Professional Issues for Engineers 4

Systems Engineering Assignment 2: System Requirements Exercise

COVID-19 Vaccine Delivery System for Remote Villages in Uganda

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1 System Requirements

In this exercise we are considering the **system requirements** of a COVID-19 vaccine delivery system designed to reach remote villages in Uganda, one of the countries supported by the COVAX (COVID-19 Vaccines Global Access) initiative [1]. In order to identify eight key requirements for this system the PESTLE (Political, Economic, Social, Technology, Legal and Environmental) analysis framework was used to compile a list. This was then shortlisted to the requirements in Table 1 below.

Requirement	**Type (Functional, Performance, Operational, Environmental, Cost)**	**Description**	**Specification**	**Principal Stakeholders**
Ability to traverse difficult terrain over long range (50km) and overcome poor weather conditions.	Performance	Method of transportation chosen must be designed for off road travel, narrow tracks, steep hills, shallow water such as swamps and small streams. Heavy jungle. May need to traverse bodies of water (Lake Victoria) to reach isolated island communities [2].	Four Wheel Drive (if applicable), Spare fuel and parts, repairability if damaged, relatively small, durable and robust. Some amphibious capabilities.	Vehicle Manufacturer, Driver, Passengers (if applicable).
Must be a cost effective solution for delivery of the vaccines	Cost	Currently the COVAX organisation helps to deliver vaccines to over 90 developing world countries [1]. A report estimated the cost of delivering vaccines to just 20% of the population of these countries is $2.088 billion [3]. It is clear then why the cost of any delivery mechanism is important.	Use of cheaper vehicles can keep costs down, passive vaccine coolers (which use ice packs) [4] rather than mobile refrigeration units which require a power supply, training less personnel, more fuel efficient means of transport.	COVAX, Developed Countries financing vaccine distribution, WHO, Private Donors, Delivery/ Health care personnel (affects their pay), Ugandan government.
Keep vaccines at a suitable temperature and insulated from damage during transit to reduce waste.	Performance	Vaccine wastage has been estimated by the WHO to be about 22.1% [5]. Most vaccines are only safe for use if kept at a temperature between 2°C and 8°C. Ambient temperature in Uganda is between 8°C and 30°C. The vials also should not break from being transported across rough terrain.	There are various cooling products that can be used. UNICEF supplies passive "Vaccine Carriers" and "Cold Boxes" which are kept cool using ice packs [4]. Newer innovations by private companies include solar powered refrigerators (Vaccibox [6]) or conventional refrigerators which require a power source (battery).	Manufacturers of the various vaccine cooling and transport products, Delivery / health care personnel, WHO, People receiving the vaccine (know it is safe).

Table 1 continued from previous page

Must be able to track vaccine shipments and locate where they are in the delivery chain (traceability).	Functional	Political unrest such as the ADF insurgency, and corruption in Uganda within the public sector means there is reason to believe that vaccines may be stolen or tampered with for personal/ financial gain [7, 8]. Tracking capabilities on the vaccine shipments are important to stop this.	GPS Monitoring devices could be fitted to vaccine carriers as was done in the United States during "operation warp speed" [9].	Public sector officials, criminal organisations, Delivery / Health care personnel, Vaccine companies who can track shipments, People receiving the vaccine (know it has not been tampered with).
Must have the capability to deliver a large volume of vaccines in a day (500 packs)	Functional	Distribution centres should deliver a minimum of 500 packs per day. Each pack contains 10 vials and each vial contains 10 doses (5ml)	Delivery method must be fast and scalable. Must be able to make stops at many different locations. Vaccine carriers must be lightweight to speed up any "last mile" travel on foot to remote areas.	Vaccine companies (Pfizer, Moderna), COVAX, WHO, Delivery/ Health care personnel, People receiving the vaccine (receive it faster).
Health Care and Delivery Personnel delivering the vaccines must be Protected (security).	Operational	Distribution personnel must be adequately protected from catching COVID-19 themselves. They should also be kept as safe as possible from any threat that crime, corruption or violent unrest may pose in certain Ugandan regions.	Adequate PPE must be stored in the vehicle to prevent spreading the disease. For increased safety personnel should not travel alone, always with at least one colleague, transport should have means of carrying passengers.	Delivery/ Health care personnel, PPE manufacturers, criminal organisations.
There must be high levels of public trust in the vaccine delivery system.	Operational	According to several reports, vaccine hesitancy is a problem in Africa [10] due to misinformation propagated online and even by some governments such as the Tanzanian president [11]. It's important that any delivery system has the trust of the community in order to increase uptake of the vaccine.	Ensure that local health care/ delivery personnel known by the community are well trained to administer the vaccine, Campaigns on social media to "debunk" anti-vaccination sentiment.	Delivery/ Health care personnel, COVAX, WHO, People receiving the vaccine.
Must be able to monitor vaccine temperature and whether any damage has been sustained by the vials.	Functional	Personnel need to be able to tell if vaccine contents have been spoiled by being stored at too high a temperature or if damage has occurred to the contents.	Fitting passive vaccine carriers with monitoring technology [12] such as an integrated digital thermometer. Vaccine vial monitors which check the heat exposure of individual vials as recommended by the WHO effective vaccine management strategy (EVM).	Delivery/ Health care personnel, manufacturers of monitoring equipment, WHO, COVAX.

