Costs Associated with the Use of Unmanned Aerial Vehicles for Transportation of Laboratory Samples in Malawi

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VillageReach is a global health innovator that develops, tests, implements and scales new solutions to critical health system challenges in low-resource environments, with an emphasis on strengthening the "last mile" of healthcare delivery.

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Acronyms

UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aircraft System
VL	Viral Load
EID	Early Infant Diagnosis
SDP	Service Delivery Point
KCH	Kamuzu Central Hospital
HIV	Human Immunodeficiency Virus
AIDS	Acquired Immunodeficiency Syndrome
DBS	Dried Blood Spot sample
ART	Anti-Retroviral Treatment
PCR	Polymerase Chain Reaction

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Executive Summary

In Malawi, there are currently major barriers to the efficient and timely transportation of laboratory samples and results between health facilities and laboratories. Unmanned Aerial Vehicles (UAVs) offer an alternative method of transportation because they are often battery powered, do not require a driver, and are not affected by the quality of the roads. The purpose of this analysis is to provide insights into the costs associated with an Unmanned Aircraft System (UAS) for moving laboratory samples and results between health facilities and laboratories in Malawi. In order to contextualize the results, the UAS costs were compared to the standard method of transporting samples via motorcycle.

Data was collected through four methods: a document review, structured surveys, key informant interviews, and a market survey. Then, costs were analyzed for four scenarios. In each scenario, motorcycle costs were analyzed to provide a baseline. ***Scenario 1*** examined costs for transport of Early Infant Diagnosis (EID) dried blood spot (DBS) samples using loops, in which a vehicle visits multiple service delivery points (SDPs) before returning to the laboratory. ***Scenario 2*** modeled costs for the same transportation loops, but for both Viral Load (VL) and EID DBS. ***Scenario 3*** looked at costs for EID transport for only the SDPs within the 25 kilometers UAV flight range of the laboratory. Vehicles (motorcycles or UAVs) used hub and spoke routes to travel from the laboratory to each SDP to pick up samples, and then immediately returned to the laboratory to drop off the samples. Finally, ***Scenario 4*** estimated costs for transportation of DBS for VL testing in addition to EID samples using the same hub and spoke routes.

In all four scenarios, costs per kilometer were higher for the UAS than for the motorcycle system. Total monthly transportation costs in Scenarios 1, 2 and 4 were also higher for the UAS than for the motorcycle system. However, in Scenario 3, when both modes of transportation only carried EIDs, the ***total*** costs for UAS were 15% less than those for the motorcycle system. This is because UAVs could take the shortest possible path between two points and arrive more quickly than motorcycles, reducing vehicle- and personnel-related costs. These time- and distance-savings were great enough to balance out the higher per kilometer costs in this scenario, but were not great enough to outweigh costs in Scenarios 1, 2 and 4. Future studies should examine how transportation systems could include both motorcycles and UAVs to best take advantage of the benefits of each transportation mode.

In both motorcycle systems and UAS, the costs of the vehicles themselves were important cost drivers. However, the vehicle costs in the motorcycle system were higher because the useful lifetime of motorcycles was lower than that of UAVs. Additionally, in the motorcycle systems, fuel costs were significant, representing about 20% of total costs, while they were only 0.05% of the total costs of the UAS. On the other hand, the costs of batteries, chargers, and landing devices were important costs in the UAS, but were not relevant to the motorcycle system.

It is important to note that UAV technology is very immature, and it is expected that the costs of the vehicles and equipment will decrease significantly in the future. Additionally, this analysis only estimated costs of each scenario; it did not attempt to quantify the impact of improvements in transportation speed on the efficacy of the logistics system overall. In any supply chain, the transportation mode is not chosen simply based on cost; rather, the supply chain managers should look at cost-effectiveness and select the mode that achieves the required level of service at the lowest cost.

As a next step, a much deeper analysis on the benefits that a UAS could provide in Malawi should be conducted. Optimal use cases should be developed to demonstrate the specific logistical challenges and problems in the current system to which a UAS could effectively respond. Ultimately, the goal of the supply chain for DBS is to get HIV+ patients on appropriate treatment plans more quickly. Where current technologies and systems fail to achieve this, we must consider new and innovative systems that can increase access to high-quality health services and life-saving treatments.

Introduction

A functional laboratory system for diagnostic testing is critical for the effective and timely treatment of diseases. This is true for both HIV and tuberculosis, where the quick results of tests are essential for initiating and adjusting treatment. Currently, in Malawi, rapid point of care diagnostic tests for HIV-exposed infants are currently available in only seven health facilities as part of a national pilot. EID and VL testing are done in reference laboratories using DBS. In order to improve pediatric uptake of antiretroviral therapy (ART) and to effectively monitor VL of patients on ART, laboratory samples must be delivered from the health center to the laboratory and the results must be returned as quickly as possible. Similarly, tuberculosis testing of sputum samples should be done immediately in laboratories that offer culture or polymerase chain reaction (PCR)-based diagnosis.

In Malawi, although 650 sites provide HIV services to HIV exposed children, only nine laboratories have the capacity to run PCR assays. Median turn-around time for EID is 29 days, with 75% of results returned between 22 and 41 days after sample collection. For VL tests, median turn-around time is 37 days, ranging from 12 days to 54 days.[1] Therefore, there is a need to enhance the current laboratory service delivery system.

There are barriers in the laboratory logistics systems related to transportation, including poor infrastructure and sometimes inaccessible roads during the rainy season, sites not reachable by land transportation (islands), cost and price variability of fuel ($1.00-1.50 per liter, with significant fluctuation), and delays in transferring samples from SDPs to the district and onwards to one of the nine laboratories capable of conducting PCR assays. These delays in transporting patient samples and returning the test results can lead to morbidity and even death of patients that could have been treated.

UAVs offer an alternative method of transportation with potential to address these issues because they are battery powered, do not require a driver, and are not affected by the quality of the roads. To further explore the feasibility of using this technology in Malawi, Unicef worked with the Government of Malawi, Matternet, a UAV supplier based in the United States, and VillageReach, a local public health non-profit, to import prototypes into Malawi and conduct test flights in March 2016.

In conjunction with these field tests, VillageReach was also commissioned to estimate and analyze the costs associated with an Unmanned Aircraft System (UAS). A UAS consists of one or more UAVs, the associated equipment (launch/landing stations, batteries and charging equipment, etc.) as well as software and personnel needed to control the UAV. This report details the methods used in this analysis, as well as results and insights related to the costs for moving laboratory samples and results between SDPs and laboratories in Malawi using a UAS. In order to contextualize the results, the UAS costs were compared to a standard method of transporting samples via motorcycles currently used in the country.

Outputs of this cost analysis included:

- Monthly estimated costs for sample transport by type;
- Cost per health center by type of transport; and
- Cost per sample transported by type of transport.

These results are intended to provide a framework for understanding the costs of the UAS in comparison to a current transportation system. While this analysis provides important insights into the costs of a UAS for DBS transport, it should not be seen as an accurate estimate of the definitive transportation costs if a UAS were to be implemented at scale in Malawi. Because the UAS technology is still relatively early in

[1] Malawi Ministry of Health (2015). *Integrated HIV Program Report, October-December 2015*.

development, costs represent current best estimates, and will likely change significantly as the technologies and systems are refined for production and deployment at scale.

Additionally, this analysis only estimated costs of each scenario; it did not attempt to quantify the impact of improvements in transportation speed on the efficacy of the logistics system overall. It also did not examine scenarios for system optimization, which should be examined closely to define use cases and implementation plans in the future. In any supply chain, the transportation mode is not chosen simply based on cost; rather, the supply chain managers should look at cost-effectiveness and select the mode that achieves the required level of service at the lowest cost. These results can be used to inform the design of future studies to determine if this technology can improve indicators of health system performance, and if a sound case can be made for integrating UAVs into the laboratory sample supply chain.

Methods

Cost analysis approach and modelling tool

The geographic scope of this cost analysis was limited to Lilongwe district, and more specifically, to the sub-set of SDPs that send DBS to KCH via motorcycle transport (referred to as the KCH network). The list of facilities included in this network is available in ***Appendix A.*** Transportation costs for both UAS and motorcycles systems are likely to vary across Malawi based on geography, transportation services available, laboratory and SDP infrastructure, and volume of DBS collected. Although the results of this cost analysis are not necessarily representative of nation-wide costs for sample transport, they provide initial estimates to inform next steps in exploring and better defining the potential role of a UAS in the Malawian laboratory logistics system.

Costs[2] associated with DBS transportation were estimated using a Microsoft Excel-based cost modeling tool developed by VillageReach.[3] Additional details on the cost modelling tool are available in ***Appendix B***. Our distribution costing model costs the supply chain from SDPs to the laboratory to collect samples, and from the laboratory back to the SDPs to return results. Our approach takes into account collection system settings and incorporates inputs related to vehicle costs and the cost of time of personnel involved in sample and results transportation activities, as detailed in Table 1 below. More details and assumptions related to the inputs collected for each type of transport are available in ***Appendix C***.

Table 1. Cost analysis inputs

Node information
Number and location of all nodes (laboratory and SDPs)
Routes and schedule for transportation of samples/results to/from each node
Kilometers traveled per month based on transportation routes
Volume of DBS for EID and VL testing for each SDP per month, as a percentage of total payload volume[4]
Vehicle costs and characteristics
Vehicle range[5]

[2] All inputs were in USD. Data collected in MWK were converted to USD based on the OANDA exchange rate of 688 MWK/USD.
[3] For more details on the cost modelling tool used in this analysis, see *MIT-Zaragoza, Transaid, and VillageReach (2011). "Framework on Distribution Outsourcing in Government-run Distribution Systems."* and *VillageReach (2009). "Comparison of Costs Incurred in Dedicated and Diffused Vaccine Logistics Systems."*
[4] Monthly payload volume for EID and VL samples and results for each SDP were estimated using UNICEF's forecasts for 2015.
[5] Flight distance before the battery must be changed, only applicable to UAVs.

	Payload capacity for DBS
	Number of vehicles needed to cover routes
	Vehicle base costs
	Other equipment costs
	Expected useful lifetime
	Vehicle insurance costs per kilometer
	Fuel costs[6] per kilometer
	Routine maintenance costs per kilometer, including parts and labor
	Battery, charger, and landing device costs (UAV only)
	Data/airtime costs (UAV only)
Personnel costs	
	Number of personnel dedicated to transportation
	Salaries for personnel involved in transport of DBS
	Per diem for personnel involved in transport of DBS
	Initial training costs

Only costs directly related to the lab sample transport system being evaluated are included. For example, if a motorcycle driver spends two days in a month picking up samples and returning results, only that percent (two days out of a total 22 working days in a month) of his or her salary is included in final costs. If only 70% of a driver's payload is DBS, then only 70% of his or her salary was included in the cost estimate.

The same principle is applied to estimate per-kilometer costs for sample transport. Costs, including salaries, vehicle, and fuel costs, are allocated to each route. For each SDP, the route associated with that SDP includes the kilometers from the previous stop on the route to the SDP in question. If 70% of a driver's payload is DBS, 70% of the per-kilometer costs associated with that route are included in the estimate.

