Vaccine 34 (2016) 4062–4067

Contents lists available at ScienceDirect

Vaccine

journal homepage: www.elsevier.com/locate/vaccine

The economic and operational value of using drones to transport vaccines

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ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form 24 May 2016
Accepted 3 June 2016
Available online 20 June 2016

Keywords:
Immunization
UAV
Simulation modeling

ABSTRACT

Background: Immunization programs in low and middle income countries (LMICs) face numerous challenges in getting life-saving vaccines to the people who need them. As unmanned aerial vehicle (UAV) technology has progressed in recent years, potential use cases for UAVs have proliferated due to their ability to traverse difficult terrains, reduce labor, and replace fleets of vehicles that require costly maintenance.

Methods: Using a HERMES-generated simulation model, we performed sensitivity analyses to assess the impact of using an unmanned aerial system (UAS) for routine vaccine distribution under a range of circumstances reflecting variations in geography, population, road conditions, and vaccine schedules. We also identified the UAV payload and UAS costs necessary for a UAS to be favorable over a traditional multi-tiered land transport system (TMLTS).

Results: Implementing the UAS in the baseline scenario improved vaccine availability (96% versus 94%) and produced logistics cost savings of \$0.08 per dose administered as compared to the TMLTS. The UAS maintained cost savings in all sensitivity analyses, ranging from \$0.05 to \$0.21 per dose administered. The minimum UAV payloads necessary to achieve cost savings over the TMLTS, for the various vaccine schedules and UAS costs and lifetimes tested, were substantially smaller (up to 0.40 L) than the currently assumed UAV payload of 1.5 L. Similarly, the maximum UAS costs that could achieve savings over the TMLTS were greater than the currently assumed costs under realistic flight conditions.

Conclusion: Implementing a UAS could increase vaccine availability and decrease costs in a wide range of settings and circumstances if the drones are used frequently enough to overcome the capital costs of installing and maintaining the system. Our computational model showed that major drivers of costs savings from using UAS are road speed of traditional land vehicles, the number of people needing to be vaccinated, and the distance that needs to be traveled.

1. Introduction

Immunization programs in low and middle income countries (LMICs) face numerous challenges in getting life-saving vaccines to the people who need them. After entering a country, vaccine vials typically travel by road through two to four storage locations before arriving at clinics where health workers administer doses to patients [1]. Non-vaccine costs of routine immunization systems are expected to rise by 80% between 2010 and 2020, with more than one-third of these costs attributable to supply chain logistics [2]. Supply chain bottlenecks and inefficiencies can cause vaccines to spoil and valuable resources to be wasted before vaccines reach the people who need them, suggesting a need for innovative and lower cost methods for distribution. As non-military unmanned aerial vehicle (UAV) technology has advanced in recent years, interest in potential humanitarian and development use cases for UAVs have proliferated due to their ability to traverse difficult terrains, reduce labor, and replace fleets of vehicles. UAVs have already been successfully deployed for surveillance and aid

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http://dx.doi.org/10.1016/j.vaccine.2016.06.022
0264-410X/© 2016 Published by Elsevier Ltd.

delivery in humanitarian sectors and commercial systems are currently being developed to transport medical samples and supplies, including vaccines [3–5].

Despite this growing interest, limited evidence is available regarding the impact of UAVs for routine delivery of medical supplies. As with any new technology, the costs of purchasing, maintaining, and operating UAVs and their supporting launch/recovery and maintenance infrastructure – collectively called an unmanned aerial system (UAS) – may be prohibitive. The limited carrying capacity and required flight conditions of UAVs may also pose significant obstacles. Determining whether a UAS would be beneficial to an immunization program is difficult without a model to forecast supply chain performance and costs. We used simulation modeling to assess the impact of using a UAS for vaccine distribution under a range of circumstances and to identify the necessary conditions for a UAS to be favorable over traditional land-based transport.

