Design of a Human-Powered Utility Vehicle for Developing Communities

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This thesis titled

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ABSTRACT

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There is a need for many appropriate technologies in the developing world today. As international development efforts such as projects by Engineers Without Borders attempt to fulfill this need, the design process needs to be examined as it spans borders and cultures. This project examines the criteria for appropriate technology and design process steps through the execution of an appropriate technology development project from start to finish.

The project executed was the development of a Human Powered Utility Vehicle to fulfill the transport needs of rural communities in Sub-Saharan Africa. In order to establish basic infrastructure, a sustainable, affordable method of transporting goods and services is essential. This research project fulfills this need by the design of an appropriate utility transportation solution for such communities, with multiple applications for farming and other productivity. The researcher took a total of three trips, two for assessment and benchmarking, and one for a final implementation of the design for customer feedback and performance testing. The design was also taught to local workers and made public-domain such that it can be produced if the design is successful.

Approved: ____

Gregory G. Kremer

Associate Professor of Mechanical Engineering

ACKNOWLEDGMENTS

While most of the people who had a hand in making this project possible will go unnamed here, my deepest thanks go out to you all. One is bound to encounter a diverse set of needs when travelling alone through Africa, transitioning jobs and spending long nights missing one's fiancée – my story is no different. Without the mentoring, the companionship, the financial support and the moral support I received from so many people, none of this project would have been remotely possible.

To my dad, I thank you for your guidance over the years and for the insatiable desire for knowledge you have passed on. You are the best teacher I will know.

To my mom, I thank you for supporting me, even when my decisions don't seem to be the safest or the sanest. You can only hope my son will do the same someday.

To my brothers, thank you for your belief in what I'm doing and for the countless ways you have helped me throughout this process. You have been the best friends a man could ask for, and have shown me what it is to be a good husband and father.

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Lastly and mostly, to my beautiful fiancée. Jess, it has been undoubtedly the hardest period of our lives so far, but it has been among the best. If you aren't keeping my fever down and running blood samples to the hospital, you're keeping me sane with letters and midnight phone calls, or translating when my French isn't as good as I'd hoped. Thank you for everything, and I look forward to our next adventure. I love you.

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1. INTRODUCTION

A major problem developing communities face is a lack of transportation infrastructure (Njenga and Davis 2003, Hilling 1996, Darrow and Saxenian 1986). The absence of reliable roads, vehicles, and other transport facilities in such areas stalls economic growth. Because goods and services cannot be effectively moved from one point to another, the trade thereof cannot occur. As humans, we rely on this movement for many of life's tasks: whether they be potable water, food, medicine or some other necessity, the many items needed to fulfill our hierarchy of human needs come from different places. In the words of Njenga and Davis, "Transport is necessary in achieving a wide range of objectives including economic growth, personal welfare, governance and empowerment as well as security." (Njenga and Davis 2003)

One of the most severe economic problems resulting from a lack of transport infrastructure is subsistence farming (Conroy 2006, Perrings 1996, World Bank 1989, Mellor 1988). Farmers face difficulties on different levels, from limitation of their ability to plant and harvest crops to difficulties moving surplus crops to a demanding market. Without reliable help from tractors, trucks and in many cases, animals, farmers must do all work manually. This effectively limits the acreage a farmer can tend in a given season to levels that cannot even sustain a single family. In such areas, farmers rarely tend more than two to four acres of land, and thus consume 80 to 100% of their crops. This, combined with the prohibitive cost of moving goods to markets only fifteen to twenty miles away, prevents distribution of food to the markets that need them (Perrings 1996). Farming communities can't sell their crops locally because of the resultant surplus, and what would otherwise be a prosperous market is stifled (World Bank 1989). In many areas, appropriate mechanisms for even general tasks are non-existent, or of inadequate design. Figure 1 shows a typical Ghanaian push cart, which proves unstable and difficult to use, but is the only available option for moving goods in a village such as Maase. Figure 2 shows the Cameroonian equivalent, called a pousse-pousse.

Figure 1: Typical Ghanaian push cart.

Figure 2: Cameroonian pousse-pousse at a well.

While modernized transportation solutions exist in many of these rural communities, their use creates problems not typically present in areas with more developed infrastructure: “Informed observers note that few modern vehicles fit the needs of the developing countries well; in most cases, the designs or the machines themselves are imported. These vehicles…bring with them high foreign exchange requirements for purchase and fuel costs, problems of maintenance and spare parts, and low durability when operated over rough terrain,” (Darrow and Saxenian 1986). The use of these solutions in developing communities has proven unsustainable in terms of operating cost, maintenance and replacement, largely because they were specifically designed for a different level of infrastructure. Failures that would in other parts of the world warrant only a quick repair can be responsible for the complete breakdown of a vehicle. The same “informed observers” previously referred to will also note the inordinate number of broken-down modern machines one encounters in the developing world – usually due to a part failure that either could have been fixed for little cost or wouldn't have failed in a more developed area (Hilling 1996, World Bank 1989, Schumacher 1973). Such a vehicle is shown in Figure 3. The ever-present problems with modern transport systems also apply: most methods are still reliant on the availability of petroleum for fuel and cause environmental concern with emissions.

Figure 3: A diesel shovel resurfaces a dirt road behind a defunct water tanker.

Table 1 compares gross national income (GNI) per capita, average gasoline price, and the percent of the GNI per capita for the cost of 100 liters of gasoline. Values are taken from the World Bank's World Development Indicators, 2006 and The Deutsche Gesellschaft für Technische Zusammenarbeit (German Technical Cooperation) International Fuel Prices 2007. While indicators of poverty are widely a subject of dispute in the economic community, this table provides at least some insight to a cost comparison of gasoline for households in the United States to that in the countries under study by this project. Note that the effective cost is roughly two magnitudes more expensive in Sub-Saharan Africa than in the United States.

Table 1: Cost comparison of average gasoline price based on GNI per capita for each country

Country	GNI Per Capita [USD]	Avg. Gasoline Price [USD/Litre]	% GNI/C
United States	$44,970.00	$0.63	0.14
European Union	$34,149.00	$1.29	0.38
Ghana	$520.00	$0.86	16.54
Cameroon	$1,080.00	$1.14	10.56
Sub-Saharan Africa (avg.)	$842.00	$1.02	12.11

All designs must begin with the consideration of a customer and an understanding of the cultural and societal contexts in which the end product will be used. The use of more advanced systems than a society is ready to support can cause more harm than good (Adas 2006, Hazeltine and Bull 1999, Darrow and Saxenian 1986).

Appropriate technology (AT), as its namesake implies, is simply an application of technology with an emphasis on the direct societal and cultural needs and limitations likely to be encountered. For example, where a modern manufacturing plant might use an electric-powered winch to lift a load, an appropriate technology for a rural village in a developing nation for the same task might be something like a block-and-tackle, for reasons of economy, availability of energy sources or simplicity of its use. Appropriate technology provides an effective alternative where modern technology and “indigenous technology”, as referred to by E.F. Schumacher, cannot meet specific needs: “The idea of intermediate technology does not imply simply a 'going back' in history to methods now out-dated...The real achievement lies in the accumulation of precise knowledge, and this knowledge can be applied in a great variety of ways, of which the current application in modern industry is only one.” (Schumacher 1973) Throughout the literature concerned with aid in the developing world, calls for appropriate technology are multifarious (Adas 2006, Njenga and Davis 2003, World Bank 1989).

While many sources explain different needs and applications thereof, several universal design constraints and criteria ring true. The following is a list of seven criteria for appropriate technology, compiled from the general themes found in the AT sources mentioned, to be followed over the course of this design. Appropriate technology should:

1.) require only small-scale capital investment
2.) be buildable and maintainable using locally available materials and technologies.
3.) be labor-intensive in its operation.
4.) be affordable to the local populace.
5.) be understandable to local people for construction, maintenance and modification.
6.) be adaptable for different uses, locations and circumstances.
7.) be environmentally friendly and sustainable.

