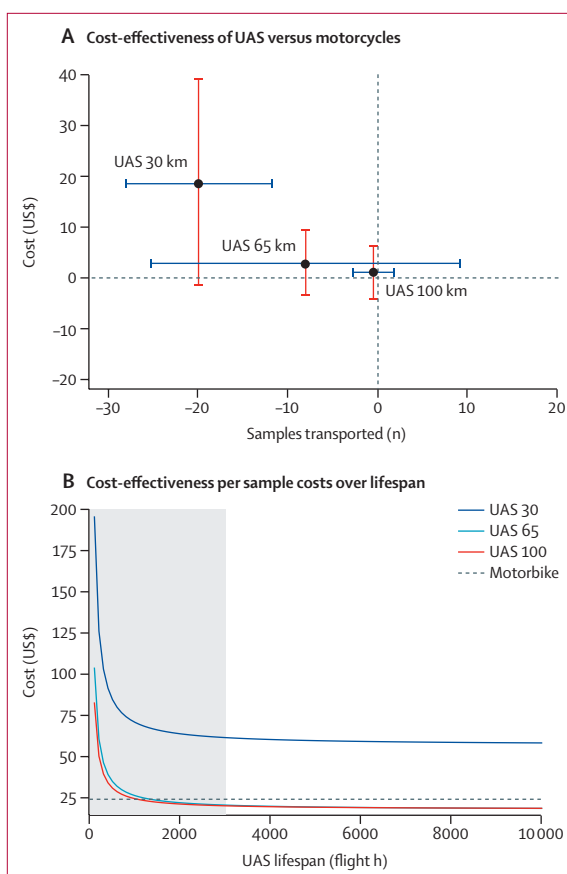


Figure 5: Cost-effectiveness plane (A) and per-sample costs over lifespan (B) under emergency scenario

Values shown for the aircraft operational collection ranges of 30 km (UAS30), 65 km (UAS65), 100 km (UAS100), and motorbikes. Scenario based on a UAS lifespan of 3000 h and cost of US\$10 000. Error bars show 95% CIs based on 10 000 simulations. Shaded area represents plausible lifespan. Additional motorbikes required in short-range UAS scenario. UAS=uncrewed aircraft systems.

determinants of UAS costs. The break-even point for UAS occurred at a purchase price of \$10 000, operational range of 65 km, and lifespan of 3000 flight hours. Systems costing over \$30 000 were not cost-effective under all scenarios. Per sample costs were most sensitive to lifespans. Assuming a 100 km operational radius, a purchase price of \$30 000, the base case assumptions, and varying the lifespan between 1000 and 3000 h, the weighted sample transport costs ranged from \$23.72 to \$187.81 (appendix p 7).

Discussion

Our simulations suggest that short-range UAS are less cost-effective than motorbikes for transportation of laboratory samples under most scenarios in Liberia; however, there is potential scope for longer-range UAS, especially if prices decrease and operational lifespans increase.

There have been suggestions for using UAS as complements, rather than substitutes, for land-based

transport systems.⁴ UAS could be deployed to cover hard-to-reach areas, while motorcycles and trucks would cover more proximal locations. This scenario would be highly dependent on the operational range of the UAS, the location of the UAS base stations, road density, and the location and number of remote clinics. Most of the hard-to-reach facilities fall outside the range of the UAS30. For scenarios where remote locations fall outside UAS ranges, additional means of transportation (air, water, and land) will be required, increasing operational costs. Programmatic tradeoffs would need to be made to defray costs associated with underuse of UAS personnel and equipment under these mixed transport systems if the UAS cannot be reallocated to other duties.

The operational lifespan and accident rates of most civilian UAS aircraft are unknown. There is also the risk of interference, including theft. In field trials, WeRobotics, a non-governmental organisation, had a failure rate of 7% in 44 flights, including the permanent loss of an aircraft over the Peruvian Amazon.¹¹ Additional research is required to address concerns about useful operational lifespans, failure rates, weather operability, multistop functionalities, and operational aircraft mix. Such studies can also provide evidence for lifting of line-of-sight UAS piloting restrictions that are in place in some countries. We suggest that laboratory specimen transport systems, land-based or air-based, should have robust sample recovery protocols to mitigate losses. This is vital if biohazardous materials are to be transported.

The issues raised in this study suggest that cost-effectiveness of UAS depend on a country's geographical and health-system design context. For example, South Pacific islands with high road densities might still need UAS to serve isolated islands, even if the intra-island road networks are reliable. The operational assumptions we made for laboratory sample transport might be inappropriate for UAS use in transport of time-sensitive medical supplies or for disease surveillance.

Our analyses had several limitations. We did not account for cost savings that could accrue from bulk purchasing or equipment rentals. We assumed single-programme use under both systems and did not consider potential concurrent uses. We also used a single-stop spoke-hub model, whereas most programmes dynamically optimise their transport models by using variations of multistop strategies. We did not consider downstream benefits of UAS including faster diagnostic turnaround times during public health emergencies. It is unclear whether temporal savings in the magnitude of minutes to several hours will be relevant in bending the epidemic curve conditional on laboratory capacity.²⁰ Temporal benefits also have to be viewed in the context of fundamental public health protocols such as early case definitions and rapid institution of isolation measures, which might translate to more lives saved. These

comparative speed advantage arguments also extend to transportation of long-tail, time-sensitive supplies such as snake antivenom, where health systems face realities such as an absence of technical expertise and infrastructural capacities for administering potentially risky treatments in remote clinics.

To make our models tractable, we assumed existence of well-established UAS infrastructure within a country at the start of a public health emergency. This helped us abstract from the uncertainties around the duration of the public health emergency, the inherent logistical challenges around procurement and deployment of the transport systems and learning curve effects. In reality, the procurement and deployment realities and uncertainties about the nature of the public health emergency effectively preclude last-minute emergency buys.

Programmes considering the use of UAS could adopt the aviation industry practice of having a mix of short-haul, medium-haul, and long-haul aircrafts to serve different geographical areas and needs. This will reduce costs since longer-range UAS are more expensive than short-range ones. We anticipate that greater UAS technological diffusion will result in lower prices and better performances, making them more attractive for both emergency and routine use.

Contributors

WOO, TY, CS, VK, and KK conceived the project and worked out the technical details for the analysis. SLY and WOO collected the data. WOO did the simulations and designed the figures. WOO wrote the manuscript with input from all the authors. All authors reviewed the results and made corrections on multiple iterations of the manuscript.

Declaration of interests

We declare no competing interests.

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