Finally, we assume that for every DBS sent to the laboratory, a corresponding result was returned to the SDP on the next trip to the SDP for sample collection. No additional trips were made to return results. Thus, the costs for delivery of DBS to the laboratory and return of results to the SDPs were identical. For the sake of simplicity, we refer to costs associated with DBS throughout this report, with the understanding that these costs are relevant for understanding results transportation as well.

Data Collection

Data was collected through four methods: a document review, structured surveys, key informant interviews, and a market survey.

Document Review

A document review was conducted to collect qualitative information about requirements and possible use cases for DBS sample logistics and understand the current laboratory logistics system in Malawi. Broadly, three categories of documents were reviewed:[7]

1. Peer-reviewed literature, grey literature, and news articles to understand the role of EID in detection and treatment of HIV in infants, the challenges in transporting samples and results specific to Malawi, and current strategies in addressing these challenges in Malawi;

[6] For motorcycles, the fuel input is liters of petrol per kilometer. For UAVs, "fuel" is considered the electricity to charge the battery, in kilowatt-hours per kilometer.

[7] A complete list of documents reviewed is found in the "Works Consulted" section of this report.

2. Programmatic planning documents and reports that contained budgetary data used to inform the inputs for the cost analysis; and
3. Reports, editorials, and news articles detailing potential use cases for Unmanned Aircraft Systems for payload delivery in the health sector.[8]

Structured Surveys

To collect quantitative data and define the inputs for the cost analysis, structured surveys were conducted with key informants at Matternet, the UAS supplier, and local motorcycle transportation providers[9] currently managing motorcycle transportation of samples. After an initial kick-off call or in-person meeting to explain the objectives of this activity, informants were provided with a written survey via email. Subsequently, VillageReach staff followed up with informants either in-person and by phone to clarify any questions about the survey. Then, informants provided written responses to survey questions. VillageReach staff reviewed the completed surveys and contacted informants either by email, by phone, or in-person to clarify any responses as needed. This was an iterative process, with a series of conversations taking place both before and after the written surveys were returned by the informants. The written survey tools are available in ***Appendix D.***

Key Informant Interviews

In addition to the interviews conducted in conjunction with the structured surveys, we also conducted informal, unstructured interviews with key informants to gain additional insights into the transportation networks. These included interviews with staff at KCH and Bwaila District Hospital, Unicef and CDC representatives in Malawi, and the Malawi Ministry of Health Diagnostics Department.

During these interviews, we also discussed, defined, and validated the assumptions made about the laboratory sample transportation system in Malawi in order to model relevant scenarios and estimate costs of transportation.

Market Survey

We also gathered data to fill in remaining gaps in inputs needed for the cost analysis by collecting information about the typical costs of goods and services in Lilongwe. Specifically, we interviewed motorcycle mechanics about routine maintenance costs. We also interviewed VillageReach and other NGO staff in Malawi to understand typical costs of common motorcycle models, typical salaries for motorcycle drivers, the cost of petrol, the cost of data for an internet connection on a smartphone, and the cost of electricity from ESCOM, the electricity supplier. This survey was informal and the cost data collected was specific to that point in time.

Scenarios

Costs were analyzed for four scenarios. In each scenario, motorcycle costs were analyzed to provide a baseline. ***Scenario 1*** examined costs for transport of EID samples and return results using loops, in which a vehicle visits multiple SDPs before returning to a central location. ***Scenario 2*** modeled costs for the same transportation loops, but for both VL and EID DBS. ***Scenario 3*** looked at costs for EID samples and results transport for only the SDPs within the 25 kilometers UAV flight range of KCH. Vehicles (motorcycles or UAVs) used hub and spoke routes to travel from the laboratory to each SDP to pick up samples and return results of previously samples, and then immediately return to the laboratory to drop off the samples.

[8] Many of these sources are publically available, but some are either still to be published, or are internal reports protected by non-disclosure agreements.

[9] Due to the unavailability of exact cost data for the motorcycle transportation provider at the time of this analysis, the motorcycle transportation costs are estimates for a generic motorcycle transportation system that uses routes, schedules, and equipment similar to those used in Lilongwe district.

Finally, ***Scenario 4*** estimated costs for transportation of DBS and results for VL testing in addition to EID samples and results using hub and spoke routes within 25 kilometers of the laboratory.

Scenario 1: EID Transportation via Loops

This scenario was informed by the current motorcycle transportation system for DBS samples, based on the qualitative and quantitative information collected about the current system through structured surveys and key informant interviews. Under this system, four motorcycles are used to transport all laboratory samples and results in a network of SDPs to KCH. Motorcycle drivers travel on loops and visit multiple SDPs on each trip, then drop them at a batching location, Bwaila District Hospital, where they are picked up by another motorcycle and taken to KCH once a day. Laboratory samples outside of DBS samples for VL and EID are collected by these drivers; EID tests represent about 4% of the total number of samples, DBS and otherwise, in the average payload.

In parallel, costs for UAV transportation of EID samples and results via similar loops were also modeled. Because UAVs are not currently in use for EID transport (or for transport of any kind), the routes used to estimate UAV transport costs are possible scenarios based on the current constraints of the technology. In this scenario, UAVs would only transport EIDs; this model did not include any of the other samples currently transported by motorcycles. As in the motorcycle scenarios, transportation routes to SDPs were loops, in which a UAV visited multiple SDPs to collect samples and distribute results before returning to the origin to drop off the DBS collected. The same subset of SDPs was visited in this scenario as in the motorcycle scenarios, however, the routes were designed to allow the UAVs to visit as many SDPs as possible before returning to the lab under the following constraints:

1. One UAV could transport no more than 60 DBS;
2. Average flight speed for a UAV was 40.5 kilometers per hour;
3. UAVs could fly six hours a day, five days a week; SDPs were open from 9 am to 4 pm with a 1-hour lunch break;
4. The distance between two subsequent SDPs on a route could not exceed 25 km; and
5. Each SDP must be visited at least twice a week.

Under these constraints, two UAVs could provide the required level of service using four routes. The UAS was based at KCH, and all loops originate and end at that location. Thus, UAVs transport results to SDPs on the trip from KCH to the SDP, and return with a payload of samples. Batching at Bwaila before transport to KCH was not appropriate for UAVs because of their relatively small payload capacity compared to the motorcycles. Thus, UAS operations were centralized at KCH, under the responsibility of a UAS coordinator. The UAS Coordinator is not an existing cadre in the Malawian health system, but a cadre to supervise and navigate would need to be developed if a UAS were deployed. UAS Coordinators would be responsible for launching the UAV from the laboratory, ensuring it is stored and handled correctly, communicating with SDPs about arrival and launch by SDP workers, and reporting any issues with the UAV.

Candidates for this position would need to have basic computer literacy but the Matternet business model includes initial training on UAS coordination. We estimate their salaries would be higher than the motorcycle drivers' are currently, based on interviews with key informants. The UAS coordinator would launched and monitored each UAV using either a smartphone with the Matternet Transporter App, or a traditional mobile phone using SMS messages. In order to launch the UAV from a SDP, a health worker at the SDP would alerted the coordinator by phone that the UAV was ready for launch. The UAV would was only be at KCH at the beginning and end of each loop.

Scenario 2: VL and EID Transportation via Loops

Scenario 2 used the same network and routes as Scenario 1, but modeled the costs to transport DBS for VL testing as well as DBS for EID. In order to transport the higher volume of DBS, UAVs had to make additional trips to SDPs that produce more than 120 DBS per week, due to the 60 DBS limit of the payload boxes[10]. In fact, in order to carry the total DBS volume, each route must be traveled up to 18 times a week. To achieve this, the system needed to include 13 UAVs. In this scenario, the combined volume of the DBS represented 70% of the total supply chain carried by motorcycles. As in Scenario 1, for the UAS, a supply chain 100% dedicated to the commodities in question was examined.

Scenario 3: EID Transportation via Hub and Spoke Routes

Although loops are a realistic and probable transportation routes using motorcycles and/or UAVs, the two transportation modes must use different routes and schedules due to their varying characteristics. Outputs from these analyses provide useful insights into system costs, but the costs of the two scenarios are difficult to directly compare. In order to provide costs for motorcycle and UAV transportation that are comparable, transportation systems were modeled to provide costs for UAVs and motorcycles using the same routes and supply chains. In these scenarios, we examined costs for EID transport for only the SDPs within 25 kilometers of KCH. Vehicles (motorcycles or UAVs) used hub and spoke routes to travel from KCH (the hub of the system) to each SDP to pick up samples and return results, and then immediately return KCH to drop off the samples. We assumed that UAVs could travel from KCH to each SDP on the shortest possible route, with a circuity factor of 1.[11] Because motorcycles cannot travel from one node to the next on the shortest possible route, we adjusted the hub-and-spoke distances for the motorcycles using a circuity factor 1.52.[12]

For the baseline, which modeled motorcycle transportation of EID samples, routes and schedules were determined under the following constraints:

1. The average speed for a motorcycle was 27 kilometers per hour, based on information about current motorcycle routes and schedules.
2. Motorcycles could travel six hours a day, five days a week; SDPs were open from 9 am to 4 pm with a 1-hour lunch break.
3. Each SDP must be visited at least twice a week.

The UAS operated under the same constraints detailed in Scenario 1.

Scenario 4: VL and EID Transportation via Hub and Spoke Routes

In parallel to Scenario 2, Scenario 4 used the same network and routes as Scenario 3, but modeled the costs to transport DBS for VL testing as well as DBS for EID. The UAVs were subject to the same 60 DBS per payload constraint, and again, had to make more trip to pick up the forecast volume of DBS. As a result, on average, SDPs within 25 kilometers were visited 3.7 times a week. As in scenario 3, in the motorcycle baseline, SDPs were visited only twice a week in compliance with National Sample Transportation Guidelines, and a circuity factor of 1.52 was used to estimate route distances.

Routes and schedules for all scenarios are available in ***Appendix E***. Inputs for all scenarios are detailed in Table 2 below. Sources for all inputs are available in ***Appendix F.***

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[10] We assumed that the packaging and space requirements of VL DBS are the same as EID DBS, so the UAV payload can fit up to 60 DBS for both types of samples. In reality, packaging is not identical, so this scenario should be considered illustrative of how costs would change with a higher volume supply chain.

[11] In reality, UAVs may have to deviate from the shortest possible route due to air space restrictions. However, these restrictions for UAVs are not available at this time and must be determined by the Malawian Aviation Authority.

[12] The circuity factor is a coefficient used to compare the shortest possible distance between two points to the actual distance a vehicle must travel due to road or other geographic conditions. A circuity factor of 1.0 indicates that the vehicle is able to travel between two points in a perfectly straight line; a circuity factor of 2 indicates the vehicle must travel twice as far as the shortest possible distance. For this analysis, the circuity factor for the KCH network was determined by comparing distances between SDPs used in the motorcycle routes used in Scenario 1 to the straight-line distances between those same points. From this data set, the circuity factor was estimated at 1.52 with a standard deviation of 0.37.