The goal of this project was to examine the design process as it spans borders and cultures, testing and determining key criteria and constraints for projects in developing communities. The proposed project was to develop a robust, sustainable machine for rural transport and utility in developing countries. Design of the machine focused on the application of appropriate, sustainable technology. The vehicle was human-powered and manufactured using available parts, materials and technologies in a local city center. Development included as much input from local end-users and customers as possible, gathered on assessment trips to locations in rural Sub-Saharan Africa, and included adaptability for as many local tasks as was practical for the design. A prototype was constructed and tested using terrain benchmarking from these locations. In addition, a specific manufacturing plan and basic cost analysis was presented for easy adaptation and real-world application in different areas, to ensure the design was affordable to the intended user.

2. CUSTOMER NEEDS AND SPECIFICATIONS

Significant research, on-site benchmarking and customer interviews were completed to establish specific design criteria and constraints. Information was gathered over the course of a two-week trip to Maase Offinso, Ghana and a two-month trip to Mèri, Cameroon (both shown in Figure 4). Both locations are rural farming communities in their respective countries, and have similar climate, demographics, geography, economics, and even crops and customs. Most Ghanaians are Anglophones, while most Cameroonians are Francophones.

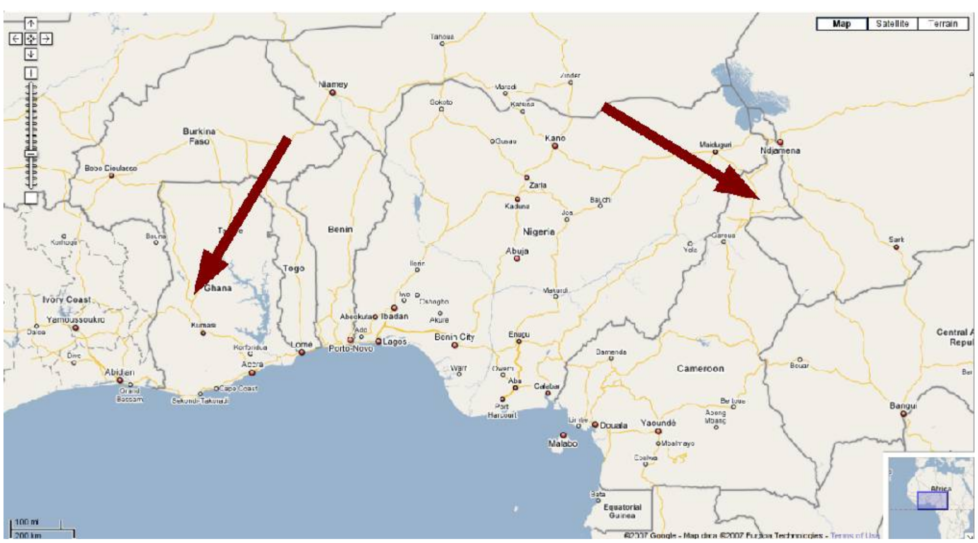

Figure 4: Map of West Africa showing villages visited. (Google 2007)

Terrain data was taken by hand-held GPS to establish gradeability and distance requirements, as well as to benchmark travel speed when using current transportation methods. Periodically, the GPS numbers for elevation change were verified with a simple inclinometer shown in Figure 5. A total of 16 track files were recorded and processed into raw data using a conversion program and a spreadsheet, including both short-range trips on farm fields and long-range trips on roads between cities. An example of the raw spreadsheet data can be found in Appendix A, and a profile from the data is shown in Figure 6. In addition to the GPS data, interviews were conducted with farmers, Peace Corps volunteers, and general village laborers to determine needs for the vehicle's ability to cover distances and terrain in the area, such as the road shown in Figure 7.

Figure 5: Inclinometer used to verify GPS grade measurements.

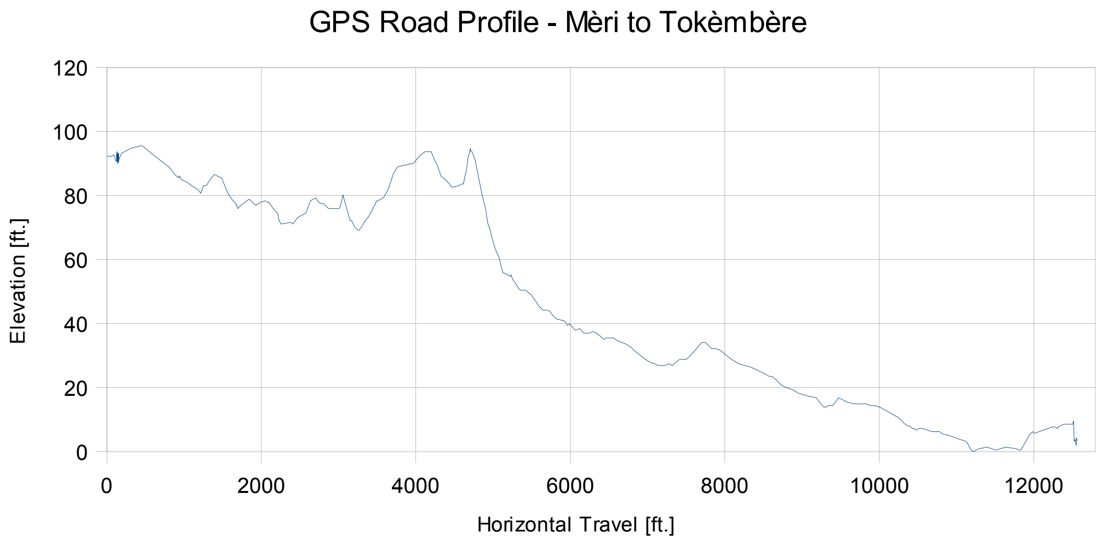

Figure 6: GPS profile of the road between Mèri and Tokèmbère, Cameroon.

Figure 7: A view over the head of a motorcycle driver of a “good” road in Cameroon.

During the interviews, a preliminary list of uses for the vehicle was generated to identify key product constraints, as well as basic profitability models for the vehicle's use. These specific uses can be divided into two drive modes, a short-range, high-load mode and a long-range, low-load mode. High load applications include transport of water in bidongs (large plastic tubs like those shown in Figure 2), concrete blocks, sacks of different foods, firewood, and people. Low-load cargo includes up to a half sack of food, a small amount (20 lbs.) of firewood, a weekend's worth of clothing and supplies (water, food, etc.), or a 25 liter bidong (container) of gasoline. While low-load applications need to be as fast as a bicycle to show an improvement, high-load applications simply need to be sustainable under human power. Dimensions and weights for the different cargoes are listed in Table 2. Several interviewees mentioned that the ability to traverse shallow water or loose sand and mud was desirable.

Table 2: List of possible cargo and their weights/dimensions

Cargo	Wt. [lbs.]	l x w x h [in.]
25 L bidong of gasoline	40	14 x 10 x 12
25 L bidong of water	57	14 x 10 x 12
Sack of millet/corn/peanuts	75	39 x 20 x 12
Unit of firewood	20	24 x 12 x 12
Typical market bag of food	35	24 x 8 x 24
Person	150	30 x 15 x 67

It was also noted that applications beyond simple transport would provide significant added value to the customer. If the vehicle could act as a way to power farm implements or other sundry mechanisms such as pumps, mills and the like, it would provide a useful, atypical portability for mechanically powered devices. One idea that excited a mechanic from Maroua was to include a standard keyed shaft as an output option for connection to many different types of machines.

In addition to design criteria, design constraints were also developed during the trips to West Africa. These constraints were derived around a conceptual manufacturing plan through which the vehicle would be produced and be fully serviceable in a local city center (typically 20 miles or less from the point of use). It would also need to be repairable at the point of use to at least the extent that the user could ride it to the local city center for more major repair. This would ensure that the vehicle would provide a long-lasting, sustainable machine.

Available materials and manufacturing technologies were assessed and additionally researched from the United States. A typical city center had a basic machine shop with a mill and lathe. Larger city centers in both countries had more significant machine shops with the capability to broach gears and perform basic aluminum and brass casting. Braze welding and basic motorcycle maintenance were also available in the villages, with MIG welding, extensive motorcycle repair and basic car repair common in city centers. These capabilities were found to be consistent with several literature sources as well (Carr 1985). Most locales provided access to steel bar (known as rebar), and businesses in city centers could obtain common steel shapes (tube and angle) in small sizes (less than 1.5”) if ordered in large number, but non-ferrous metals were more difficult to come by. The cost of this steel was significantly reduced by increasing the size of the order, to the point of having similar material cost as a developed country.