2. Methods

2.1. HERMES models of Gaza province, Mozambique vaccine supply chain

Our team used our HERMES (Highly Extensible Resource for Modeling Event-driven Supply Chains) software platform, described in previous publications [6,7], to develop a discrete-event simulation model of the World Health Organization (WHO) Expanded Program on Immunization (EPI) supply chain in Gaza, a province in southern Mozambique with a 2015 population of 1,416,810 [8]. This HERMES model includes virtual representations of each vaccine vial, facility, storage equipment, transport device, route, and personnel in the supply chain. Vaccines flow according to ordering and shipping policies in an attempt to meet the anticipated demand at each immunization location. The model includes characteristics of the vaccines in the 2015 EPI schedule, as well as new and upcoming vaccine introductions, summarized in Table 1.

The traditional multi-tiered land transport system (TMLTS) for distributing vaccines throughout Gaza consists of three tiers (Fig. 1A). One provincial store picks up vaccines from the national warehouse quarterly using a 4 × 4 truck (taking additional trips as needed, due to limited cold storage and transport capacity) and delivers monthly to 12 district stores. Districts distribute vaccines to 123 health centers each month using a combination of pick-up truck or motorbike deliveries and health workers traveling via public transit to pick up vaccines. Health workers administer vaccines to the population at each health center.

One commercial UAS currently under development for the distribution of medical samples and health products utilizes fixed-wing, battery powered vehicles and fixed hubs for vaccine storage and the launching, recovery, storage, and maintenance of UAVs. We modeled a potential implementation of this system in Gaza province (Fig. 1B) in which the provincial store delivers vaccines monthly to three UAS hubs supplying the 106 health centers in southern Gaza via UAV shipments on an as-needed basis to meet population demand. Modeling scenarios assumed that each UAV can carry 1.5 L of vaccines to a health center as far as 75 km from its hub, a range and payload well within currently available UAV specifications (for example, Wings for Aid offers a UAV that can carry up to 100 kg with a range of 500 km) [9,10]. Because northern Gaza has a much lower population density which would require a relatively large number of hubs to supply a small number of health centers, we included the TMLTS in the northern region where 3 district stores would supply 17 health centers.

The above systems provided a baseline comparison between the TMLTS and a realistic UAS implementation – alongside the TMLTS in the north – to serve the entire province of Gaza. To account for other possible current and future UAVs, sensitivity analyses varied baseline characteristics of the UAS as well as the environment, population, and vaccine schedule and aimed to identify necessary conditions for the UAS to be advantageous. For a direct comparison between the TMLTS and a supply chain using the UAS throughout, these experiments studied a subset of the locations in the Gaza vaccine supply chain which included only the provincial store and locations within its 75 km radius. For the TMLTS (Fig. 1C), the provincial store distributes vaccines to 7 district stores which supply 69 health centers. The UAS implementation (Fig. 1D) co-locates one hub with the provincial store to deliver vaccines to the 69 health centers via UAVs.

2.2. Experiments

To compare the UAS with the TMLTS in the baseline scenario and the $\leqslant 75$ km subset, we calculated vaccine availability using the following formula:

$$\text{Vaccine availability} = \text{Number of people receiving vaccines} \div \text{Number of people arriving at health centers for immunization}$$

Another supply chain performance metric comparing the systems was the logistics cost per dose administered:

$$\text{Logistics cost per dose administered} = \text{Annual logistics costs} \div \text{Annual vaccine doses administered}$$

Logistics costs included storage (storage equipment maintenance, energy, and amortization), transport (driver per diems and vehicle maintenance, fuel/electricity, and amortization), buildings (infrastructure overhead and amortization at storage and

Table 1
Characteristics of EPI and introductory vaccines in Mozambique.

	Presentation	Doses per person	Doses per vial	Vaccine packed volume per dose (cm^3)	Diluent packed volume per dose (cm^3)
Current EPI vaccines					
Bacille Calmette-Guérin tuberculosis (BCG)	Lyophilized	1	20	1.2	0.7
Diphtheria-tetanus-pertussis-haemophilus influenza type B-hepatitis B (Pentavalent)	Liquid	3	10	2.6	n/a
Measles (M)	Lyophilized	1[a]	10	3.5	4.0
Oral polio (OPV)	Liquid	4	10	2.0	n/a
Pneumococcal conjugate (PCV)	Liquid	3	2	4.8	n/a
Tetanus toxoid (TT)	Liquid	2	10	3.0	n/a
Introductory vaccines					
Rotavirus (RV)	Liquid	2	1	17.1	n/a
Inactivated polio (IPV)	Liquid	1	10	4.8	n/a
Human papillomavirus (HPV)	Liquid	2	2	2.46	n/a

[a] A second dose of measles vaccine (MSD) is included as an introduction.