Table 2. Inputs for each scenario

	Scenario 1: Loops *(EID samples and results)*		Scenario 2: Loops *(VL and EID samples and results)*		Scenario 3: Hub and Spoke *(EID samples and results)*		Scenario 4: Hub and Spoke *(VL and EID samples and results)*	
Node information	Motorcycle Baseline	UAS	Motorcycle Baseline	UAS	Motorcycle Baseline	UAS	Motorcycle Baseline	UAS
Number of nodes (laboratory and SDPs)	38	38	38	38	18	18	18	18
Kilometers/month	11,119 km	4613 km	11,119 km	34,727 km	5141 km	3389 km	5141 km	4355 km
DBS/month	625 DBS	625 DBS	12120 DBS	12120 DBS	520 DBS	520 DBS	12120 DBS	12120 DBS
Average percentage DBS of total payload volume	4%	100%	70%	100%	100%	100%	100%	100%
Vehicle costs and characteristics								
Vehicle range	Unlimited[13]	25 km	Unlimited	25 km	Unlimited	25 km	Unlimited	25 km
Payload capacity	Unlimited	60 DBS	Unlimited	60 DBS	Unlimited	60 DBS	Unlimited	60 DBS
Number of vehicles	4	2	4	13	2	1	2	2
Personnel costs								
Number of personnel	4	1	4	1	1	1	1	1
Monthly salary/person	$150	$375	$150	$375	$150	$375	$150	$375
Per diem	0	0	0	0	0	0	0	0

[13] This assumes that fuel is always available when and where drivers need to refuel.

Results and Discussion

In Scenarios 1, 2 and 4, costs were higher for the UAS than the motorcycle system by about 1800%, 500% and 14%, respectively, as shown in Figure 1, below. However, in Scenario 3, when both modes of transportation only carried EIDs via hub and spoke routes, the total costs for UAS were 18% less than those for the motorcycle system. This is because UAVs could take the shortest possible path between two points and arrive more quickly than motorcycles, traveling fewer kilometers more quickly and saving personnel time. In this scenario, the time- and distance-savings are great enough to balance out the higher per kilometer costs. However, in Scenario 4, the UAS does not reduce the personnel time or distance travel enough to outweigh the lower per kilometer costs of motorcycles, and so is about 14% more costly than the motorcycle system.

Figure 1. Costs for UAS transportation as a percentage of motorcycle baseline costs

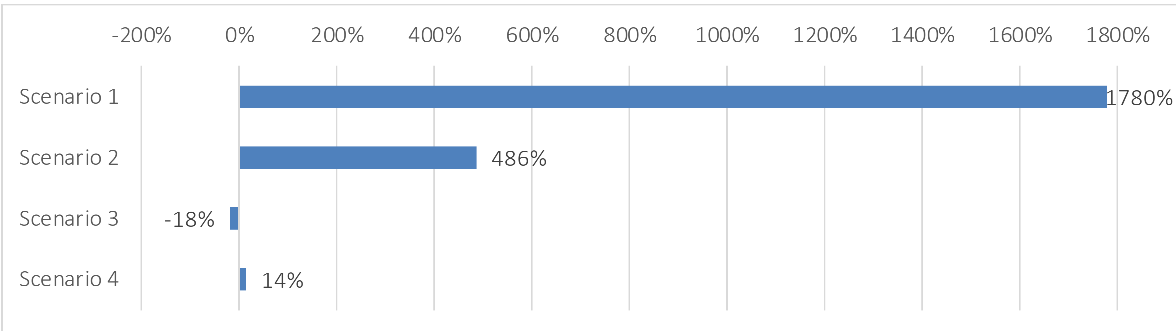
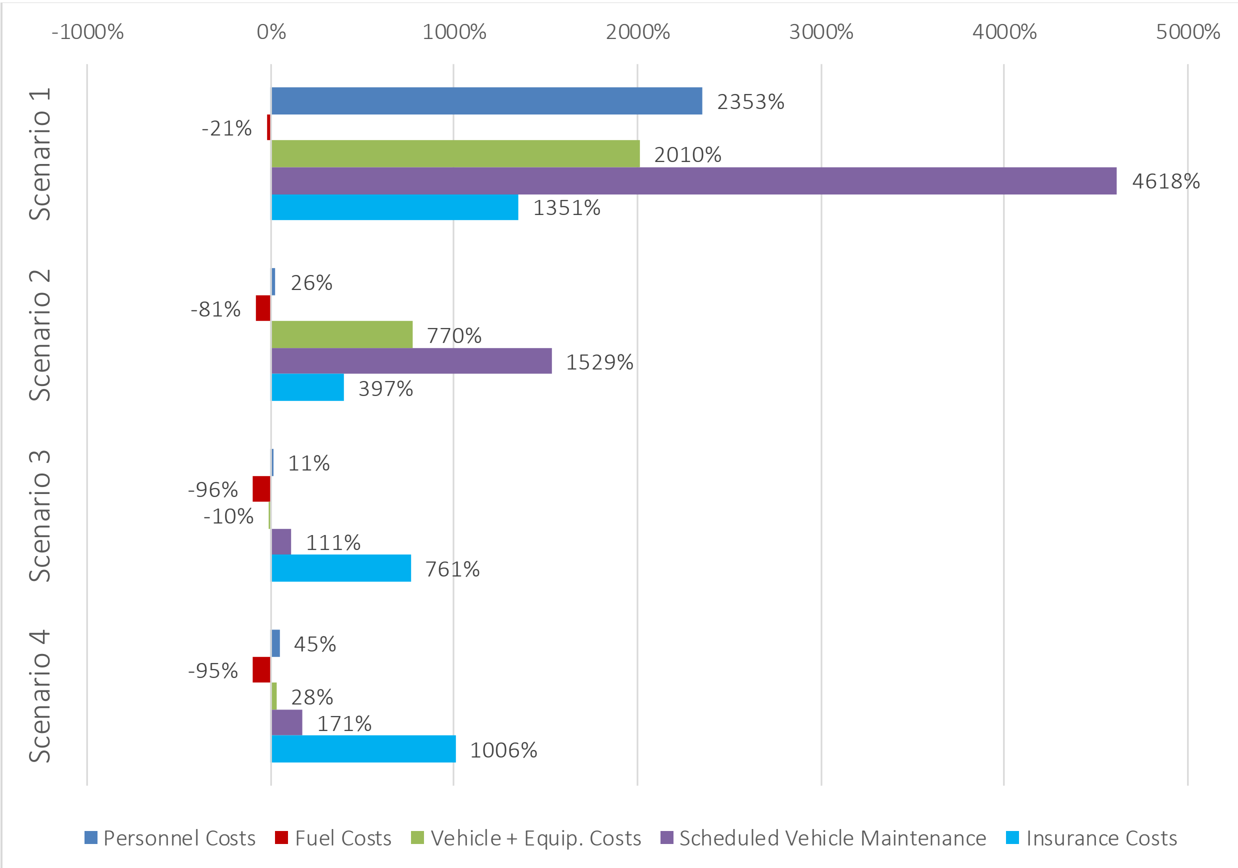


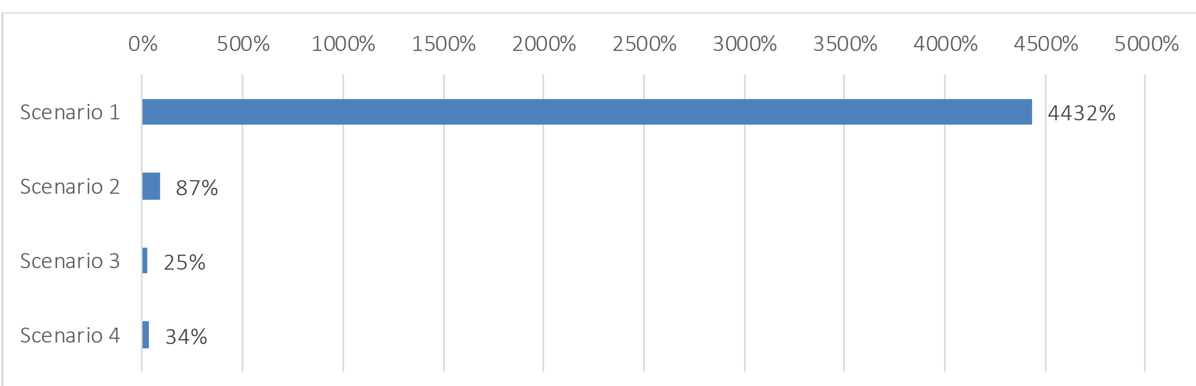
Figure 2, below, shows the breakdown of costs of the UAS as a percentage of the motorcycle baseline costs for each scenario by system element. In all scenarios, fuel costs for the UAS were less than those for the motorcycle system. In Scenario 3, vehicle and equipment costs were 10% less for the UAS than the motorcycle system.

Figure 2. Costs for UAS transportation as a percentage of motorcycle baseline costs, by system element



In all four scenarios, costs per kilometer were higher for the UAS than for the motorcycle system, as shown in Figure 3. In particular, in Scenario 1, costs were 44 times higher in the UAS than in the motorcycle system, mainly because other commodities were transported along with EIDs in the motorcycle system so only a small fraction of the transportation costs were attributable to the transportation of EID. In Scenario 2, per kilometer costs were closer – the UAS costs were about 80% greater than those of the motorcycle system - because are larger proportion of the supply chain costs for motorcycles were taken into account in this scenario.

Figure 3. Per Kilometer costs for UAS transportation as a percentage of motorcycle baseline costs



Insight: It is possible that potential efficiencies would be lost by isolating DBS into a parallel logistics system. DBS, and especially EID, only represent a proportion of the samples sent by SDPs to laboratories for testing, and a proportion of the results returned. This analysis indicates that the ability of the motorcycles to carry multiple samples and share transport costs across those samples makes this mode of transportation cost positive compared to a UAS dedicated to a relatively low-volume supply chain. However, **when the UAS was used to transport a segment of the supply chain with a volume of samples that did not exceed payload capacity, it was cost-favorable** compared to motorcycles for the same segment. This is primarily **due to the UAVs' ability to travel more quickly via direct routes, covering fewer kilometers and generating smaller personnel costs.**

Nonetheless, **there may be benefits to a dedicated supply chains for certain commodities that would outweigh these costs**, but those benefits were not explored in this cost analysis. Further studies should quantify the benefits, such as results turnaround time, related to decreases in transportation time and decreases in delays due to road conditions. If possible, benefits related to health outcomes, such as getting HIV positive patients on appropriate treatment plans more quickly, should also be identified and quantified in a next stage of analysis.