Preliminary target specs, design criteria and constraints derived from on-site benchmarking are summarized in Table 3.

Table 3: Preliminary target specs, design constraints and design criteria.

Target Spec	Value	Based On
Low-Load cargo wt.	35 lbs. (16 kg)	Max. wt. for cargo outlined in low-load uses
High-Load cargo wt.	250 lbs (100 kg)	Max wt. for cargo outlined in high-load uses
Low-Load Distance	20 mi. (32 km)	Typical distance to local city seat
High-Load Distance	1500 ft (457 m)	Typical distance across village, max. length of typical farm
Low-Load Gradeability	9.1% Max.	GPS data from rural road systems, Avg + 3 Std. Dev's
High-Load Gradeability	6.2% Max.	GPS data from tended farmland and intra-village roads
Rut Traversal	8"wide x 8"deep	Direct measurement of typical road ruts
Step Climb	5"	Direct measurement of step between paved and unpaved roads
Low-Load Max. Speed	>10 mph	Must be as fast as unloaded bicycle with low-load on flat road
Operating Cost	$2 per day	Profitability/affordability for end-user during rental period

Constraints
Manufacturable using available technologies and materials in city center
Serviceable on-site to low-load drive mode (assessed via FMEA)
Completely serviceable in city center
Petroleum/Electric power independent
Future value cost must be recovered over vehicle life

Design Criteria (Value enhanced by)
Low weight
Portability
Ability to perform additional tasks (plowing, powering mill, etc.)
Ability to traverse rough/muddy terrain
Ease of use
Low operating cost
On-site serviceability
Durability/extended design life

3. LITERATURE SEARCH

Extensive research was done to establish the existing products and technologies that apply so as to better understand what needs are yet to be met, as well as provide a starting-off point for the conceptual design process. Searching included use of Ohio

University's ALICE, InfoTree (including Compendex and INSPEC), Google, Google Books and Google Scholar (tailored for Academic Search Complete through Alden Library). The following are the findings of this search. Keywords searched for included all possible combinations of human, power$, utility, vehicle and developing country. Reference lists of all articles found through this method were also searched, as well as lists of work by pertinent authors. Communication was also established with Dr. David Wilson, a former president of the International Human-Powered Vehicle Association and a leading expert on the use of human power.

3.1 Existing Designs/Products

One of the largest repositories for vehicle design with similar goals to this project is the Institute for Affordable Transportation's Basic Utility Vehicle (BUV) design competition. Figure 8 shows the current design for their BUV, as presented on their website (Institute for Affordable Transportation 2007). Its listed applications are as follows: delivery services, bus for children, ambulance, water distribution, and use as a mosquito fogger, with target regions of southern and eastern Africa as well as Latin America. The design uses an axle and leaf springs from a truck, and is powered by a 10 horsepower petroleum-driven engine. Figure 8 shows a picture as shown on the website.

While this vehicle meets this project's needs with respect to the rugged terrain and ease of use, one of the very important factors in making a vehicle accessible to the rural populace in Sub-Saharan Africa is energy independence. This vehicle is reliant on petroleum for operation, which is either unaffordable or unobtainable for an average African farmer. Its construction, however, meets our needs in that it uses parts from trucks and other vehicles that may be obtainable in the bush. The three-wheeled design provides a simple steering mechanism with few parts, and the large trailer has enough room for many different tasks. This vehicle would likely be too heavy for human power, but the basic frame layout and three-wheeled concept may prove useful.

Figure 8: The Institute of Affordable Transportation's Basic Utility Vehicle. (Institute of Affordable Transportation 2007)

Oxtrike

The Oxtrike was a heavy-load human-powered trike developed by Stuart Wilson in Oxford. It is shown in Figure 9, as taken from Pedal Power. The aims of the design were similar to the goals of this project, in that it provided a solution for moving heavy loads by human power. It featured a heavy steel chassis, 20-inch (small for that period of time) wheels, and a Sturmey-Archer hub gear (gear reducer) for torque conversion. The rider would sit in an upright position quite similar to a “cruiser” bicycle, and the load would be placed between the two back wheels. Also featured was a prominent foot-operated brake for the rear wheels that was powerful enough to hold the vehicle on a slope with a large load. Unfortunately, it was never mass-produced by the company that commissioned its design, for unknown reasons.

This vehicle is a one-of-a-kind design that would be very applicable to the needs of this project. Its simple frame design would be easy for a local African welder to assemble in a jig, and it uses parts that would mostly be available in rural areas. The foot brake is a useful feature for operating the vehicle on hilly terrain that is not found elsewhere. This vehicle does lack a faster, lighter drive mode for personal transport applications as well as a suspension for particularly rough terrain, but addresses our high-load needs. The gear reducer design may prove useful for this project. Figure 9 shows the Oxtrike's chassis without the cargo bay attached, presenting the frame more effectively.

Figure 9: Stuart Wilson's Oxtrike chassis. (McCullagh 1977)

Bicycle Trailers

Bicycle trailers can be found as consumer products in select places around the world. They are mentioned in the International Human Powered Vehicle Association's publication *Human Power* in Volume 5 with a figure (as shown in Figure 10), as well as in Pedal Power (McCullagh 1977) and *Bike Cult* (Perry 1995). They are designed for attachment to a diamond-frame bicycle, and typically sell for $300 - $500. Two of the largest manufacturers are BoB Trailers and Croozer, whose trailers are shown, respectively, in Figures 11 and 12.

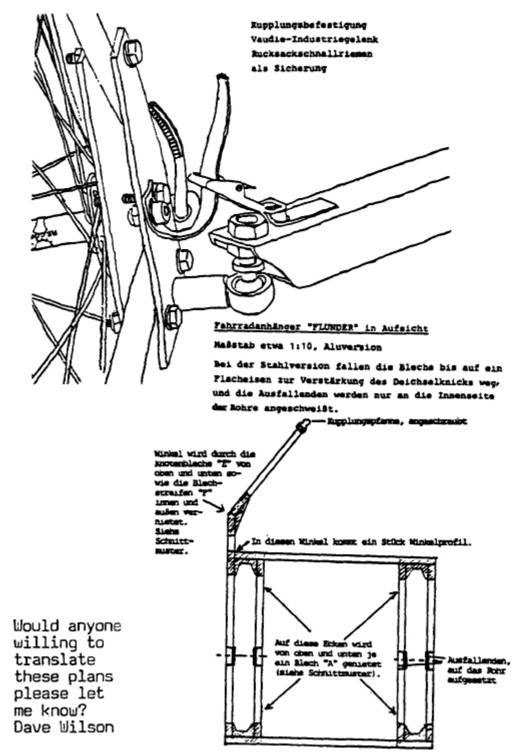

Figure 10: Bicycle trailer hitch design from Human Power, Vol. 5. Similar designs are found in many two-wheel consumer trailers today. (Wilson 1986)

Figure 11: BoB's Ibex one-wheel trailer. (Lipton 2007)

Figure 12: Two-wheeled bicycle trailer produced by Croozer. (BicycleTrailers 2007)

All the trailers act as passive rear loads, with connections designed for attachment to a standard rear bicycle wheel, and are capable of carrying loads up to 100 lbs, with maximum cargo dimensions of 30” long, 17” wide and 30” high. While the dimensions fulfill the preliminary specs for cargo, the maximum weight for these trailers is far too low. The two wheel trailers use a hinged connection so some tilting is permitted between the bicycle and the trailer, which forces the load to be centered on the trailer's axle. For loads representing a significant portion of the total vehicle mass, location over a passive axle will result in a decrease of the vehicle's traction limit. Single wheel trailers can tilt with the bike (and thus have more robust connections, as seen in Figure 9), but have less space (only up to 2 cubic feet) and less load capacity (only up to 70 lbs.).