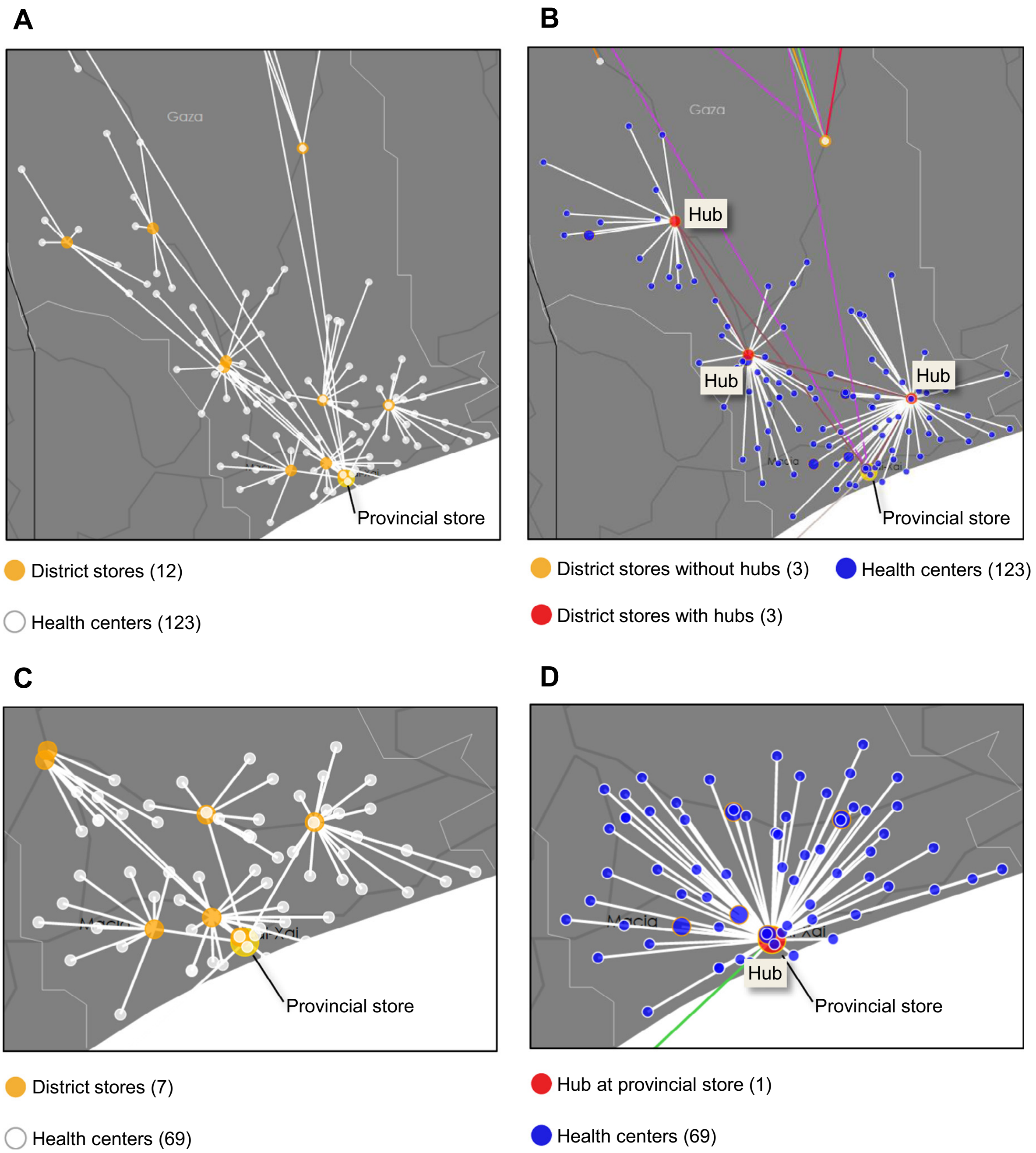

Fig. 1. HERMES visualizations of TMLTS and UAS modeled in Gaza province. (A) TMLTS in Gaza province (southern region shown), (B) UAS in southern Gaza province (with TMLTS supplying northern health centers, not shown), (C) TMLTS in ⩽75 km subset locations, (D) UAS in ⩽75 km subset locations.

immunization locations), and labor (personnel wages for time dedicated to supply chain logistics) and are defined in detail in a previous publication [11].