Table 1: System Requirements for COVID-19 Vaccine Delivery System to Rural Ugandan Villages

2 Technology Solutions

2.1 List the technologies that could fulfill the requirements in Section 1.

A list of the possible technologies that could be used to fulfill the system requirements is given below:

- Refrigerated Trucks - These are able to transport vaccines in bulk across long distances (> 50km), and keep them at the right temperature. Their size may make travel across Uganda's terrain difficult. Five trucks were procured by UNICEF for Uganda's health service in September 2021. The use of cold trucks improved the efficiency of vaccine delivery from 54% to 96% [13].
- Motorbikes ("Boda-Bodas") - UNICEF provides Motorbikes in Uganda that can be used to deliver COVID-19 vaccines [4]. They can carry an additional passenger. A cold storage "Vaccine Carrier" with a capacity between $1 - 2$ litres can be mounted on the bike [14].
- Quad Bikes - Similar to motorbikes, but can have four wheel drive, easier to travel on some terrain, can carry larger vaccine carriers such as a "Cold Box" with capacity between $5 - 15$ litres or solar powered refrigerator such as the "Vaccibox" with a 40 litre capacity [14, 6].
- Seaplanes - Can be used to access isolated island communities in Lake Victoria [2], landing on the sea. Large capacity for vaccine storage. Requires a trained pilot so harder to hire locals. Tricky to find areas to land. Can't travel in bad weather. Not fuel efficient and has an expensive up front cost.
- Animals (Donkeys, Horses) - Donkeys can be used to deliver vaccines as a low cost option, for shorter trips. During times of insecurity they can be useful. As an example in Mali in 2019 motorbikes were banned due to militia groups using them so donkeys were the only alternative [15].
- Four Wheel Drive Jeeps - Jeeps are robust vehicles, unlikely to break down, and can travel off road and through swamps and small streams. Can carry lots of "Cold Boxes", "Vaccine Carriers" and "Vacciboxes" of various capacities. Can also power vaccine refrigerators.
- Helicopters - These have similar aerial advantages/ disadvantages to seaplanes. They are easier to land near to villages, but can't land on the water. Large storage capacity for vaccines and can use the helicopter to power refrigerators.
- Bicycles - Can be used as a low cost alternative to motorbikes for shorter trips [16]. No space for passengers. Can carry a small UNICEF "Vaccine Carrier" ($1 - 2$ litres) to keep vaccines cool [14].
- Speed Boats - Can access areas unreachable by land vehicles. For example, flooded areas due to extreme weather and isolated island communities on Lake Victoria [2, 16]. Plenty of storage in boats for large "Cold Boxes" kept cool with ice packs or solar powered "Vacciboxes".
- Local Banana Boats (Row Boats) - Cheaper alternative to speed boats carved out of tree trunk, local health workers are likely to have access to these boats, similar storage capability but slower.