Freight Cycles

A small number of freight bicycles and tricycles are sold in select places around the globe, all comparable to the ones shown in Figures 13 and 14. They typically feature a front or rear-mounted cargo bay and use exclusively an upright body position, but typically provide no significant torque conversion. They do allow for large cargo sizes and are not extraneously heavy when unloaded, but maximum wheel loads limit their ability to carry significant loads such as those outlined in this project's needs. Also, as most of these designs are two-wheeled, and thus lack the stability needed for slower movement in farm or high-load applications.

A form of freight trike driven by hand is common in the developing world due to the high incidence of polio and the resulting disabilities in the victims' legs. These trikes are of the 'teardrop' frame design (with one wheel in the front, two in the back), and have a wooden floor, but little cargo space.

Figure 13: Danish Long John freight bike, originally produced by Monark. (Jong 2007)

Figure 14: Cargo trike, with 3 empty milk jugs. (Wikimedia Commons 2006)

Other Mechanisms

Many other pedal-powered mechanisms have been used for different tasks. Many of these designs are outlined in the book *Pedal Power* by James McCullagh. One design that may be useful is a foot-powered winch capable of performing tasks such as plowing and towing. The example from the book is shown in Figure 15. A winch could be very useful as livestock is not as common in West Africa for use to plow or move heavy loads. The vehicle could be fixed in place with a winch connected to the frame, or the winch could be fixed to a stationary object. The book goes on to outline many specific uses of pedal power such as pumps and drills, but those specific applications are beyond the scope of this project.

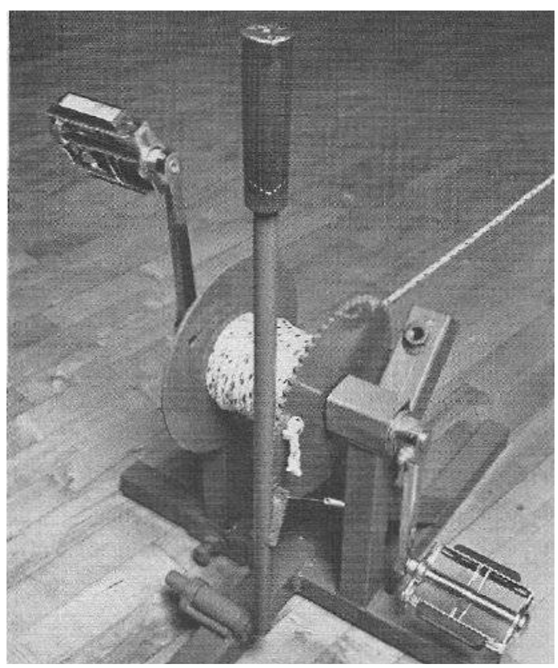

Figure 15: Pedal-powered winch as pictured in *Pedal Power* (McCullagh 1977)

Another possibly useful mechanism for this design is a mechanical constantly-variable transmission (CVT) designed by William Beale. Figure 16 shows the working drawing of the system as shown in U.S. Patent no. US 7,011,322 B2. The system uses springs and a ratcheting mechanism (which could be susbstituted on-site with strips of sheet metal and bicycle freewheels) to create a simple mechanism that provides extremely high gear reduction with small losses.

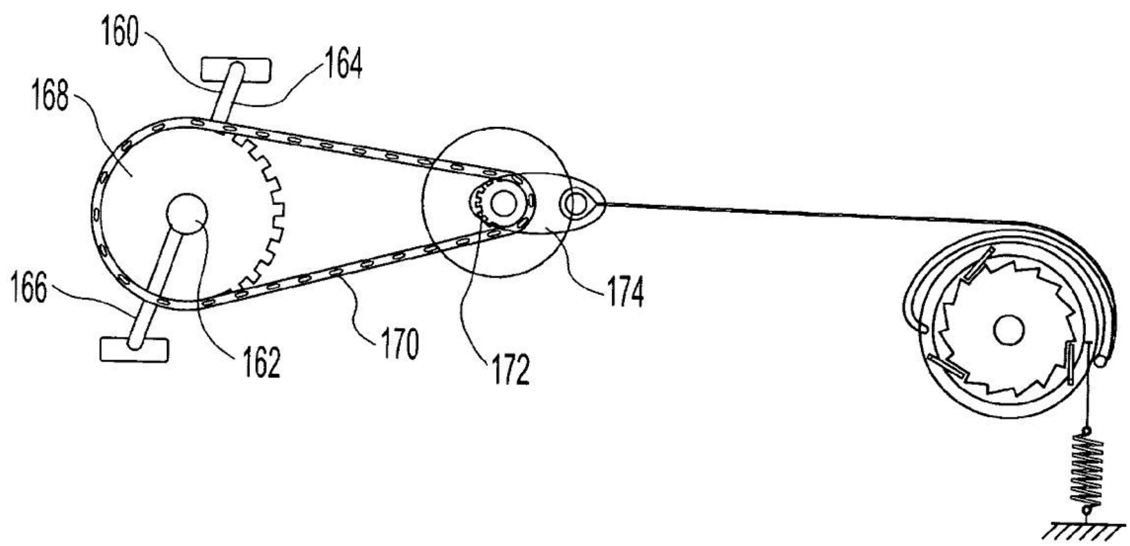

Figure 16: Beale's mechanical CVT, as shown in US Patent 7,011,322 B2.

The book *Bike Cult* by David Perry provides an extensive history of human-powered vehicles including information on designs over 130 years old. It outlines many different products, but none that fit into a class not before mentioned in this report. Several interesting designs are featured (such as a tree-climbing bike, and a rail bike comparable to a modern train), but none that truly fit within the scope of this project.

3.2 Background Information

Human Power

Human power has been researched in many different capacities, although none so significantly as upright bicycling. Two of the most significant repositories of technical information surrounding the use of human mechanical power for pedaling are *Bicycling Science* by David Wilson (2004) and *Human-Powered Vehicles* by Allan Abbott and David Wilson (1995). The latter combines many different sources of information on the use of human power for transport in many different capacities, including flying and boating. A point of interest with respect to this project is its discussion of human power output capability and presentation of the different research that has taken place in that field over the past 5 decades.

There are many theories describing the ways by which human power production is limited, but none are universally true (Morton 2006). Figure 17 shows a compendium of data plotted by Abbott (1995) of time to exhaustion vs. input power for various levels of athletic ability. Noting that the plot is semi-logarithmic, it is easily seen that the relationship between the two variables is highly nonlinear over the entire range of values. With respect to designing human-powered machines, however, one is not concerned with such a wide range of power production values; for most applications, the only relevant power levels are those which do not exhaust the human in less than 10-30 minutes. It should also be noted that exhaustion as referred to here is total exhaustion of the human, the physical result being an incapability to perform any useful work at the end of the prescribed time, until significant rest has been taken. Thus, we find that typical humans are capable of producing 75 Watts sustainably (as confirmed by Wilson (2004)), but cannot sustain 300 Watts for any more than 10 minutes.