We also calculated the cost savings of the UAS over the TMLTS:

$$\begin{aligned}&\text{UAS cost savings per dose administered}\\&\quad=\text{Logistics cost per dose administered}_{\text{TMLTS}}\\&\qquad-\text{Logistics cost per dose administered}_{\text{UAS}}\end{aligned}$$

Sensitivity analyses using the ⩽75 km subset locations varied the following factors:

- *Population: throughput* varied the population served by all health centers from 50% to 200% of the current population.
- *Population: distribution* placed as much as 90% of the total population at three urban centers and, at the other extreme, evenly distributed the population across all health centers.
- *Geography: road speed* varied the average speed of TMLTS vehicles from 5 km/h to 100 km/h.
- *Geography: road distance* varied travel distances for TMLTS routes from 50% to 200%.
- *Seasonality*, leading to impassable roads, caused up to 80% of health centers to be unreachable by TMLTS for four months annually.
- *Vaccine introductions* added rotavirus (RV), inactivated polio (IPV), human papillomavirus (HPV), and a second dose of measles (MSD) vaccines to the 2015 EPI schedule.

Additionally, we identified cost savings thresholds (i.e. tipping points at which the UAS ceases to achieve cost savings over the TMLTS) for the following UAS characteristics, both under the 2015 EPI schedule and after vaccine introductions:

- *Payload* is the maximum volume of vaccines each UAV can carry in a single shipment. While the above analyses used estimates for UAS costs and useful lifetimes for production at scale, we identified the payload threshold under both at-scale and current cost/lifetime estimates, for both vaccine schedules considered.
- *Cost per UAV round trip and annual hub cost* include the costs of energy, amortization, and maintenance. We identified cost thresholds under both vaccine schedules with no flight delays, as well as with each flight having a 50% probability of a delay lasting between one and four weeks.

3. Results

3.1. Baseline scenario

In the baseline scenario, implementing the UAS improved vaccine availability (96% versus 94% for a 2% increase) and reduced costs ($0.33 (2015 USD) versus $0.41 per dose administered for cost savings of $0.08 per dose administered) as compared to the TMLTS. Vaccine availability improved due to the UAS relieving transport bottlenecks in several routes supplying health centers. These bottlenecks arose in the TMLTS where vaccine carriers lacked sufficient capacity to hold a one-month supply for health centers; UAV shipments were able to occur more frequently and were thereby able to distribute the necessary quantities of vaccines. The UAS offered cost savings through lower transport, per diem, and labor costs that offset the additional hub infrastructure costs.

Results were heterogeneous across the province, and comparing the TMLTS to the UAS in individual regions revealed that one of the UAS hubs did not produce cost savings over the TMLTS in the area it served, instead raising logistics costs by $0.11 per dose administered. Of the three hubs, this location served the smallest total population, with the lowest average number of patients per health center. The TMLTS was therefore able to effectively supply the region via monthly shipments, while the UAS hub was not sufficiently utilized for its lower per-trip costs to offset its higher annual infrastructure costs.

3.2. ⩽75 km subset scenarios

These findings were fairly robust to sensitivity analyses. In fact, the benefits of the UAS increased with certain variations on each parameter, with the exception of vaccine introductions. For the ⩽75 km subset locations, implementing the UAS raised vaccine availability to 100% (versus 97%) and produced cost savings of $0.08 per dose administered ($0.22 versus $0.31) as compared to the TMLTS, and the UAS maintained cost savings in all sensitivity analyses performed (summarized in Fig. 2). Varying road speed had the greatest impact and only improved the cost savings offered by the UAS. Raising the average road speed from the baseline of 59 km/h to 100 km/h had no effect on cost savings, while reducing road speed to 5 km/h raised the cost savings per dose administered to $0.21. Population throughput produced the second-greatest effect and was able to both raise and decrease the cost savings achieved. A 100% increase in the average birth cohort (from a baseline of 360 newborns annually to 720 newborns) decreased cost savings of the UAS to $0.05 per dose administered, while a 50% reduction (to 180 newborns annually) raised cost savings to $0.16.