It will also be important to identify the root causes of delays in results turnaround time and define use cases where a UAS is the most appropriate form of transportation. For example, some SDPs are difficult and expensive to reach by motorcycle. Key informants identified Likoma Island, which is not reachable by motorcycle and Kabuwa Health Center, which is not far from the laboratory but requires drivers to circumvent a forest and add up to a day of travel to avoid the risk of snake bites, as use cases that would be worth exploring. Other use cases of interest could be SDPs that produce very small volumes of samples and so cannot enjoy the efficiencies related to the motorcycles' high payload capacity, or supply chains segments for samples that, if the results were returned more quickly, could lead to positive outcomes that would outweigh any costs.

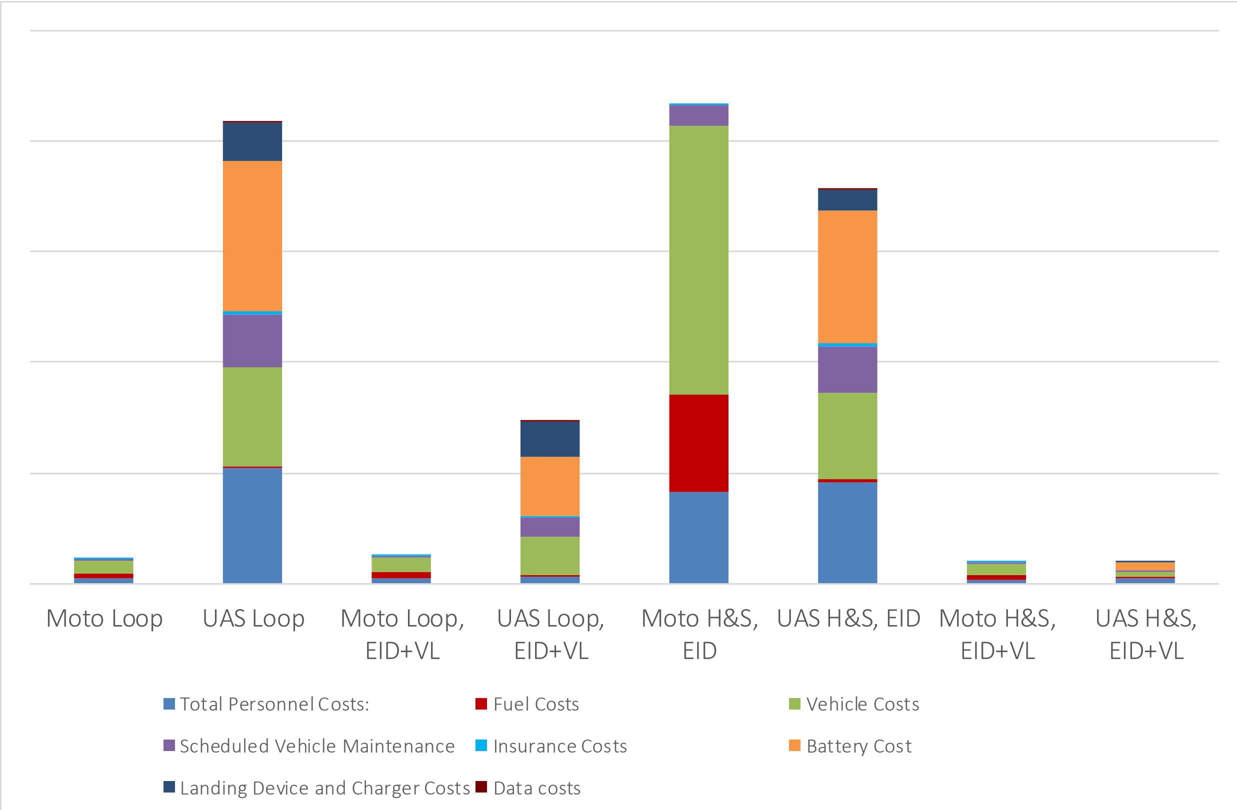
Comparing Costs per Sample[14]

A similar trend was observed in examining costs **per DBS**, as shown in Figure 2. Costs were much lower per sample when the motorcycle system is modeled to transport a range of commodities; in Scenario 1, costs per sample are over 17 times greater for the UAS than for the motorcycle system. In Scenario 2, when 70% of the volume, and 70% of the costs, of the supply chain for the motorcycle transportation were included, the two systems came closer in cost per sample, although the UAS was still almost 6 times more costly per DBS than the motorcycle system. Again, this was due to the limited payload capacity of the UAVs; they had to make many more trips and cover many more kilometers than motorcycles to serve higher-volume SDPs.

In parallel to the trends in total costs, when dedicated sample transport systems were compared for transporting EID alone, costs were 18% lower for the UAS than the motorcycle system in Scenario 3. In Scenario 4, cost per sample for both modes was much lower than in Scenario 3, due to the much higher volume of samples, but cost per sample was about 14% more for the UAS than the motorcycle system.

[14] The comparison per result is identical to the comparison per sample.

Figure 4. Comparison of absolute cost per DBS for all scenarios



Insight: It is important to remember that the systems analyzed in this report have not been optimized, and the two visit per week requirement may not be optimal for SDPs that produce far fewer that the full 60 DBS payload for UAVs. **Further analysis, and more data, is needed to develop optimized systems for transporting laboratory samples and results using UAVs.**

For example, Matternet envisions an optimal system using more advanced software to develop optimal routes or loops based on real-time data from SDPs on the volume of samples they have ready for pick-up. Even under the two visit per week constraint, optimized loops could be developed based on reported DBS ready for pick up to ensure each UAV filled its payload box while covering the minimum possible distance. Such a system could significantly reduce the distances needed to pick up higher volumes of samples for supply chains such as those modeled in Scenarios 2 and 4. Furthermore, an optimal system would likely be multi-modal; using both UAVs and motorcycles to capitalize on the benefits of each transportation mode. Developing these optimal systems will require more work on the UAV technology as well as further study of the capacity and bottlenecks in the laboratory logistics system overall.

Cost Drivers

In both the motorcycle system and the UAS, personnel costs and the costs of the vehicles themselves were important cost drivers. Personnel costs were higher for the UAS due to the high cost of training personnel on a completely new technology. The vehicle costs of the motorcycle system were higher because the useful lifetime of motorcycles was lower than that of UAVs, and outweighed the lower upfront of cost of the motorcycle. The useful lifetime of the UAV was an estimate, since the technology is still in development, but generally, combustion engines experience more wear and tear than electric motors, and motorcycles driving on poor roads would be expected to be subjected to more stress than UAVs flying through the air.

Additionally, the longer lifetime of the UAVs was supported by higher preventative maintenance costs. For example, routine maintenance costs for UAVs included multiple replacements of the motor, propellers, bearings, and electrical components, while routine motorcycle maintenance only included replacement of filters and oil changes.

In addition, in the motorcycle system, fuel costs were also significant, representing about 20% of total costs, while they were only 0.05% of the total costs of the UAS. It is important to note that in Malawi, currency has been very unstable so the cost of petrol, as well as other variable costs, fluctuates. Finally, the costs of batteries, chargers, and landing devices were important costs in the UAS, but were not relevant to the motorcycle system.

Insight: Because electricity represents such a small proportion of the costs of the UAS, the costs of this system may be more stable over time. At the time of the data collection, petrol costs in Malawi were relatively low compared to historical prices. This analysis only looks as costs collected at one point in time. Given the significance of the petrol costs in the motorcycle system, understanding how the price of petrol effects laboratory logistics would be an important step in better understand the costs and level of services of the current system. A potential benefit of a UAS could be reducing reliance on petrol. For example, ***if petrol cost per liter increases to $4, as has been observed historically in sub-Saharan Africa, costs for the motorcycle system in Scenario 2 would increase by more than 50%. In this case, the UAS becomes even more cost-favorable.***

However, availability of electricity is also variable in many rural areas in Malawi, and should be considered in developing use cases for a UAS. In areas without a grid connection, or with frequent outages, SDPs would rely on generators or solar power to charge the UAV batteries. This analysis only looked at cost of ESCOM electricity, but in further studies, costs and reliability of other sources of electricity should also be considered.

Finally, UAV technology is very immature, and it is expected that the costs of the vehicles and equipment will decrease significantly in the future as production for UAVs becomes possible at scale and suppliers are able to recover start-up costs. We do not expect any significant change in the costs of motorcycles due to the maturity of that technology, while Matternet estimates that equipment costs will drop by about 50% by 2020. Additionally, the growing market for UAVs may drive these costs down further. Because the cost of the equipment, which are likely to decrease, drove the cost of the UAS, rather than costs of personnel or electricity, there is reason to believe that a UAS will become a competitive option of transportation of laboratory samples and results. To illustrate the magnitude of the decrease needed for UAS costs to match motorcycle system costs, in Scenario 4, ***if battery costs were to decrease by about 38%, the UAS would become cost-favorable. Similarly, if battery, landing device, and charger costs all dropped just over 25% in cost, the UAS would become cost-favorable***. These cost decreases are possible through a decrease in the cost of the equipment itself, or through an increase in the lifetime of the equipment.

Limitations

One important challenge in the current system is the turnaround time at the laboratory for processing the DBS. There is evidence of delays up to eight weeks in returning results to SDPs, but delays are not included in this model, because they do not seem to be directly related to transportation. Key informants at KCH reported that they receive motorcycle deliveries of samples and pick-up of results daily. The delay in results dissemination is reportedly due to a backlog of DBS at KCH, likely resulting from staff shortages.

Similarly, there are indications that there are delays in the SDPs between the time of the sample collection and when it is handed off to motorcycle drivers for transport. These delays were not explored in this analysis. We recommend that a representative sample of SDPs are surveyed to elucidate the bottlenecks in the laboratory logistics system in general, and conduct a study to quantify transportation time with more precision and accuracy.

Additionally, we assumed that all samples tested by the laboratory return results, but in reality, some samples are compromised and do not return results. Any initiatives aimed at improving laboratory logistics in Malawi should clearly identify the challenges and bottlenecks in the system, and ensure that solutions address those bottlenecks.

This analysis considered a hypothetical motorcycle system based on interviews with a limited number of informants. Detailed data on the costs of the actual motorcycle system were not available. To better understand the bottlenecks in the system, further studies should collect more information on how the motorcycle system actually functions in Malawi.

Another limitation in assessing the costs of the motorcycle system was lack of availability on the true costs of maintenance related to unexpected breakdowns. Maintenance costs are likely to be higher than estimated, but additional maintenance may also extend the lifetime of the vehicles beyond the estimates used in this analysis. It would be useful to obtain logs of motorcycle maintenance to gain a better understanding of the true costs of the current system.

Finally, the scenarios modeled in this analysis did not include the upfront costs for procuring, importing and setting up the UAVs. These fixed costs should be considered if budgets are developed for UAS deployment. However, data was not available for procuring, importing, and setting up a motorcycle transportation system, so these costs were not analyzed in the scenarios modeled.

Conclusion

In spite of the limitations of this cost analysis, it does contribute to a very small, but growing, body of work that quantifies the costs of UAV transportation for the public health sector in low- and middle-income countries. Excitement about the potential of this technology is increasing – the field trials conducted in conjunction with this cost analysis made international headlines.[15] It is important to understand that this technology is still in development, and any decisions to deploy it should be informed by further cost analysis to quantify expected costs, as well as benefits.