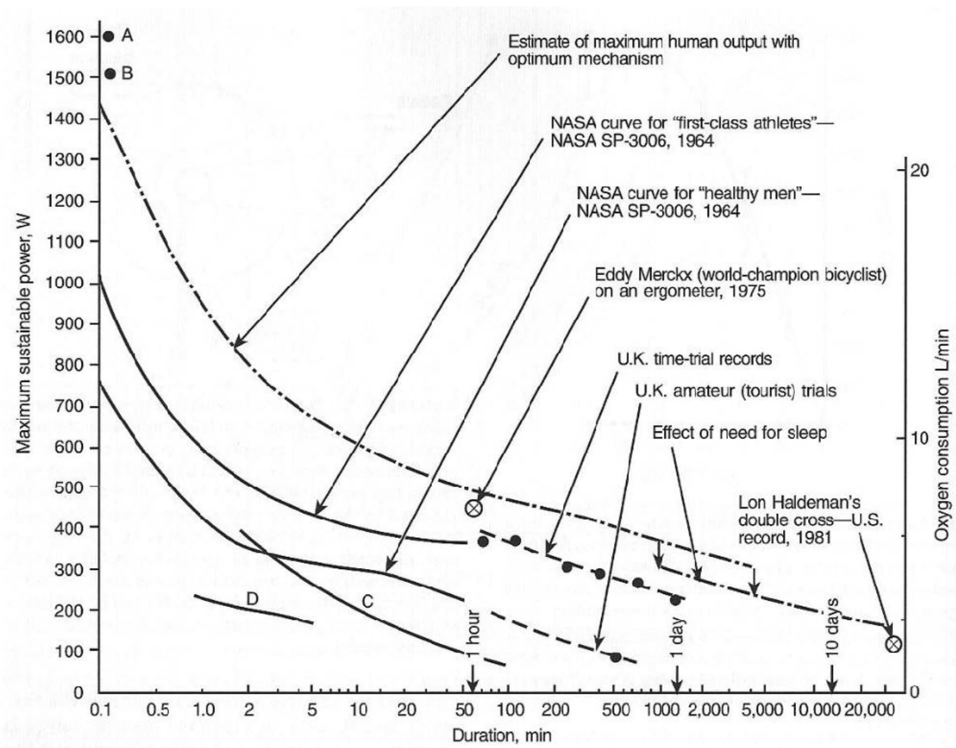

Figure 17: Compilation of human power capability curves as presented in Human-Powered Vehicles. (Abbott 1995, 32)

The relationship between power output and time to exhaustion in this range (75 to 300 Watts) is very nearly linear on a semi-log plot, and can thus be easily described by a logarithmic relationship, as will be shown in simulation later. Malewicki (1983) noted that curves such as those shown in the previous figure should include error bars, which would likely show a wide range of possible values. For the purposes of this project and others like it, however, this curve will suffice for describing human power capability.

Urieli, Lyles and Ross (1999) proposed a new unit of measure for human power, known as the "hup" (short for <u>hu</u>man <u>p</u>ower). This unit is equivalent to 75 Watts, or roughly 0.1 HP, and is useful for quantifying power in levels familiar to a human. One hup can be sustained all day, two hups can be sustained for roughly two hours, 3 hups for about 30 minutes and 4 hups only momentarily.

The human body also has differing performance with respect to varying torque levels, crank arm lengths and pedaling speeds. Martin and Spirduso (2001) showed that while variation of crank length did affect power production, this was due to the resulting change in pedaling rate for a given power and torque level. Martin, Malina and Spirduso (2002) went on to show that variation of crank length within a certain range did not significantly affect pedal power output, making adjustments to account for variation in pedaling speeds during the experiments. Most common cranks on bicycles today are well within this length range. Kohler and Boutellier (2005) discussed optimal pedaling rates with respect to both oxygen efficiency and power output, finding that the most common pedaling rate (90 to 100 RPM) is optimal for power production, and that power production efficiency is significantly affected by pedaling speed, based on the Hill model for muscle force vs. shortening velocity. Other studies have shown that power capability remains constant in different body positions and arrangements, even when one uses different muscle groups entirely (Brown, Kautz and Dairaghi 1996).

Kautz, et al (1991) studied torque production and pedaling technique, showing both that pedaling technique affects peak torque output, but not power production, and that their test subjects were capable of sustainably producing mean values of 50 to 80 N-m of torque on 170mm crank arms at constant workloads on an ergometer. McCartney et al (1985) also studied the torque-velocity relationship in cycling, producing a set of performance envelopes shown in Figure 18. These envelopes, according to the report, represent extremes of the human power capability range, with torque values up to 220 N-m. These tests were done in an isokinetic fashion, highlighting the differences between sustainable and instantaneous power production. A reasonable value for human torque production at low speed is their bodyweight times the crank arm length, or around 130 N-m for a 170 lb. Rider.

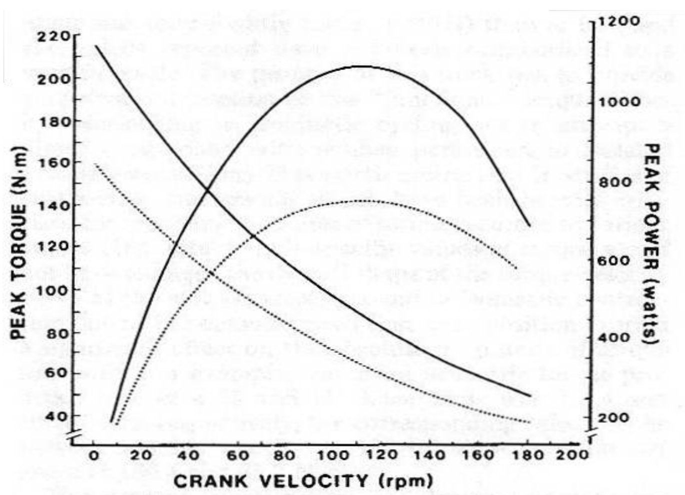

Figure 18: Peak torque and power during isokinetic pedaling (McCartney 1985, 1460)

Assuming that power production remains roughly constant over the range of speeds, one can produce a torque-speed curve useful for simulation. Such a set of curves is shown in Figure 19, for power levels of 1 to 4 hups, for a 170 lb. rider using 170mm pedal crank arms. At low speed, the limitations on the human's ability to produce force limits their power production (and, thus, torque production) capability.

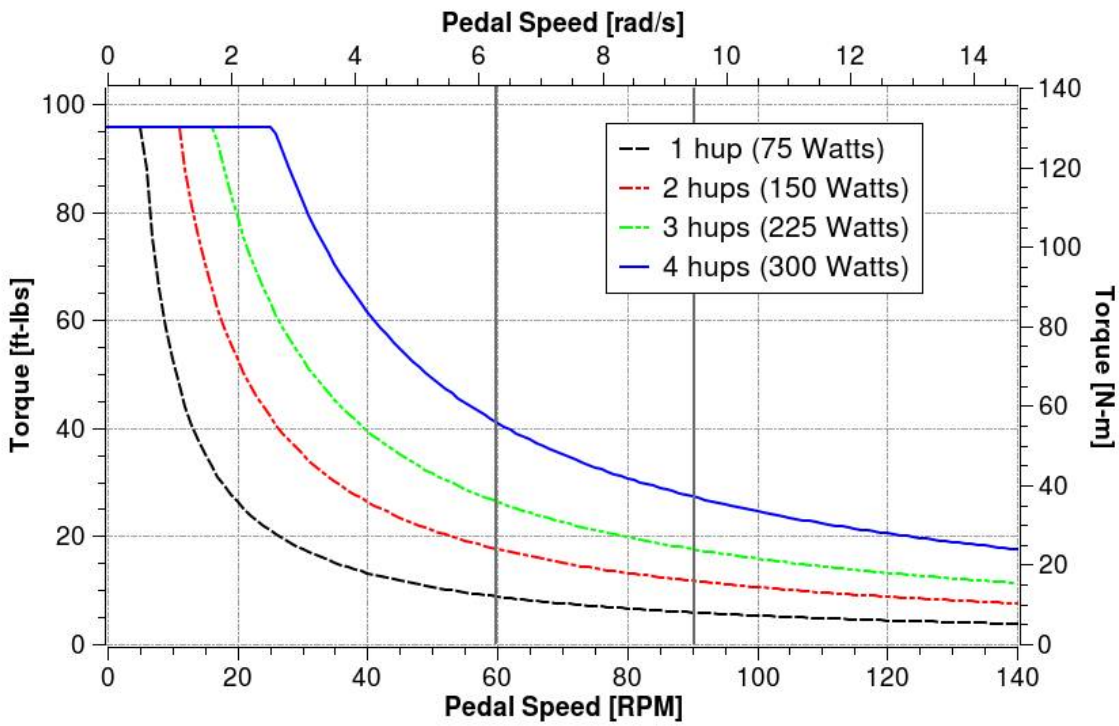

Figure 19: Torque-speed curve for a typical 170 lb. human at various power levels.