Varying road distance was also able to both raise and decrease UAS cost savings, yielding the third-greatest impact. Raising the average one-way distance of all routes from a baseline of 77 km to 154 km raised cost savings of the UAS to $0.14, and reducing the average distance to 39 km decreased cost savings to $0.06 per dose administered. Distributing the existing population evenly across all health centers had no effect on cost savings, while placing 70% of the population at three urban centers raised cost savings of the UAS to $0.12 per dose administered. Seasonality causing 80% of health centers to be unreachable by land transport for four months annually also raised UAS cost savings to $0.12 per dose administered. Finally, introducing RV, IPV, HPV, and MSD to the EPI schedule slightly decreased cost savings by <$0.01 per dose administered.

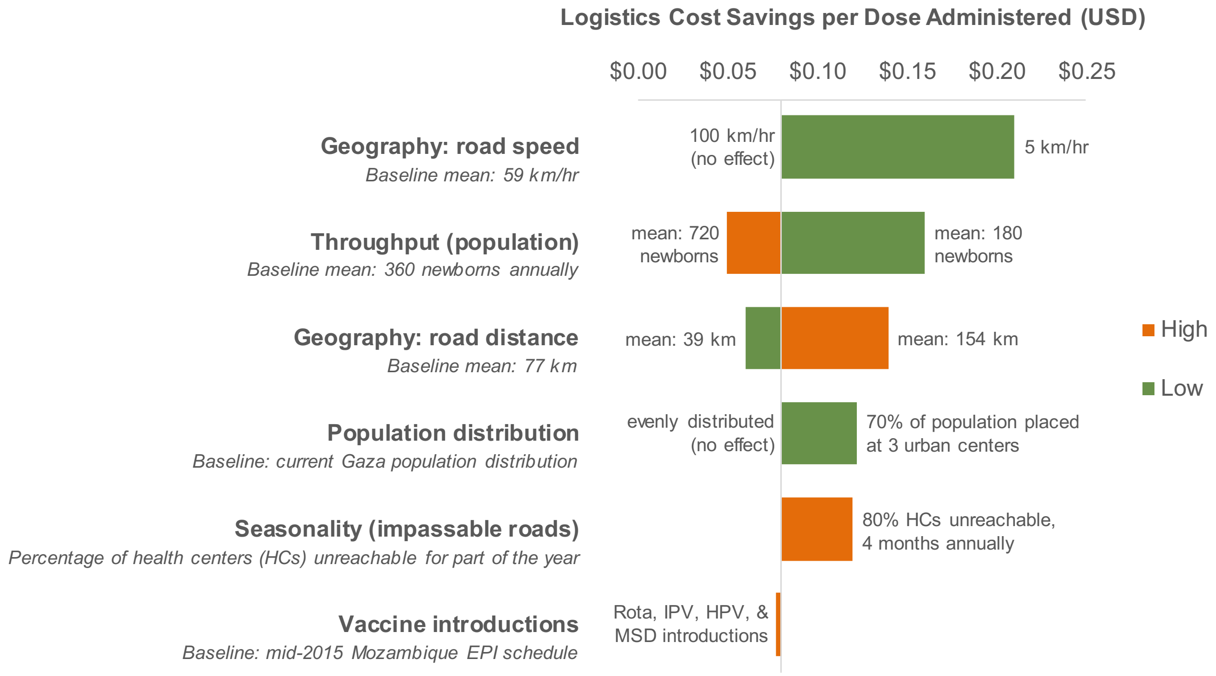

Fig. 2. Tornado diagram of UAS cost savings under varying conditions.

3.3. Cost savings thresholds

The minimum UAV payloads necessary to achieve cost savings over the TMLTS, for the various vaccine schedules and UAS costs and lifetimes tested, were substantially smaller than the currently assumed UAV payload of 1.5 L. In order to achieve cost savings over the TMLTS, each UAV was required to have a payload of at least 0.15 L for the baseline EPI schedule and 0.20 L after RV, IPV, HPV, and MSD were introduced, assuming at-scale estimates for UAS costs and useful lifetimes. Using current estimates, the minimum payload to achieve cost savings was 0.20 L under the baseline EPI schedule and 0.40 L after vaccine introductions.