2.2 Select two of the technologies in the list and explain how they could be deployed in practice.

Many of the technologies above are impractical due to their high cost, for example, while a helicopter or seaplane may be able to avoid harsh terrain and reach remote villages or island communities, the capital expenditure is too prohibitive for the Ugandan health service. The other discarded technologies are low cost but are also slow and lack cold storage such as bicycles and animals. I selected the two most practical and cost effective options for vaccine delivery: a Motorbike and a Four Wheel Drive Jeep

2.2.1 Four Wheel Drive Jeep

The jeeps would be fitted with GPS trackers for traceability and security. The jeep would carry a driver and a trained health worker. Health workers known to the local community would be hired. This will increase public trust in the initiative. In regards to cooling technology there are three main options: passive coolers such as UNICEF "Cool Boxes" which use ice packs [14], solar powered refrigerators or "Vacciboxes" (40 litre capacity) [6]. Finally, jeeps can be fitted with vaccine refrigerators such as the

Toyota Land Cruiser 78 retrofitted with a CF850 vaccine refrigerator with a capacity of 396 litres (or 400 packs) [17]. Vaccine cooler would be fitted with a temperature sensor. PPE and spare fuel would be stocked in the jeep. The jeep would be able to make the maximum round trip distance of 100km (50km each way). As an example, the average miles per gallon of a Toyota Land Cruiser is 13MPG (tank size 20G) [18] which would give an approximate range of 400km. Due to the large storage capacity, very few jeeps would be required ($1-2$ jeeps could deliver the 500 packs).

2.2.2 Motorbike ("Boda-Boda")

Motorbikes are used by UNICEF to distribute vaccines to remote locations. The motorbike would carry a driver and a health worker on the back. It would be tricky to load the bike with PPE or other supplies but a GPS tracker could be fitted. For cooling, each motorbike has the capability to mount a small-medium "Vaccine Carrier" [14] with a passive cooling system (ice packs). The vaccine will be kept cold for a limited time so deliveries must be quick. There is limited storage capacity ($1-2$ litres) which is enough for $\simeq 20-50$ packs (each pack contains 10×5ml vials). A fleet of $10-20$ motorbikes would be required to deliver 500 packs and would still make repeat trips in a day. Locals would be hired to make trips to their communities where they are known. The motorbike can cover the 100km round trip (average range for a bike is about 193km).

3 Trade-off Study

3.1 Advantages and Disadvantages of shortlisted transport technologies.

Requirement	Four Wheel Drive Jeeps (example: Toyota Land Cruiser 98 with CF850 refrigerator fitted)		Motorbikes ("Boda-Bodas")	
	Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
Ability to traverse difficult terrain over long range (50km) and overcome poor weather conditions.	Usability in shallow water such as streams or swamps. Increased water functionality with "raised suspension" or "snorkel" which moves air intake of the car to higher location. Some jeeps can travel through water 30" deep [19]. Can go off road. Can travel in bad weather as jeep has roof. Easier to repair as can bring tools.	Not able to cross large bodies of water, quite large so will have very limited usability in forests/ jungles or along narrow tracks. Can't avoid terrain like aerial options (Helicopters, Seaplanes).	Fast and small, can travel along narrow paths, through forests and jungle. Can climb steep hills. Limited use in shallow water and swamps.	Limited usability in bad weather as there is no shelter for the driver and passenger. Cannot cross bodies of water. Can't bring spare parts or tools so hard to repair a bike if it breaks down while crossing tricky terrain.
Must be a cost effective solution for delivery of the vaccines	Only require 1-2 jeeps with large vaccine storage capacities, fuel costs likely to be lower as running less vehicles, hiring less personnel so cost of wages will be lower. Only need 1-2 refrigerators.	Expensive one off payment for the jeep and refrigerator or "Vaccibox". Expensive to replace if it is damaged. Jeep is also a single point of failure, ability to deliver vaccines halved if one breaks down.	Motorbikes are much cheaper than a jeep [20]. Less of an impact if one motorbike breaks down since the rest of the vehicles will still be operational to deliver vaccines.	Requires many more UNICEF passive cooling "Vaccine Carriers" as one is required for each bike. More bikes required. More digital thermometers required to monitor temperatures.
Keep vaccines at a suitable temperature and insulated from damage during transit to reduce waste.	1-2 expensive refrigerators used [21]. Independent battery power source keeps fridge operating (up to 16 hours on the CF850 refrigerator) [17]. Battery can be recharged by the jeep's engine. Can keep vaccines cold indefinitely provided there is enough fuel.	Single point of failure is again a problem for the jeeps. If the refrigerator malfunctions/ "Cold Box" is damaged many more vaccines will be spoiled (higher waste).	Vaccines distributed amongst bikes so if a small "Vaccine Carrier" with 20 packs is damaged then less waste occurs. All the vaccines are not affected.	Requires many more lower quality, cheaper coolers for each bike. Passive coolers utilise ice packs which can only keep the vaccines cold for a limited period of time.
Must be able to track vaccine shipments and locate where they are in the delivery chain (traceability)	Since vaccines are localised to one or two vehicles, less GPS trackers required, easier to locate vaccines.	Again single point of failure. If we lose tracking capabilities on the single vehicle, all those vaccines may be lost since they are all stored in 1 location.	Vaccines shared between the bikes. Losing GPS tracking capabilities on 1 has less of an impact.	Lots of GPS trackers required, much harder to monitor 10-20 bikes compared to 1-2 jeeps.