Human pedaling capability is also discussed in *Human-Powered Vehicles,* by Abbott and Wilson (1995). Humans have a natural pedaling speed at which pedaling efficiency is maximized and the human feels comfortable (i.e.: does not feel he/she is pedaling too fast or too slow). This speed typically lies between 60 and 90 RPM, as denoted by the two vertical lines on the plot, although it is noted that racing cyclists operate at much higher pedaling rates, in some cases up to 120 RPM, possibly due to an advantage in power output at these greater speeds, as was reviewed by Kohler and

Boutellier (2005). 60 and 90 RPM correspond to 6.3 and 9.4 radians per second, respectively. This graph also appears to be a good approximation to the torque-speed curves derived by Perrine and Edgerton (1978), which match the Hill model for the muscle contraction vs. speed relationship.

3.3 Literature Search Summary

Not many human-powered utility vehicles exist today, much less HPUVs designed specifically with the needs and goals of the current developing world in mind. While there are products that meet a few needs, there are no widely-used machines capable of meeting a significant portion of them. For example, bicycles provide cheap, reliable transportation, but they cannot safely transport large or heavy loads, and are unstable during slow movement. A substantial demand exists for an HPUV that can be manufactured, maintained, and afforded in the developing world, but no products have yet been produced to fulfill it. Elements of many previous designs will likely prove useful for a new product, but technical innovation and considerable customer input will prove crucial to the fulfillment of the specific design constraints, criteria and target specs outlined in this project.

4. CONCEPTUAL DESIGN

4.1 Concept Generation

Over the course of the first assessment trips and the many discussions with the target customers, many concepts were discussed, and the seemingly most feasible of those were sketched and expanded upon. Input was taken from farmers, mechanics and Peace Corps Volunteers, as well as engineers and non-engineers in the United States. The sketches, with notes on each are presented here, scanned directly from the author's design notebook.

Figure 20 shows a frame design for a trailer quite similar to a Cameroonian pousse-pousse. Such a trailer could be attached to a lighter vehicle, but the wheels of the trailer would need to be driven to avoid slip-limiting the vehicle.

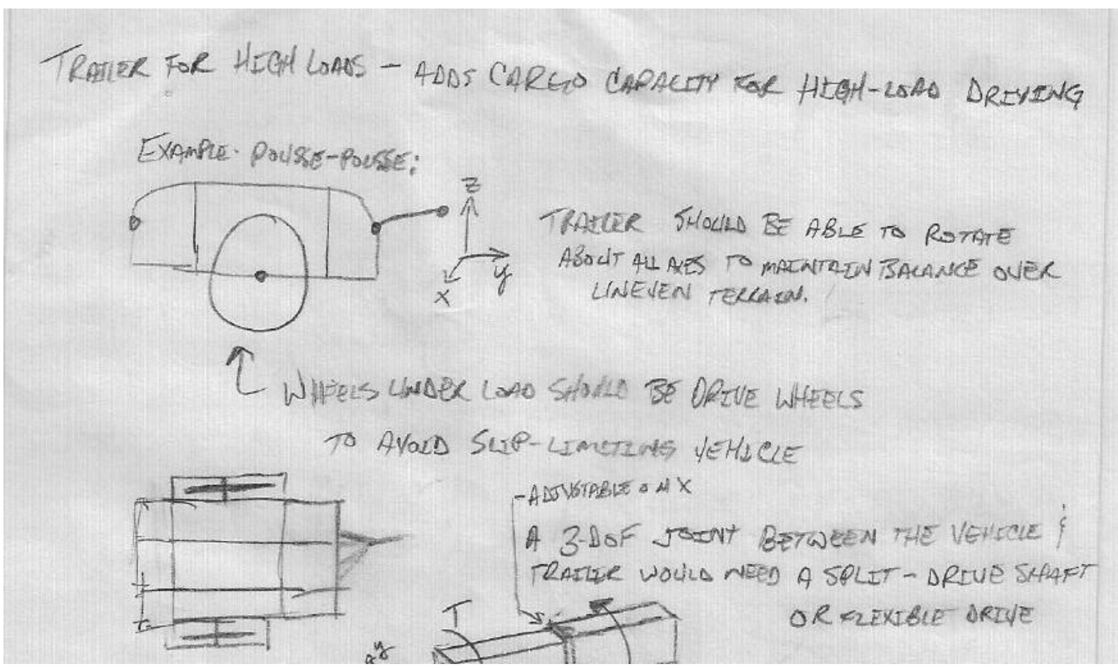

Figure 20: High-load trailer similar to Cameroonian pousse-pousse.

Figure 21 shows a split-shaft design found in the United Kingdom on a foldable bike. Such an idea could be used for a drive mechanism compatible with a suspension without a lot of machining for a split shaft. Square tubing is quite common locally.

Figure 22 shows a simple two-wheeled vehicle that could be used in conjunction with the trailer in Figure 20. The rear wheel of the two-wheeled vehicle could be swapped so the drive mechanism drives the two trailer wheels while they provide stability for the extra load.

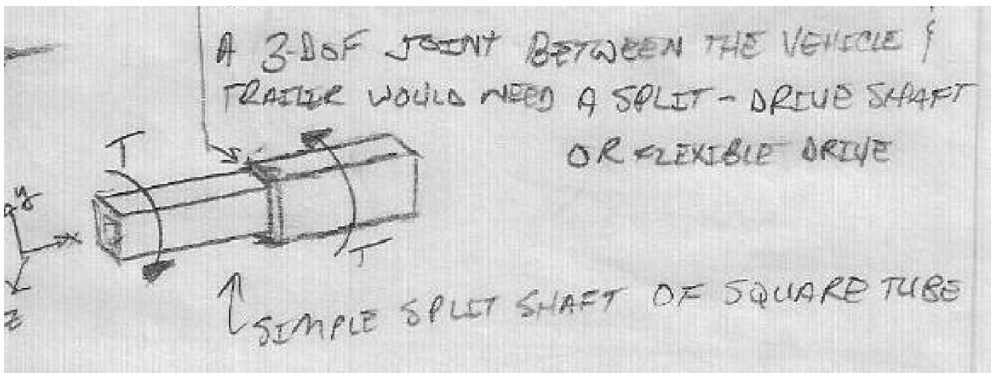

Figure 21: Simple split-shaft design from plain square tube.

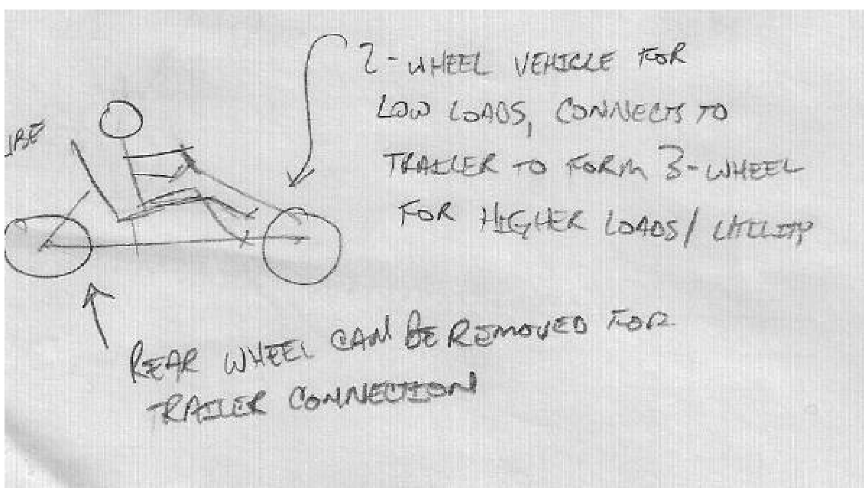

Figure 22: Simple 2-wheeled recumbent concept that attaches to trailer shown in Figure 16.

Figure 23 shows a three-wheeled tadpole (single wheel in the rear) design. This design would provide more stability at low speeds, but attachment to a trailer would be more challenging, as the connection would suffer the same difficulties as the bicycle trailers mentioned in the product Existing Designs/Products section.