Similarly, the maximum UAS costs that could achieve savings over the TMLTS were greater than the currently assumed costs under realistic flight conditions. Fig. 3 displays cost thresholds at which the UAS was no longer cost saving. Without flight delays, each UAV was required to cost less than $8.93 per round trip and each hub needed to cost under $60,120 per year (for energy, amortization, and maintenance) in order to achieve cost savings over the TMLTS under the baseline EPI schedule. When each flight had a 50% probability of being delayed by approximately two weeks, these thresholds were reduced to $7.09 per UAV round trip and $45,090 annually at each hub. A 50% chance of four-week flight delays further reduced the UAV round trip cost threshold to $2.43 and the annual hub cost threshold to $7014.

Introducing RV, IPV, HPV, and MSD reduced each of the above cost thresholds by $0.61 per UAV round trip and $5,010 per year for the hub cost, under delays lasting up to two weeks (Fig. 3). For three-week delays, vaccine introductions lowered the baseline EPI threshold by $1.23 per UAV round trip and $10,020 annually at each hub. The UAS was unable to achieve cost savings over the TMLTS if each flight had a 50% probability of being delayed by at least four weeks, regardless of the UAV and hub costs, due to low vaccine availability.

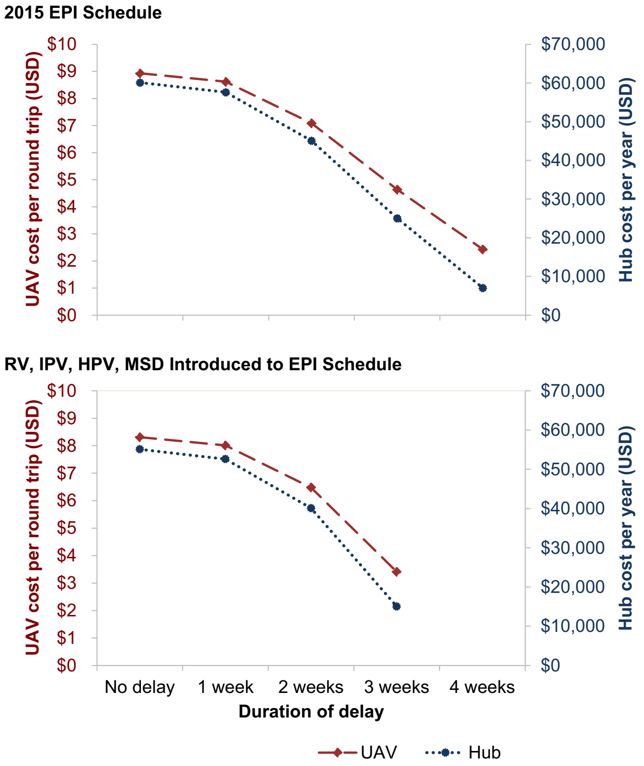

Fig. 3. UAS cost thresholds under varying flight delays and vaccine schedules. Maximum costs (including energy, amortization, and maintenance) of UAVs and hubs, for UAS to produce cost savings over TMLTS. Each UAV flight has a 50% probability of delay. The UAS was unable to achieve cost savings in the scenario with four-week delays after vaccine introductions.

4. Discussion

In addition to improving supply chain performance, the UAS reduced the logistics cost per dose administered by approximately 20% in the baseline comparison. Savings in UAS transport, per diem, and labor costs offset the additional hub infrastructure costs, however, heterogeneity in cost savings among the individual hubs suggests a tailored approach is needed as hub infrastructure costs become prohibitive when insufficiently utilized. UAS cost savings remained robust to a set of sensitivity analyses in the ⩽75 km subset locations. Where TMLTS routes required long travel times or distances, UAS cost savings rose substantially. Reducing either the size of the population served or the homogeneity of its distribution across health centers also raised UAS cost savings. Vaccine introductions had little effect on UAS cost savings but led to stricter requirements for the UAV payload, as well as hub and UAV costs. Even with vaccine introductions, the payload thresholds remained well below the baseline 1.5 L. Similarly, because flight delays of greater than two weeks are unlikely to occur in reality, the assumed UAS costs are below the thresholds given realistic durations of delay. Certain UAVs currently available for medical goods distribution, which can cost approximately the same per trip as a motorbike [12], would meet these thresholds as well. Thus, in extensive sensitivity analyses representing a variety of potential UAS in a wide range of settings and circumstances, the UAS appeared to be able to increase vaccine availability and decrease costs, as compared to the TMLTS.