Table 2 continued from previous page

Must have the capability to deliver a large volume of vaccines in a day (500 Packs).	No need to return to the distribution centre. Large storage capacity allows all 500 packs of the daily quota to be stored in 2 vehicles.	More stops required since only 1-2 jeeps servicing all the communities. If we assume each village takes 10 packs that's 25 stops in a day with 2 jeeps. May not be feasible.	More bikes are operational so can deliver to communities simultaneously. Assuming 10 packs used by each village, only 5 stops with 10 bikes. Deliver faster.	Will have to travel back and forth to the distribution centre increasing km travelled/ fuel costs. Storage capacity allows for 20 packs which may only service 2 villages.
Health Care and Delivery Personnel delivering the vaccines must be Protected (security).	Have access to PPE in the jeep to protect from COVID-19 when making deliveries, more protected from criminal groups and insurgency groups such as the ADF (Allied Democratic Forces)[7].	Lots of vaccines stored at one potential target. May make the jeeps more attractive for criminal organisations as they have a high value.	Vaccines distributed amongst the fleet of bikes in operation. Each bike therefore less likely to be targeted, has a lower value.	More vulnerable to attacks/ robberies by insurgency groups such as the ADF and other criminal organisations. No access to PPE as not enough storage space on bike.
There must be high levels of public trust in the vaccine delivery system.	Since less people are hired, can afford to train health workers better. This will likely garner more trust from the local community.	Since only 1-2 jeeps will be required, less people from the local community will be hired, will hurt the initiative's popularity. Less likely the personnel will be known by all the communities they deliver to.	Since more bikes will be used and the delivery work split between health workers from different areas, it is likely that the delivery workers will be known by the communities they visit.	Many more staff are required to drive the bikes and deliver vaccines. Some of these health workers may be poorly trained which might lower levels of trust in the initiative.
Must be able to monitor vaccine temperature and whether any damage has been sustained by the vials.	We can install programmable electronic temperature and event logger system [12] used by refrigerators (such as the CF850) to continuously measure and log temperatures at all times, as recommended by the WHO [22]. Only requires 1-2 digital thermometers.	If the digital thermometer or temperature and event logger breaks in the refrigerator then can't verify the temperature of any of the vaccines. For the motorbikes the point of failure is distributed.	If monitoring breaks for one "Vaccine Carrier" it is less of a problem, only 20 packs affected.	Requires individual digital thermometer for each small "Vaccine Carrier". Need to monitor and check more storage containers. Can't use sophisticated logging systems like on the refrigerator as too expensive. Rely on cheap thermometers.