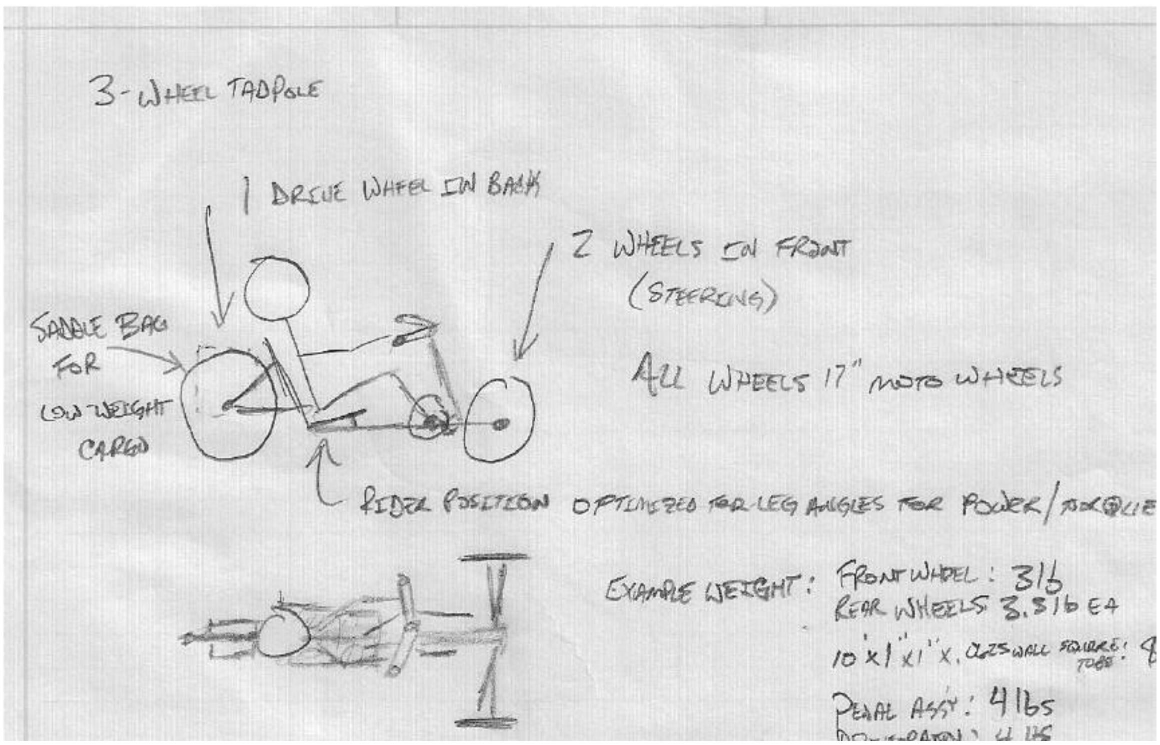

Figure 23: Three-wheeled tadpole-arrangement vehicle concept.

Figure 24 shows a teardrop (single wheel in the front) three-wheeled vehicle. This concept may be simpler to connect to a trailer, but if the rear wheels were driven, a differential may be needed. An idea initially suggested by Dr. Israel Urieli was to drive and steer the front wheel at the same time. There may be complications with the separate drive mechanisms to drive the front wheel vs. driving the rear trailer, but this could be a viable option.

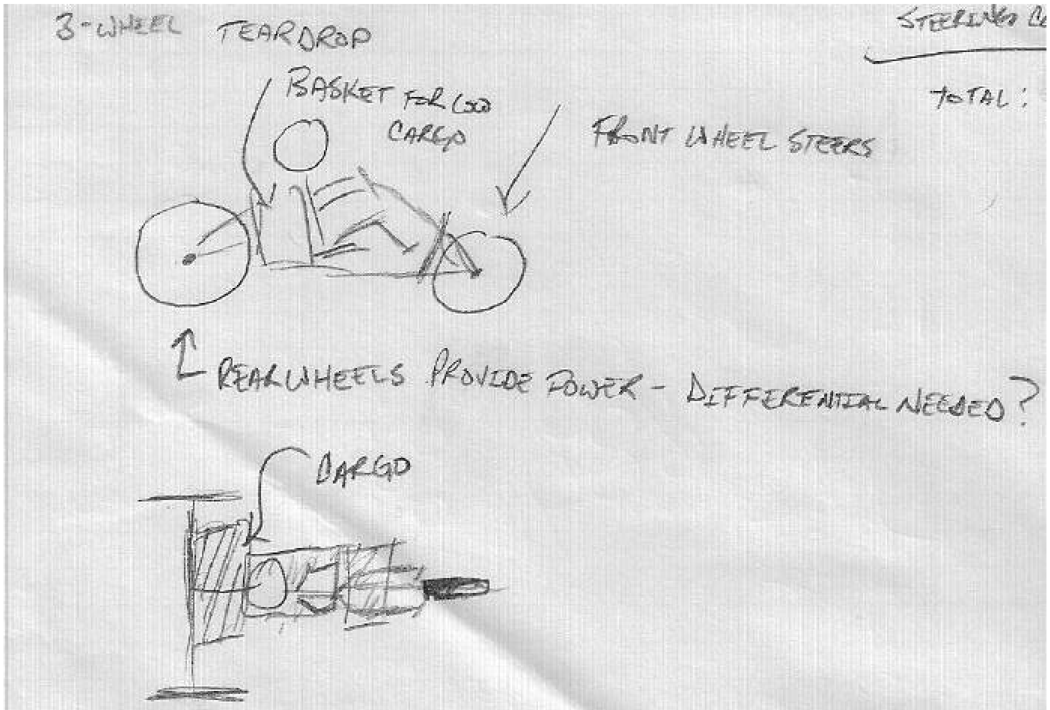

Figure 24: Teardrop three-wheeled design.

4.2 Concept Feasibility

Before starting down a path of design work, one must study the initial feasibility of the concept. Based on some initial assumptions, one can consider some objective methods to showing whether the system's operation lies in the realm of the possible. With respect to the previously mentioned design criteria and constraints (see Table 3), we can derive some basic free-body diagrams, and examine projected system performance, as well as provide some basic cost models.

From the previous section, we can see that the vehicle will likely take the form of a simple tubular frame, with two or three wheels, a simple suspension and several relatively light mechanisms for transmitting power in different capacities. Vehicle weight is assumed to be 50 lbs. maximum based on the scale of the vehicle and system components expected to be included. Figure 25 shows the free-body diagram used for initial simulation. The equation of motion is given in terms of acceleration in Equation 1.

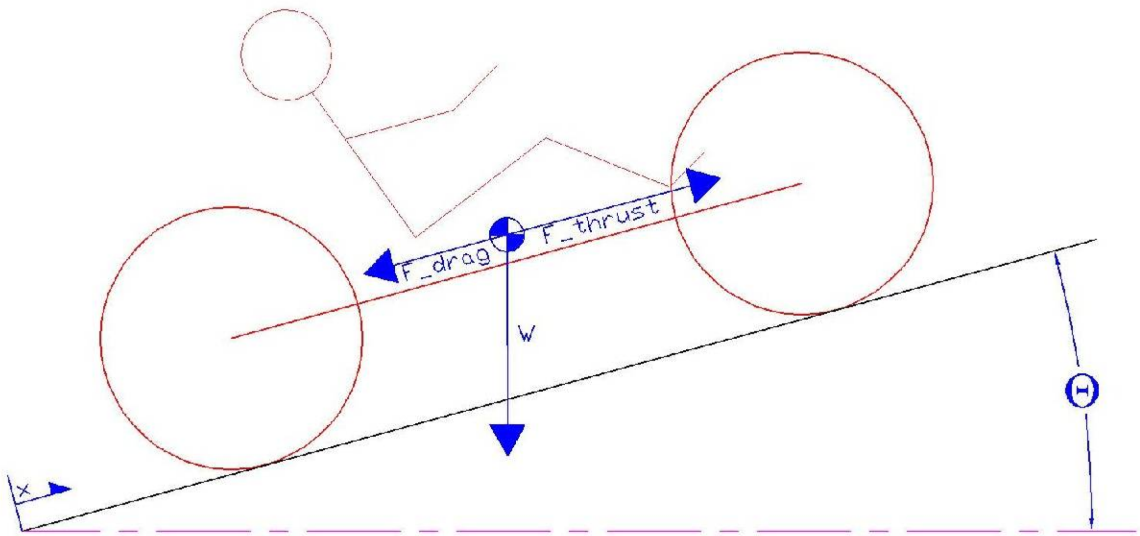

Figure 25: Simple free-body diagram for initial simulations.

$$\frac{d^2x}{dt^2}=\frac{m*g*(C_r+\sin(\Theta))+\frac{\rho}{2}*(\frac{dx}{dt})^2*C_d A+F_{thrust}}{m} \quad \text{(Eqn. 1)}$$

Constants in Equation 1 are explained in Table 4 with their corresponding nominal values used in the initial simulation. Euler's method was used to solve this equation and generate plots of vehicle speed vs. time. The source code for the program can be found in Appendix A, under “Source Code for Simulations”. A plot of performance envelopes for different loading conditions is shown in Figure 26; the higher performance line of each color represents an input of .4 HP, and the lower an input of .1 HP. The red, blue and green lines (solid, dotted and dashed, respectively) outline the loading conditions of 40 lbs. cargo at zero slope, 40 lbs. cargo at 9.1% slope and 250 lbs. cargo at 6.2% slope, respectively.