UAVs are currently under development for a variety of uses in health and medicine, including routine deliveries in difficult to access areas and temporary efforts during emergencies. Flirtey has used UAVs to deliver medical supplies to rural areas of Virginia [13], Matternet has tested UAVs for medical supply distribution in Bhutan [14] and Papua New-Guinea [15], Zipline (formerly Stork) has proposed UAVs to transport blood and essential medications in Tanzania [16], UNICEF is testing the feasibility of UAVs to transport lab samples in Malawi [17], and Delft University of Technology has tested UAVs to deliver defibrillators after cardiac arrest in the Netherlands [18]. Studies have also proposed UAVs for routine transport of blood samples in the United States [19,20]. UAViators, a network to coordinate the use of UAVs in humanitarian settings, lists case studies of UAV use in two dozen countries including disaster surveillance, search and rescue operations, risk factor mapping, and supply delivery following earthquakes [21].

While a UAS may be more effective and efficient than a TMLTS in many supply chains, it may also present unique challenges in implementation and operation. Regulatory issues have limited the ability of UAS to successfully deliver goods and commodities [22,23]. Community perception and acceptance of medical products flown by UAV may limit long-term viability. Maintaining and operating UAS equipment would require specialized tools and skills that may be difficult to access in LMICs. A person would not accompany a UAS shipment, necessitating greater coordination between personnel across locations. The UAS modeled requires levels of cellular, radio, and internet coverage which may be a limitation in remote areas. Appropriate packing to maintain vaccine quality still requires testing in operational conditions.

Modeling can not only determine whether a particular UAS could be advantageous in a given setting but may also help guide the development of any UAS to ensure that it will be broadly applicable in a wide range of settings. Our findings indicate that vaccine supply chains may benefit from a UAS, under the right conditions. Future modeling work can further help to identify primary cost drivers and circumstances under which a UAS would provide the greatest efficiencies and ultimately assist in developing a target product profile (TPP) to guide UAS development, investment, and implementation.

5. Limitations

By definition, models are simplified representations and cannot incorporate all aspects of a system. The commercial UAS industry targeting the development sector is immature and limited data are available on operational costs at scale in environments like the one modeled. Our baseline scenario used currently publicly available UAS characteristics [4,9,10,12]; however, to account for the range of possible UAS characteristics, we conducted extensive sensitivity analyses and aimed to find the thresholds at which a UAS would become cost saving. Our sensitivity analyses may not cover all possible values of each parameter studied, and it is possible that factors not included in this study may significantly impact UAS performance and costs. As commercial UAS remain under development for commodity and vaccine distribution, our study assumes that the appropriate technologies can be developed within the costs and operating parameters assumed in this study. A UAS may be prevented from functioning in reality as it would in a simulation due to factors including user error, equipment malfunctions or breakdowns, network outages, and unexpected inclement weather conditions.

6. Conclusion

Implementing a UAS could increase vaccine availability and decrease costs in a wide range of settings and circumstances if the drones are used frequently enough to overcome the capital costs of installing and maintaining the system. Our computational model showed that major drivers of cost savings from using the UAS are road speed of traditional land vehicles, the number of people needing to be vaccinated, and the distance that needs to be traveled. Modeling can help guide UAS development, investment, and implementation.

Acknowledgements

This work was supported by the Bill and Melinda Gates Foundation, the Agency for Healthcare Research and Quality (AHRQ) via grant R01HS023317, the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD), Office of Behavioral and Social Sciences Research (OBSSR) and the Global Obesity Prevention Center (GOPC) via grant U54HD070725 and NICHD via U01HD086861. The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; and preparation, review, or approval of the manuscript.

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