Table 2: Advantages and Disadvantages of Two Shortlisted Transportation Technologies as related to the System Requirements

3.2 Costing of the shortlisted delivery methods

The below costing statements give an estimated idea of how much capital and running costs would be for a distribution centre to achieve the minimum required delivery rate for one year for each transport technology. That minimum delivery rate is 500 packs a day, which equates to $182,500$ packs in a year. Considering each pack contains 100 doses, that's $18,250,000$ doses delivered in a year.

We assumed all costs delivering the vaccines to the distribution centre have already been considered. All running costs are calculated on an annual basis. WHO Documentation on Costing Vaccine delivery to 92 AMC (Advance Market Commitment) Countries was used as a guideline. For the Jeep implementation we will assume the cooling option employed is a powered refrigerator fitted into the back of the vehicle (CF850). We will assume 2 jeeps are used. For the Motorbike, passive 2.6L Vaccine Carriers will be used. We will assume a fleet of 10 Motorbikes. Other sources used for the costing are as follows: [3, 18, 20, 21, 23, 24, 25, 26, 27, 28]

Costing Spreadsheet for both Technologies

Technology 1: Four Wheel Drive Jeep (Toyota Land Cruiser 98)

Summary Table	USD($)	USD($)	USD($)
Capital Costs			
Jeep (Toyota Land Cruiser 78)	30000		
(250 packs in each)	2	60000	
Specialised CF850 Refrigerator	1600		
(can easily carry 250 packs)	2	3200	
Passive Vaccine Carriers (2.6L)	17.74		
(for short range from jeep to village)	4	70.96	
Monitoring/Tracking Devices*		143.96	
Training (per Distribution Centre)*		63	63477.92
Running Costs (Annual)			
Fuel*		17840	
Labour/ Wages*		28000	
PPE*		1223.918	
Repairs (Toyota Land Cruiser 98)	746		
	2	1492	48555.92
Total Cost of Jeep Implementation			**112033.84**

*Fuel Costing	USD($)	USD($)	USD($)
Average Daily Trip length (Miles)*	62		
Days	365	22630	
Jeeps in Operation		2	
Miles Covered in a Year		45260	
Miles Per Gallon (Toyota Land Crui	13	13	
Gallons of Fuel used in a year		3481.54	3481.54
Cost per Gallon of Fuel (Uganda)	5.133	5.133	5.133
Total Fuel Cost			**17840**
***Average Daily Trip Length**			
Each jeep has to make 25 stops in a day			
(250 packs, 10 packs used by each village)			
Kilometres (max dist. travelled away from dist. centre 50km)			100
Miles			**62**

**Training Cost: Based on median cost of training personnel for the introduction of a new vaccine at a facility*

*PPE Costing	USD($)	USD($)	USD($)
Mask	0.31		
Personnel Required	4	1.24	
Two Required Per Day		730	905.2
Biohazard Waste Bag	0.17		
One Per Jeep	2	0.54	
One Per Day		365	197.1
Hand Sanitizer (10ml)	0.0833		
Personnel Required	4	0.3332	
10ml Required Per Day		365	121.618
Total PPE Cost			**1223.918**

*Labour Costing	USD($)	USD($)	USD($)
Wage per worker (median Ugandan salary)		7000	
Personnel Required			
Jeeps in Operation	2		
Staff Per Jeep	2	4	**28000**

*Monitoring/ Tracking Devices	USD($)	USD($)	USD($)
Testo 184 T2 - Temperature Data Logger		36.99	
		2	73.98
GPS Trackers (price sourced online)		34.99	
		2	69.98
Total Monitoring/ Tracking Cost			**143.96**

Technology 2: Motorbike (Honda CGL125)

Summary Table	USD($)	USD($)	USD($)
Capital Costs			
Motorbike (Honda CGL125)	1295		
(50 packs in each)	10	12950	
Passive Vaccine Carriers (2.6L)	17.74		
(20-50 packs so repeat trips required)	10	177.4	
Monitoring/Tracking Devices*		719.8	
Training (per Distribution Centre)*		63	13910.2
Running Costs (Annual)			
Fuel*		6691.22	
Labour/ Wages*		70000	
PPE*		3187.55	
Repairs/ Maintenance (Motorbike)	200		
	10	2000	81878.77
Total Cost of Motorbike Implementation			**95788.97**