Due to the fact that the costs of a UAS are largely associated with the equipment itself, there is cause to be optimistic that as both the technology and the market for UAVs matures, costs will become more favorable. This analysis does provide indications that there may be use cases for which a UAS is more cost-favorable than existing transportation options. Additionally, there may be cases where it is not cost favorable or is cost comparable, but a UAS could provide a higher level of service in terms of timeliness and allow for lives to be saved through quicker diagnosis and treatment. Thus, we should continue to explore both costs and

[15] Media coverage including: Unicef Stories. March 14, 2016. "Malawi tests first unmanned aerial vehicle flights for HIV early infant diagnosis." Unicef Stories; http://www.unicefstories.org/2016/03/14/malawi-tests-first-unmanned-aerial-vehicle-flights-for-hiv-early-infant-diagnosis/; Allen, K. March 15, 2016. "Using Drones to Save Live in Malawi." The BBC; http://www.bbc.com/news/world-africa-35810153; Burgess, M. March 14, 2016. "Drones are being Trialed to Speed up HIV Diagnosis in Africa." Wired; http://www.wired.co.uk/article/unicef-drones-hiv-malawi-diagnosis.

benefits of this exciting technology, and begin to identify the use cases where is can make the biggest impact on the health of underserved populations.

Furthermore, there is an increasing number of UAV suppliers active in the public health sector, so as use cases in Malawi are developed, it will be important to explore how different services offered by additional suppliers can address the level of service required in the identified use cases. For example, if the use case requires longer ranges to take advantages of the benefits of UAV transportation, then other UAV suppliers with the existing technology to travel further should be explored.

Finally, a system design approach should be considered to address the challenges, and capitalize on the opportunities, in the current laboratory logistics system in Malawi. System design is a process which creates the plan, or blueprint, for how a supply chain should run, including how all of the components of the supply chain system fit together and interact. Data use then drives a continuous improvement approach through regular, system-wide assessments and improvement strategies. Data availability was a significant challenge in this analysis, and an important step in improving the laboratory logistics system will be not only to collect data for future studies, but to implement systems that ensure that data is readily available to decision-makers to design, monitor, and improve the system.

Transportation is only one component of the laboratory logistics system. Bottlenecks outside of transportation should be understood and taken into account in developing strategies to improve the laboratory logistics system, and ultimately, to diagnosis patients and get them on appropriate treatments more quickly and efficiently. Rather than isolating and attempting to improve transportation alone, comprehensive and sustainable strategies for achieving these goals should be developed and implemented. In certain cases, a UAS could play a role in reducing transportation time, especially to SDPs that are hard to reach using existing technologies. However, these cases should be carefully analyzed, benefits should be quantified and weighed against costs, and decision-makers should be thoughtful in considering how a UAS could strengthen the laboratory logistics system in Malawi.

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Appendix A – Service Delivery Points in the Kamuzu Hospital Network

Stop	Latitude	Longitude	Within 25 k[16]
Kamuzu CH[17]	***-13.9764***	***33.78512***	
ABC Clinic	-13.96816	33.74129	x
Area 18	-13.94131	33.78051	x
Area 25	-13.89272	33.77465	x
Bwaila DHO[18]	-13.99164	33.77561	x
Chadza	-14.14715	33.84167	x
Chikowa	-13.72929	33.45821	
Chileka	-14.02102	33.38544	
Chilobwe	-13.85467	33.37439	
Chitedza	-13.97684	33.64529	
Chiwamba	-13.8571	33.92926	x
Daeyang	-13.87684	33.80867	x
Dickson	-14.26626	33.65885	x
Dzenza	-13.87598	33.74689	x
Kabudula	-13.81972	33.44838	
Kamuzu Barracks	-13.98131	33.82105	x
Kang'oma	-13.97817	33.88219	
Katchale	-14.2836	33.90782	
Kawale	-13.99175	33.79757	x

Stop	Latitude	Longitude	Within 25 k
Khongoni	-13.77451	33.36761	
Likuni	-14.02683	33.70886	x
Lumbadzi	-13.77074	33.80477	x
Malembo	-13.62006	33.41507	
Malingunde	-14.16887	33.6397	
Mbabvi	-13.92808	33.67087	x
Mbang'ombe 2	-14.16945	33.37942	
Mbwatalika	-14.00387	33.5507	x
Ming'ongo	-14.07479	33.44838	
Mitundu	-14.24776	33.77465	
Nambuma	-13.72409	33.55789	x
Ndaula	-14.1385	33.50757	
Ngoni	-13.77509	33.64018	
Nsalu	-13.8855	33.5043	
Nthondo	-14.03153	33.44849	
Nyamanda	-14.00717	33.78419	x
St. Gabriel	-13.98418	33.35128	
Ukwe	-14.00768	33.81013	x

[16] Within the 25 kilometer flight radius of the UAVs, included in Scenario 2 and 3 models.
[17] Location of laboratory and hub of network.
[18] Batching location in the current, motorcycle-based transport system.

Appendix B – Costing Tool Specifications

Our distribution costing model costs the supply chain from a central warehouse to service delivery point facilities. Our approach handles collection system settings, incorporates cost of time of non-SC personnel involved in SC activities and is comprehensive including costs of transportation, inventory, commodity, management, etc. Sample or actual data including the portion of transport, personnel, cold chain, and commodity costs that apply to the supply chain being studied can be entered in the model directly into the Excel worksheets, or via macros to facilitate the data entry. As the costs are entered into the model, they are standardized to monthly costs, and the model then projects and calculates the costs for the entire study catchment at a monthly, sample, and time period selected by the user.

Additional model features include:

- Cost summaries at a time period determined by the user. For example, in addition to a monthly cost, costs can be calculated on a quarterly, bi-annual, or annual basis.
- Automated currency conversion. Costs can be entered in the model as the same or different currency than the user desires for the outputs.
- Supply chain flexibility. The model can accommodate all types of supply chain designs including hub and spoke and circular distributions, collection and delivery systems, and any combination thereof. The model is designed to accommodate situations where the supply chain is not systematic.
- Cost-effectiveness and efficiency measures. The model calculates costs per two measures selected by the user. For example, these measures can be cost per a certain health impact measure, commodity type used, dollar amount spent on commodities, km driven, etc. These measures provide an opportunity to measure cost-effectiveness and efficiency depending on the measures used.
- Labor costs categorization. The costs of labor are divided between distribution transport, warehouse, and management costs.
- Transport and associated equipment base data. The model pulls transport equipment, transport maintenance, and other equipment (such as landing devices, chargers, and batteries) data from a base of costs entered by the user. Each time those pieces of equipment are used in distribution, they are pulled from to determine the cost of that distribution segment's use.
- Flexible staff types. The user can designate the worker types (e.g. health worker, non-health worker, pharmacy, etc.) for the calculation of their costs and time in the distribution system.
- Staff time summaries. The model automatically populates and calculates the staff time used in the distribution system divided by distribution transport, warehousing, and management. These classifications are further broken down by types of staff as described above.
- Graphs for costing analysis. The model provides pie graphs for the total system costs, transport costs, equipment costs, personnel costs, and personnel time.

Appendix C – Assumptions Related to Cost Inputs

In order to model each scenario, we make a number of assumptions about the transportation system for laboratory samples in Malawi, based on key informant interviews. The core assumptions we made are listed below:

<table>
<tr><th>Node information</th><th>Motorcycle Model Assumptions</th><th>UAS Model Assumptions</th></tr>
<tr><td rowspan="2">Nodes (laboratory and SDPs)</td><td colspan="2">• The models only included health centers in the KCH network currently served by Riders for Health for DBS and results transport.</td></tr>
<tr><td></td><td>• All facilities in the network had the infrastructure requirements necessary for the UAS, including space for a landing pad and minimum electricity and telecommunications requirements to launch and receive UAVs without delays.</td></tr>
<tr><td rowspan="2">Routes and Scheduling</td><td colspan="2">• Routes were traveled on a set schedule, and SDP staff know approximately when drivers will arrive at the SDP. There was no mechanism by which SDP staff can “call” a vehicle to come pick up samples or drop of results on demand.
• Routes always took the same amount of time to travel. Weather conditions or other events that may cause delays or variable travel times were not taken into account. The model does not factor in any delays due to equipment problems or personnel tardiness.
• The National Sample Transportation Guidelines recommend that transport should be avoided on Fridays if possible.
• Each SDP must be visit at last twice a week.</td></tr>
<tr><td>• The average speed for a motorcycle was 27 kilometers per hour, based on information about current motorcycle routes and schedules.</td><td>• Average flight speed for a UAV was 40.5 kilometers per hour, including take-off and landing.
• We estimated that it would take 15 minutes for the worker to load the UAV, change the battery, and launch the UAV at each location. Cost of this time was not included in the model because we assume it is not significantly different from the time needed to prepare samples for the motorcycle. This time is accounted for in determining the number of trips a UAV can make per day.</td></tr>
</table>

		• At this stage, these routes were not developed to formally optimize factors such as flight time, flight distance, or number of samples collected on each route. There may be other possible routes that fill these requirements.
DBS	• The volume of DBS transported by both systems was assumed to be the forecasted load of DBS used for EID and VL testing for 2015, as estimated by Unicef Malawi.[19] There was no seasonality in this forecast, and monthly volume estimates were assumed to be constant throughout 2015. • The volume of results generated and distributed to SDPs was assumed to be equal to the number of DBS produced by each SDP. • Packaging and transportation requirements for VL and EID DBS were assumed to be the same. • The volume of results generated and distributed to SDPs was assumed to be equal to the number of DBS produced by each SDP. Results were transported to a SDP on the next trip after the corresponding DBS was delivered to KCH. Thus, we assumed, for any given month, the number of results transported to a SDP is equal to the number of DBS picked up from that SDP	
Vehicle costs and characteristics		
Vehicle range	• There is no practical limit to the distance a motorcycle can travel.	• With a 500 gram payload (full capacity payload of DBS) a UAV could travel 25 kilometers before it must touch down to recharge or change its battery.
Payload capacity	• DBS for EID and VL were packaged identically and have the same transportation requirements, for the sake of this analysis.	
	• There was no practical limit to the number of DBS or result a driver can transport.	• UAVs could transport a maximum of 60 DBS.
Number of vehicles	With the exception of the motorcycle system in Scenario 1, which used was based on the current system configuration, the number of vehicles was estimated to be the minimum possible number of vehicles to visit each SDP at least twice a week, collect the forecasted average load of samples, arrive at each SDP between 9 am and 4 pm with a one-hour break (six hours window per day), and with no transport on weekends and minimal transport on Fridays.	
Vehicle base costs	• This model used the February 2016 value for the make and model of motorcycle commonly used for sample transport in Lilongwe district.	• This model used the cost estimates for the Matternet TWO UAV. Although this vehicle is not available today, Matternet has determined cost estimates based on predicted costs for this UAV. In the UAS scenarios, the model assumed these costs are available today, in March, 2016 currency.