*Fuel Costing	USD($)	USD($)	USD($)
Average Daily Trip length (Miles)*	31		
Days	365	11315	
Motorbikes in Operation		10	
Miles Covered in a Year		113150	
Miles Per Gallon (Honda CGL125)	86.8	86.8	
Gallons of Fuel used in a year		1303.57	1303.57
Cost per Gallon of Fuel (Uganda)	5.133	5.133	5.133
Total Fuel Cost			**6691.22**
***Average Daily Trip Length**			
Each bike has to make 5 stops in a day (50 packs, 10 packs used by each village)			
Repeat trips required (room for 20 - 50 packs in a 2.6L Vaccine Carrier)			
Kilometres (less daily km than jeep as making 5 times less stops)			50
Miles			**31**

**Training Cost: Based on median cost of training personnel for the introduction of a new vaccine at a facility*

*PPE Costing	USD($)	USD($)	USD($)
Mask	0.31		
Personnel Required	10	3.1	
Two Required Per Day		730	2263
Biohazard Waste Bag	0.17		
One Per Motorbike	10	1.7	
One Per Day		365	620.5
Hand Sanitizer (10ml)	0.0833		
Personnel Required	10	0.833	
10ml Required Per Day		365	304.045
Total PPE Cost			**3187.55**

*Labour Costing	USD($)	USD($)	USD($)
Wage per worker (median Ugandan salary)		7000	
Personnel Required			
Motorbikes in Operation	10		
Staff Per Motorbike	1	10	**70000**

*Monitoring/ Tracking Devices	USD($)	USD($)	USD($)
Testo 184 T2 - Temperature Data Logger		36.99	
		10	369.9
GPS Trackers (price sourced online)		34.99	
		10	349.9
Total Monitoring/ Tracking Cost			**719.8**

Figure 1: Costing Spreadsheet for Two Technology Options

4 Conclusion

Based on Table 2 above and the costing analysis shown in Figure 1, the Motorbike implementation using Honda CGL125 motorbikes seems to be the best system for this region and application. This system has numerous economic, social, security and technical advantages.

Firstly, from an economic standpoint the motorbike system is superior. With a capital cost of $\$1,295$ per motorbike compared to $\$30,000$ for a Toyota Land Cruiser Jeep [20]. The Honda CFL125 is a bike regularly donated by UNICEF to developing nations due to its cost effective nature. Even using 10 bikes vs. just 2 jeeps the cost advantage is significant. The use of passive "Vaccine Carrier" coolers with 2.6L capacities over a CF850 refrigerator also makes a big difference to the cost [25]. Fuel costs are lower due to a much higher MPG on the motorbike compared to the jeep. Even though labour is significantly more expensive due to the higher number of drivers required, overall the bike solution costs $\$95,788$ while the jeep implementation costs $\$112,033$ (Figure 1).

Secondly, from a social perspective, the motorbikes will hire more people within the local area. This will increase popularity and trust in the vaccine initiative. It also means that the drivers can be sent to their own local communities to deliver vaccines. Therefore, they are more likely to be known and recognised. Thirdly, from a security perspective, since the vaccines are distributed between many different motorbikes they are less of a valuable target for the ADF (Allied Defence Forces) insurgency and other criminal groups [7]. This distribution also means that if tracking/ monitoring capabilities are damaged in one of the passive coolers, it is not too big of an issue as there are nine other coolers. Similarly, if one of the coolers sustains damage, up to 50 packs can be damaged compared to 250 packs in the case of the jeep solution.

Finally, on the technical side, since there are 10 bikes, compared to 2 jeeps, each bike's trip is quite short. This means there is less risk that the vaccine's temperature will drift outside the acceptable range of $2-8$°C. Additionally, if one bike breaks down it is not a big issue as we have nine other bikes still operational. The motorbike implementation allows us to remove any single points of failure in the system. In conclusion, while it does have some disadvantages (difficult to travel in adverse weather, can't overcome all terrain, no active cooling, less vaccine storage) it is clear why the motorbike implementation is more effective for our system requirements.

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