[19] 2015 estimates were used because the 2016 estimates were not available at the time of this study.

Other equipment costs	• For motorcycles, this included rider safety gear (helmet, jacket, first aid kit, gloves, boots, etc.) and the payload box.	• For UAVs, this included vehicle case, tools, and essentials, payload box, and software.
Expected useful lifetime (km)	• The expected lifetime of a motorcycle was expected to be 50,000 kilometers, as recommended by the Malawi 2016-2020 Comprehensive Multi-year Plan (CMyP).	• The lifetime of the Matternet TWO was estimated at 202,500 kilometers with the level of maintenance assumed in this model.
Vehicle insurance cost/km	• Insurance costs were estimated based on interviews with key informants about costs for the make and model of motorcycles commonly used in Lilongwe District.	
Fuel costs	• Fuel costs per kilometer, specific to the model of motorcycle commonly used in Lilongwe district, were determined using the March 2016 petrol costs in Lilongwe.	• All batteries and other electronic equipment were assumed to be charged using power from the electric grid (ESCOM), rather than generators
Maintenance cost/km	• Only routine, preventative maintenance costs were included. Maintenance in response to unexpected breakdowns or other curative maintenance costs were not included.	
	• Maintenance costs were estimated at 15% of vehicle fuel costs, as recommended by the Malawi 2016-2020 Comprehensive Multi-year Plan (CMyP).	• Maintenance costs for the UAV were estimated at 65% of the base cost of the vehicle. This included four motor replacements and numerous other parts replacements.
Battery cost	N/A	• Each UAV in the system was equipped with a battery with a lifetime of 800 cycles. One cycle was used each time the UAV arrived at a node. Matternet recommends that a spare battery is kept in stock at each node, in addition to some back-up stock, but these costs were not included in this analysis, as they did not affect the total number of battery cycles used and spare parts costs were not included in the motorcycle system.
Charger cost and landing device costs (including maintenance)	N/A	• Each node in the network was equipped with a charger and landing device. Lifetime of each was 5000 cycles. One cycle was used each time the UAV arrived at the node. Matternet recommends that spare equipment is kept in stock, but these costs were not included in this analysis, as spare parts costs were not included in the motorcycle system.
Data/airtime costs	N/A	• The UAS coordinator can launch and monitor the UAV using either a smartphone with the Matternet Transporter App, or a traditional mobile phone using SMS messages. These costs

		were estimated using the data bundle that would allow the UAS Coordinator to use the Transporter App on a smartphone. If a traditional mobile phone and SMS system were used, airtime costs would be less than the data costs estimated. • The cost of the mobile phone itself was not included in the model, since the costs for motorcycle drivers' phones are not included. • Airtime costs for communication between the UAS Coordinator and the SDPs were not in the model, as these costs are not included in the motorcycle transportation systems.
Personnel costs		
Number of personnel	• Only personnel directly involved in transportation of samples (motorcycle drivers or the UAV coordinator) were taken into account in this analysis. The requirements for other support personnel for both systems were assumed to be identical.	
Monthly salary/person		• The UAS coordinator position does not currently exist; based on recommendations from key informants, we set the salary for this position higher than that of a motorcycle driver in the current system, at $250 per month.
Per diem	• Drivers and UAS Coordinators did not receive per diem or any other incidentals. We assumed all benefits were included in the salary estimate.	
Initial training costs	• Costs associated with obtaining licenses for motorcycle drivers were not included in this model. Key informants indicated that Riders for Health only recruits drivers who are already licensed and otherwise qualified to drive motorcycles, so training costs are limited to handling samples and administrative procedures.	• Training costs included a two weeks of Matternet staff time in Malawi to conduct in-person trainings for all actors who would interact with the UAS, including UAS coordinators, SDP staff, and laboratory staff. These costs also include training materials, logistics, and participant costs.

Appendix D – Survey Tools

Unmanned Aircraft System Survey Tool

Objective: To collect data in order to model the costs associated with transportation of DBS for Early Infant Diagnosis (EID) and Viral Load (VL) testing from health centers to Kamuzu Central Hospital by the Matternet UAS.

Instructions: *Please provide the information requested in the questions on the following pages. In this questionnaire, the term "health centers" refers to all points of care that collect DBS from patients.*

The fields in this document will expand as you type in them. If the information has been documented in other formats (spreadsheets, reports, or other documentation) please feel free to provide these electronically to Nora Phillips at nora.phillips@villagereach.org rather than transcribing it on this form.

Name of respondent: ______________________________

Title of respondent: ______________________________

Date: ______________________________

1. Please provide information about the costs of the elements of the Unmanned Aerial System (UAS), listed in the table below. If there are elements of the UAS not listed in the table below, please add them. For each element, also list the expected useful lifetime. Use the "notes" column to describe how costs were estimated or provide additional information. Feel free to add rows as necessary. If this information is available in other documents, please send them directly to Nora instead of filling out the table below.

Description of Item	Base Cost per unit (USD)	Expected Useful Lifetime	Notes
Unmanned Aerial Vehicle			
Payload box (if not included in UAV cost – indicate in notes)			
Battery (if not included in UAV cost – indicate in notes)			
Battery charging equipment			
Landing pad			
iPhone for operating the Matternet iPhone App			
Licensing fees for Matternet iPhone App			
List other items…			

2. How many flights per day are recommended for one UAV? What factors could limit the number of flights a single UAV can complete per day?

3. How many batteries are recommended to be available for each UAV? (For example, 3 are recommended – one to be kept charged at the laboratory, one to use during flight, and one to be kept charged at the health center)

4. Is battery charging equipment recommended at all launch and retrieval sites (e.g. at all health centers in the network and at the laboratory)? If not, how many facilities are recommended to be served by one charging station?

5. Is an iPhone required for each facility (lab and health centers)? If not, how many facilities can be served by one iPhone?

6. If there are licensing fees for the Matternet iPhone App, how many iPhones can use the app under one license?

7. How much data is expected to be used by the Matternet iPhone App for one flight?

8. What infrastructure (internet connectivity, reliable electricity, etc.) is required for charging, launching, and controlling the UAV?

9. Please provide any information you have calculated on amortization of the UAV and/or other elements of the UAS. Explain how these amortization rates were calculated. If you have not calculated amortization, you may leave this field blank.

10. What is the expected energy usage per kilometer for a UAV? If this is not known, what is the expected energy usage per flight?

11. What is the expected maximum flight speed? What factors could affect flight speed?

12. What is the expected maximum flight distance without battery recharge? What factors could affect the flight distance?

13. List all anticipated maintenance needs for the UAV, the launch equipment, and for any other related equipment listed in Question 1, the estimated cost of each maintenance activity, and the expected frequency of the activity per year. If this information is provided in other documents, you may provide them to Nora instead of completing the table below.

Maintenance Activity	Equipment involved	Estimated cost of activity (USD)	Expected frequency (per year)

14. What factors could cause delays in UAV flights? What are the protocols for determining if it is safe to fly the UAV when these factors are present? How often are delays anticipated (for example, what proportion of planned flights are expected to be executed on time?)?

15. What skills or professional qualifications (degrees, certificates, etc.) are needed to for programming and management of the UAS?

16. What skills or professional qualifications are needed for UAV launch, navigation, and landing?

17. How many personnel would be needed both manage the UAS and perform launch, navigation, and landing support for UAV flight? Would the "hub" of the UAS (where the UAS and these personnel are based) be housed at the lab, or at other locations? Would the number of personnel needed at the "hub" vary with the number of UAVs deployed? If so, what is the recommended ratio of staff per UAV?

18. What level of technical or computer literacy will be required for staff at the health centers to operate the UAVs?

19. How does Matternet envision a UAS working at scale? Who would manage the system? (Government? Partner non-profit? Private sector contractor?)

20. What are the risk factors that have you seen or might you anticipate that could result in technology failure?

Motorcycle Transport System Survey Tool

<u>Questionnaire: Riders for Health Motorcycle Transportation of Dried Blood Spot (DBS) Samples to Kamuzu Central Hospital</u>

Objective: To collect data on the costs associated with transportation of DBS for Early Infant Diagnosis (EID) and Viral Load (VL) testing from health centers to Kamuzu Central Hospital (CH) by motorcycle.

Instructions: *Please provide the information requested in the questions on the following pages. These questions refer to the* ***entire network of health centers and other points of care that send DBS to Kamuzu Central Hospital for testing.*** *In this questionnaire, the term "health centers" refers to all points of care that collect DBS from patients.*

The fields in this document will expand as you type in them. If the information has been documented in other formats (spreadsheets, reports, or other documentation) please feel free to provide these electronically or in hard copy to Carla Blauvelt, VillageReach Malawi Country Director (carla.blauvelt@villagereach.org) rather than transcribing it on this form.

Name of respondent: ______________________

Title of respondent: ______________________

Date: ______________________

1. Which of the options below best describe the routes used to visit health centers to/from Kamuzu District Hospital. Please check all boxes that apply by clicking on the box next to the applicable options and provide additional details about the transportation routes in the fields below each option. **If you have any maps or charts showing transportation routes available to share, please provide them to the Country Director.**

   ☐ Motorcycle drivers complete loops for sample transport, visiting many health centers before returning to Kamuzu Central Hospital.

   ☐ Motorcycle drivers make out-and-back trips, visiting only one health center on each trip

   ☐ Other (Describe)

2. Describe how visits to health centers are scheduled. Please check all boxes that apply by clicking on the box next to the applicable options and provide additional details about the visit schedules in the fields below each option.

   ☐ Each health center is visited on a set schedule known by the health center staff (for example, every Monday, every other Tuesday, etc.)

   If health centers are visited on a scheduled basis, is the frequency of the visit the same for each health center (once a week, every other week, etc.) or does it vary between health centers? If it varies, how is the visit frequency determined?

   ☐ Health centers are visited on an *ad hoc* basis

If visits are ad hoc, how do drivers know when to visit a health center? **Are there any costs associated with dispatching a driver (SMS, data, airtime, etc.)?** If there are communication costs, please indicate whether costs are weekly, monthly, etc.

☐ Other (describe)

3. What are the factors that could delay a trip? What is the protocol for determining if a trip is delayed? How frequent are delays?

4. From whom at the health center does the driver typically pick up samples? To whom at Kamuzu Central Hospital does the driver typically give the samples (what cadre of worker – nurse, laboratory technician, administrative staff, etc.)? If either of these vary, please explain why and how they do so.

5. Do drivers pick up samples other than DBS? If so, estimate the proportion by volume of the driver's payload that is used for DBS.

6. Are there any constraints that would prevent a driver from being able to transport DBS back to Kamuzu Central Hospital (for example, would they ever not have enough space to carry the samples?) If so, what is the protocol for transporting these samples (are they picked up the next visit, is another mechanism used to transport them, etc.)?

7. Are the transportation systems that Riders for Health uses to transport DBS to Kamuzu Central Hospital different from the systems that Riders uses elsewhere in Malawi? If so, explain the differences and why they exist.

8. In 2015, how many DBS did Kamuzu Central Hospital receive each month, via Riders transport? (Provide all available data. If this data is available in other sources, please provide them directly to the Country Director.)

Month	Number of DBS
January 2015	
February 2015	
…	
December 2015	

9. Please list all the routes Riders uses to transport DBS to the Kamuzu Central Hospital in 2015. For each health center, please provide the following information in the table below or, if this information is compiled in other sources, provide these sources to the Country Director:
    a. Frequency each route is traveled (per week or per month, as appropriate)
    b. The name of each health center on the route, in the order in which they are visited
    c. The time, in minutes, it takes on average to travel from each health center to the next health center on the route
    d. The distance, in kilometers, from each health center to the next health center on the route.

    If you are filling in the table below, please copy and paste this table for each route. Note that the End of the Route should be the same as the origin, if the route in a loop. Please add rows for additional stops as needed.

Route A	Frequency route is used (number of times per week or month):		
	Health Center Name	Time to next stop (minutes)	Distance to next stop (km)
Origin:			
Stop 1:			
…			
End of Route		N/A	N/A

Route B	Frequency route is used (number of times per week or month):		
	Health Center Name	Time to next stop (minutes)	Distance to next stop (km)
Origin:			
Stop 1:			
…			
End of Route		N/A	N/A

10. For each health center listed above, please provide the number of DBS samples collected each month in 2015 either in the table below (add rows as necessary), or, if it is available in other sources, please provide them to Carla.

Health Center Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec

11. Describe how motorcycles are assigned to routes. Please check all boxes that apply by clicking on the box next to the applicable options and provide additional details about the route assignment in the fields below each option.
    ☐ Drivers always follow the same routes, and each driver is responsible for a fixed set of health centers

☐ Drivers vary the routes used to travel to health centers, but each driver is responsible for a fixed set of health centers

☐ Drivers vary the routes used to travel to health centers, and different drivers visit different health centers each trip

12. If there is variation in the routes that drivers use, explain the reasons for the variation in routes.

13. If there is a fleet of motorcycles dedicated to serving only Kamuzu Central Hospital, please provide the information specified below **for each individual motorcycle**. If motorcycles are used in other regions as well, please provide **the average information for each make and model used in the Kamuzu Central Hospital network**. Please add rows as necessary, or if this information is available in another document, please provide it to the Country Director.
    a. Make
    b. Model
    c. Year
    d. Base cost
    e. Type of fuel
    f. Average kilometers per liter of fuel
    g. The amortization rate per kilometer
    h. Expected useful lifetime of the vehicle at purchase
    i. Expected useful lifetime of vehicle remaining

Make	Model	Year (if applicable)	Base cost	Type of Fuel	liters/ 100km	Expected lifetime at purchase	Expected lifetime remaining	Amort. km	Insurance Costs per year

14. How often is routine maintenance performed on each motorcycle? **How much did each instance of maintenance cost, on average, in 2015?** Does frequency and/or cost of maintenance vary by make and model? If so, please specify frequency and cost of routine maintenance for each make and model.

15. On average, in 2015, how often was emergency maintenance performed on each motorcycle in the Riders fleet? How much did emergency maintenance cost on average, per motorcycle in 2015. *(If emergency and routine maintenance costs are not disaggregated, you can report maintenance costs in either question 12 or 13, but please explain how the costs were calculated.)*

16. What is the salary for motorcycle drivers who serve Kamuzu Central Hospital? If drivers receive different salaries, please provide the average salary for drivers who serve Kamuzu Central Hospital.

17. **How many drivers serve Kamuzu Central Hospital?** Do these drivers serve only the Kamuzu Central Hospital or do they serve labs in multiple networks? If drivers serve multiple labs, is there another measure available (such as full time equivalent) to show how many salaries are allocated to this network?

18. Do drivers receive any additional compensation when transporting DBS, such as per diem? If so, please describe the rates for additional compensation.

19. What percentage, on average in 2015 for the Kamuzu Central Hospital network, of drivers' time is allocated to transporting samples (as opposed to administrative tasks, vehicle maintenance, etc.)?

20. Are there other factors that could contribute to costs associated with sample transport not included on this survey? Please explain.

Results transportation logistics

21. Which of the options below best describe the routes used to deliver **results** from DBS to health centers from Kamuzu District Hospital. Please check all boxes that apply by clicking on the box next to the applicable options and provide additional details about the transportation routes in the fields below each option.

☐ Results are delivered on the same trips and along the same routes used for picking up samples. That is, a driver transports results ***only*** when they are going to a health center to pick up samples. Drivers ***never*** transport results unless they are going to a health center pick up samples on regularly scheduled trips.

☐ Results are ***usually*** delivered during the same trips and along the same routes used for picking up samples, but sometimes, drivers make additional trips to deliver results. *If this is the case, please describe how often these trips are made (how many times per week or month, as appropriate) and what routes are used (is only one health center visited or do the drivers complete a loop to deliver results to multiple health centers in one trip?).*

☐ Results are ***never*** delivered during the same trips used for picking up samples. Drivers make completely separate trips to deliver results using different routes. *If this is the case, please describe how often these trips are made (how many times per week or month, as appropriate) and what routes are used (is only one health center visited or do the drivers complete a loop to deliver results to multiple health centers in one trip?).*

22. **If drivers sometimes or always use different routes to deliver results than the routes used to pick up samples,** please list all the routes used to transport results to health centers from the Kamuzu Central Hospital in 2015. For each health center, please provide the following information in the table below or, if this information is compiled in other sources, provide these sources to the Country Director:
    a. Frequency each route is traveled (per week or per month, as appropriate)
    b. The name of each health center on the route, in the order in which they are visited
    c. The time, in minutes, it takes on average to travel from each health center to the next health center on the route
    d. The distance, in kilometers, from each health center to the next health center on the route.

    IF DRIVERS USE THE SAME ROUTES TO BOTH PICK UP SAMPLES *AND* DELIVER RESULT, SKIP THIS QUESTION.

    If you are filling in the table below, please copy and paste this table for each route. Note that the End of the Route should be the same as the origin, if the route in a loop.

Route X	Frequency route is used (number of times per week or month):		
	Health Center Name	Time to next stop (minutes)	Distance to next stop (km)
Origin:			
Stop 1:			
…			
End of Route		N/A	N/A

23. Provide number of results sent to each health center from Kamuzu Central Hospital each month via Riders for Health transport in 2015.

Health Center Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec

24. Are results sent by Riders for Health to all health centers from which Riders for Health collects DBS?

    ☐Yes, Riders for Health distributes results to all health centers from which it collects DBS.

    ☐No, Riders for Health only distributes results to health centers that do not have SMS printers because those health centers do not need to receive paper results

    ☐No, Riders for Health does not distribute results to all health centers for other reasons (please specify below)

Appendix E – Routes and Schedules

Scenario 1: EID Transportation via Loops

The motorcycle routes used in Scenario 1 were based on information about the schedules and routes gathered through structured surveys with local transportation providers. Volumes of EID samples were provided by Unicef. All samples are batched at Bwaila DHO, and then transported approximately once a day to Kamuzu Central Hospital, along with the samples generating at Bwaila DHO. Most SDPs are visited on multiple routes.

Routes for Motorcycle Loops

Route	SDPs per trip[20]	Trips per week	KM per trip	Avg. EID per trip
1	8	1	251	4.7
2	3	1	137	2.8
3	9	1	189	3.7
4	8	2	160	5.6
5	5	1	112	2.4
6	10	1	278	18.7
7	7	1	138	2.7
8	13	1	235	15.8
9	5	1	114	2.0
10	5	1	102	4.7
11	5	2	164	1.4
12	7	1	135	4.7
13	8	1	110	11.4
14[21]	2	5	8	14.1
15	2	1	100	1.1

Transportation routes for UAVs to SDPs in scenario 1 were developed as loops, in which a UAV visits multiple SDPs to collect samples and distribute results before returning to the origin to drop off the DBS collected. The UAS is based at KCH, and all loops originate and end at that location. There is no batching location in this model, but Bwaila DHO is the last visited location on each loop since it produces more DBS than other locations, and it is likely desirable to collect the majority of samples later in the flight to reduce risk of damage during transport.

The same subset of SDPs was used in these routes as in the motorcycle scenarios, however, the routes are different in order to accommodate the constraints on the UAS. All SDPs can be visited under the constraints on four routes using two UAVs.

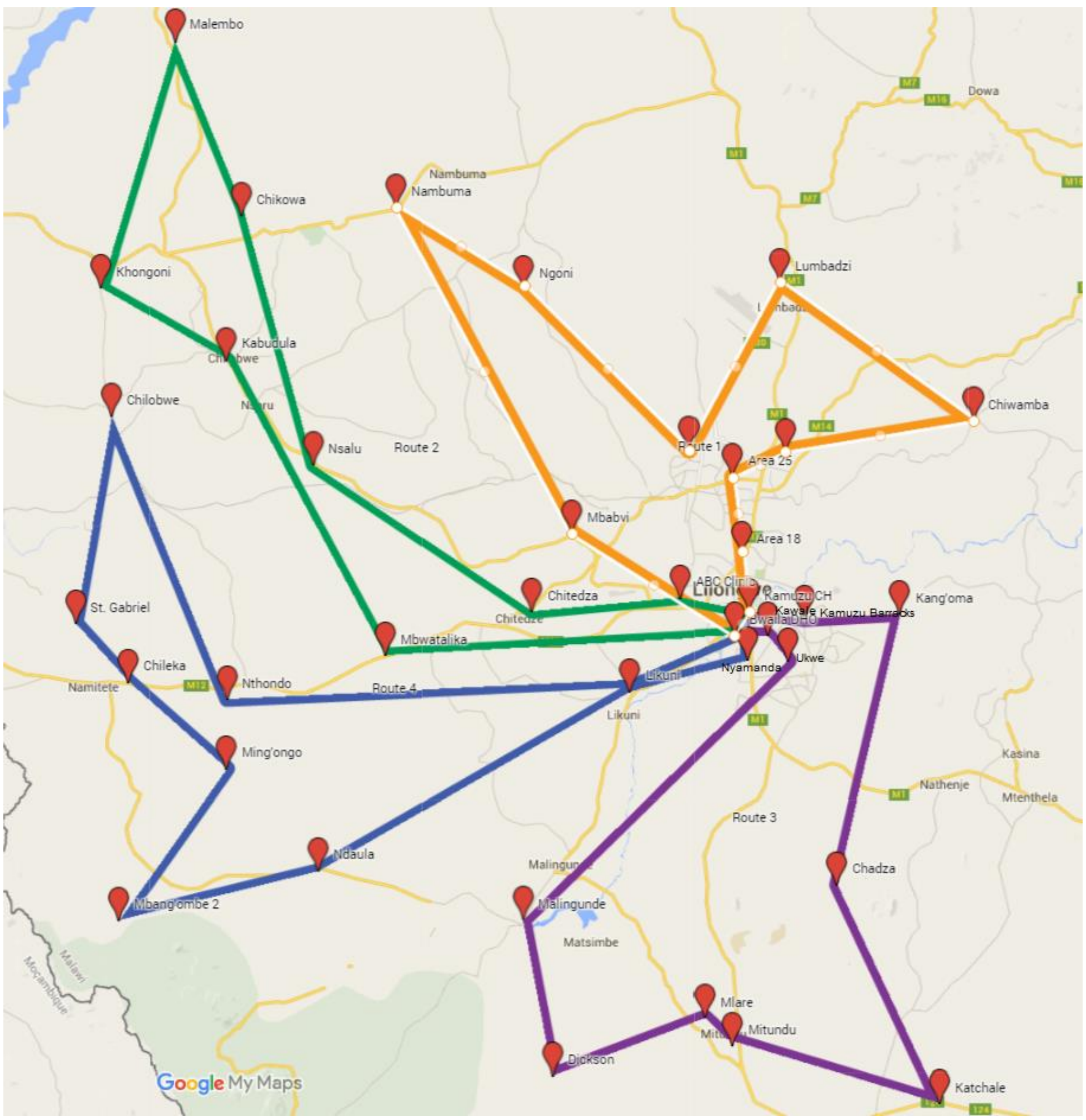
[20] Total number of SDPs visited on the route, including SDPs that do not send EID and/or VL DBS to KCH
[21] This route provides transportation from Bwaila DHO to Kamuzu CH, which serves at the batching location for sample transportation to Kamuzu CH as well as producing a high volume of DBS itself.

It is important to note that these routes are not optimized for cost-effectiveness or any other factor. They represent one possible and feasible option for transportation for the sake of this analysis.

Routes for UAS Loops

Route	# SDPs	Trips per week	KM per trip	Time per trip	Avg. EID per trip
1	10	2	121	299	24.9
2	9	2	142	316	12.1
3	11	2	118	310	19.4
4	11	2	149	356	15.7

Map of UAS Loops



Scenario 2: VL and EID Transportation via Loops

In Scenario 2, both motorcycles and UAVs use the same routes as in Scenario 1, but collect VL DBS in addition to EIDs. The motorcycles could travel the exact same schedule, since their payload boxes had no practical limit. However, the UAVs had to make many more trips to accommodate the additional volume of samples.

Routes for Motorcycle Loops

Route	SDPs per trip[22]	Trips per week	KM per trip	Avg. DBS per trip
1	8	1	251	87.4
2	3	1	137	58.3
3	9	1	189	84.1
4	8	2	160	117.5
5	5	1	112	85.4
6	10	1	278	433.8
7	7	1	138	99.1
8	13	1	235	412.0
9	5	1	114	42.5
10	5	1	102	127.7
11	5	2	164	28.6
12	7	1	135	134.4
13	8	1	110	249.2
14[23]	2	5	8	260.4
15	2	1	100	20.8

Routes for UAS Loops

Route	# SDPs	Trips per week	KM per trip	Time per trip	Avg. DBS per trip
1	10	18	121	299	1060.2
2	9	11	142	316	629.1
3	11	16	118	310	959.0
4	11	16	149	356	918.1

[22] Total number of SDPs visited on the route, including SDPs that do not send EID and/or VL DBS to KCH

[23] This route provides transportation from Bwaila DHO to Kamuzu CH, which serves at the batching location for sample transportation to Kamuzu CH as well as producing a high volume of DBS itself.

Scenario 3: EID Transportation via Hub and Spoke Routes

In Scenario 3, vehicles go directly to each SDP, collect samples, and return to the laboratory. Each SDP is visited twice a week.

Details for Hub and Spoke Transport of EIDs

Stop	Moto. Round Trip (KM)	Moto. Round Trip Time (min)	UAV Round Trip (KM)	UAV Round Trip Time (min)	Avg. EID per Trip
Bwaila DHO	5.9	13.1	3.9	20.8	28.1
Kawale	6.4	14.2	4.2	21.2	7.1
Nyamanda	10.3	22.9	6.8	25.1	0.2
Kamuzu Barracks	11.7	26.0	7.7	26.4	0.3
Area 18	12.1	27.0	8.0	26.9	4.3
Ukwe	13.2	29.3	8.7	27.9	0.2
ABC Clinic	14.7	32.7	9.7	29.4	0.6
Area 25	28.8	64.1	19.0	43.1	7.1
Likuni	30.3	67.4	20.0	44.6	4.1
Katchale	31.7	70.5	20.9	46.0	0.2
Daeyang	34.6	76.9	22.8	48.8	2.6
Dzenza	36.1	80.2	23.8	50.3	0.4
Mbabvi	41.0	91.0	27.0	55.0	0.5
Chitedza	45.8	101.8	30.2	59.7	1.3
Chadza	60.5	134.5	39.9	74.1	0.3
Chiwamba	62.0	137.9	40.9	75.6	0.3
Lumbadzi	69.8	155.1	46.0	83.1	2.1
Mbwatalika	75.9	168.6	50.0	89.1	0.2
Weekly Total (2 trips per week)	**5140**	**1313**	**779.0**	**1694**	**119.9**

Scenario 4: VL and EID Transportation via Hub and Spoke Routes

In Scenario 3, vehicles go directly to each SDP, collect samples, and return to the laboratory. Each SDP is visited at least twice a week; UAVs must visit some SDPs more often if the volume of DBS exceeds the maximum payload capacity.

Details for Hub and Spoke Transport of VL and EIDs

Stop	Moto. Round Trip (KM)	Moto. Round Trip Time (min)	UAV Round Trip (KM)	UAV Round Trip Time (min)	Avg. DBS per Trip	UAS trips per week
Bwaila DHO	5.9	13.1	3.9	20.8	59.1	23.0
Kawale	6.4	14.2	4.2	21.2	52.5	4.0
Nyamanda	10.3	22.9	6.8	25.1	2.3	2.0
Kamuzu Barracks	11.7	26.0	7.7	26.4	45.6	2.0
Area 18	12.1	27.0	8.0	26.9	49.0	4.0
Ukwe	13.2	29.3	8.7	27.9	6.7	2.0
ABC Clinic	14.7	32.7	9.7	29.4	43.0	2.0
Area 25	28.8	64.1	19.0	43.1	54.7	5.0

Likuni	30.3	67.4	20.0	44.6	49.1	5.0
Katchale	31.7	70.5	20.9	46.0	7.0	2.0
Daeyang	34.6	76.9	22.8	48.8	49.6	2.0
Dzenza	36.1	80.2	23.8	50.3	9.2	2.0
Mbabvi	41.0	91.0	27.0	55.0	8.1	2.0
Chitedza	45.8	101.8	30.2	59.7	19.1	2.0
Chadza	60.5	134.5	39.9	74.1	8.3	2.0
Chiwamba	62.0	137.9	40.9	75.6	13.8	2.0
Lumbadzi	69.8	155.1	46.0	83.1	33.4	2.0
Mbwatalika	75.9	168.6	50.0	89.1	10.5	2.0
WeeklyTotal	**5140**	**1313**	**1002.3**	**2489.9**		**67**

Appendix F – Sources for Cost Inputs

Data sources for motorcycle scenarios

Data Element	Source
Node information	
Number and location of all nodes (laboratory and SDPs)	Document review (Unicef documentation), Structured Survey (local transportation provider)
Routes and schedule for transportation of samples/results to/from each node	Structured Survey (local transportation provider)
Kilometers traveled per month based on transportation routes	Structured Survey (local transportation provider)
Volume of DBS for EID and VL testing for each SDP per month, as a percentage of total payload volume[24]	Key informant interview (Unicef), Structured Survey (local transportation provider)
Vehicle costs and characteristics	
Vehicle range[25]	Structured Survey (local transportation provider)
Payload capacity for DBS	Structured Survey (local transportation provider)
Number of vehicles needed to cover routes	Structured Survey (local transportation provider)
Vehicle base costs	Structured Survey (local transportation provider), Key informant interviews
Other equipment costs	Market survey
Discount rate for depreciation	Document review (Malawi Comprehensive Multi-year Plan)
Expected useful lifetime	Document review (Malawi Comprehensive Multi-year Plan)
Vehicle insurance costs per month	Key informant interviews
Fuel costs[26] per kilometer	Market survey, Key informant interviews
Routine maintenance costs per kilometer, including parts and labor	Market survey, Key informant interviews
Personnel costs	
Number of personnel dedicated to transportation	Structured survey (local transportation provider)
Salaries for personnel involved in transport of DBS	Key informant interviews
Per diem for personnel involved in transport of DBS	Key informant interviews
Initial training costs	Key informant interviews

[24] Monthly payload volume for EID and VL samples and results for each SDP were estimated using UNICEF's forecasts for 2015.
[25] Flight distance before the battery must be changed, only applicable to UAVs
[26] For motorcycles, the fuel input is liters of petrol per kilometer. For UAVs, "fuel" is considered the electricity to charge the battery, in kilowatt-hours per kilometer.

Data sources for UAS scenarios

Data Element	Source
Node information	
Number and location of all nodes (laboratory and SDPs)	Document review (Unicef documentation), Structured Survey (local transportation provider)
Routes and schedule for transportation of samples/results to/from each node	Informed by structured survey (UAV supplier), routes developed based on constraints detailed in scenarios section
Kilometers traveled per month based on transportation routes	Informed by structured survey (UAV supplier), routes developed based on constraints detailed in scenarios section)
Volume of DBS for EID and VL testing for each SDP per month, as a percentage of total payload volume[27]	Key informant interview (Unicef), Structured survey (UAV supplier)
Vehicle costs and characteristics	
Vehicle range[28]	Structured survey (UAV supplier)
Payload capacity for DBS	Structured survey (UAV supplier)
Number of vehicles needed to cover routes	Structured survey (UAV supplier)
Vehicle base costs	Structured survey (UAV supplier)
Other equipment costs	Structured survey (UAV supplier)
Discount rate for depreciation	Structured survey (UAV supplier)
Expected useful lifetime	Structured survey (UAV supplier)
Vehicle insurance costs per month	Structured survey (UAV supplier)
Fuel costs[29] per kilometer	Market survey, Structured survey (UAV supplier)
Routine maintenance costs per kilometer, including parts and labor	Structured survey (UAV supplier)
Personnel costs	
Number of personnel dedicated to transportation	Structured survey (UAV supplier)
Salaries for personnel involved in transport of DBS	Key informant interviews
Per diem for personnel involved in transport of DBS	Key informant interviews
Initial training costs	Structured survey (UAV supplier)

[27] Monthly payload volume for EID and VL samples and results for each SDP were estimated using UNICEF's forecasts for 2015.
[28] Flight distance before the battery must be changed, only applicable to UAVs
[29] For motorcycles, the fuel input is liters of petrol per kilometer. For UAVs, "fuel" is considered the electricity to charge the battery, in kilowatt-hours per kilometer, plus the data needed to navigate the UAV using the smartphone application, in bytes per kilometer.