The maximum speed response for 40 lbs cargo surpasses the requirement of 10 mph with steady-state values between 16 and 19 mph. The two maximum slope tests also test feasible, as both envelopes are of sufficient speed (at least walking pace). This initial graph, thus, shows that the three loading conditions as outlined by the Target Specs in Table 3 can be met. Again, it is noted that these power levels are not sustainable over long distances, but such distances are not required by the criteria as listed in Table 3.

Table 4: Variables from Equation 1 and their nominal values.

Variable	Meaning	Nom. Value [Eng]	Nom. Value [SI]
m	Mass of vehicle, rider and cargo	8.08 [slug]	117.9 [kg]
g	Gravity constant	32.2 [ft/s^2]	9.81 [m/s^2]
Cr	Coefficient of rolling resistance	0.1	0.1
Cd	Coefficient of drag	0.77	0.77
A	Frontal area	3.8 [ft^2]	0.35 [m^2]
r	Air density	0.081 [slug/ft^3]	1.297 [kg/m^3]

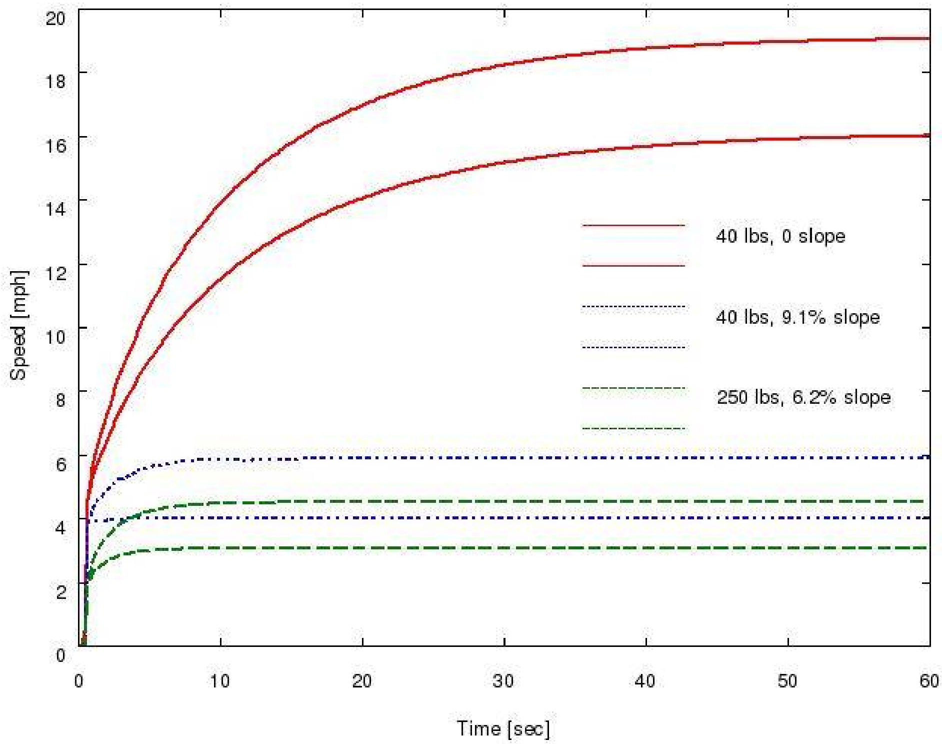

Figure 26: Graph of vehicle performance envelopes for inputs of 0.1 and 0.4 HP at various loading conditions.

In addition to being physically feasible, vehicle must also be affordable to the intended customer to be useful. The cheapest method of long-distance (greater than 20 miles round-trip) travel with cargo in the intended area of usage is on a motorcycle. Travel one-way from Mèri to the local city center, for example, costs 1500 CFA, or $2.73 US. This is too expensive for most people to travel to the local city center more than one or two times a month, and the motorcycle is also limited in its ability to transport cargo of size greater than 1-2 cubic feet. A form of transport that could move larger loads (as outlined in Table 2) to the city center would increase the profitability of the trip, making more trips feasible. Reduction of cost of the transport method used would also increase profitability and generate more use of the vehicle.

The business model most often used for tools, machines, push carts and the like in West Africa is an hourly or daily rental to the end-user. For example, to use the push cart shown in Figure 1, the customer would rent the cart from the owner, paying for the usage period upon his or her return with the cart. The same idea could be applied to an HPUV, and using some basic assumptions, the cost feasibility of the vehicle can be derived. Based on the widespread use of bicycles and how much business local motorcycle drivers get, one can assume the HPUV would be used 70% of the time or better if the cost was significantly less. At a cost of 50% of using a motorcycle, the vehicle earns \$1.37 US per day of use. Assuming it is used 255 days per year, the vehicle earns \$349.35 per year. Over the course of the vehicle life (2 years), it earns \$698.70.

Table 5 shows projected production costs based on assessments and initial guesses on the materials and labor to be used. Specific parts such as wheels, etc. were priced in local markets around Mèri, so prices should be relatively accurate. With a total price of roughly 312,000 CFA or \$585.45, the machine generates a net profit over its two years of life. Equation 2 shows the relationship of future value and present value through compounding interest, and can be used to find an equivalent interest rate for investment in the vehicle.

Table 5: Basic price list based on site-assessment and vehicle concept

Cost (CFA)	**Cost (USD)**	**Part/Labor**
40,000	$72.73	Bicycle parts (derailleur, brakes, pedals/cranks, etc.)
5,000	$9.09	Transport from production site to village
25,000	$45.45	Steel for frame (tubular steel)
30,000	$54.55	Wheels (2 moto wheels, 1 bicycle wheel)
2,000	$3.64	Seat material
10,000	$18.18	Gearing material
10,000	$18.18	Winch cable
200,000	$363.64	Labor (1000 CFA/hour for 200 man-hours)
322,000	$585.45	**Total**

$$F = P(1+i)^n \qquad \text{(Eqn. 2)}$$

In Equation 2, F represents the future value, P the present value, i the interest rate and n the number of compounding periods. With a future value of $698.70, a present value of $585.45 and a life of two years, this solves to an annual interest rate of 9.22%. By current standards this is a strong rate of return, should the vehicle be built by a profit-earning company; in the case of an NGO, the vehicle could be made for an operating cost of 670 CFA ($1.22 US) per day, recouping the vehicle cost over its life while matching depreciation due to inflation.

4.3 Concept Refinement

Throughout this stage of the project, the author met weekly with two advisors who assisted in the development of new ideas, as well as the critique of design work in progress. Concepts were refined and filtered using conventional tools such as plus-minus charts (as shown in Table 6) and decision matrices (as shown in Table 7), focusing on both the criteria for appropriate technology and the customer-specified constraints and criteria outlined in Table 3. Also, simulations of overall vehicle performance and frame strength were refined through this process, providing information for these tools. Results from these simulations will be discussed in the next section.

Table 6: Example of a plus-minus chart for design refinement

3-wheel tadpole		1-wheel hybrid		3-wheel teardrop		2-wheel hybrid	
+	-	+	-	+	-	+	-
Good weight distribution	Hitch mechanism needed	Adaptability for other tasks	Different frames for different tasks	Combined steering and drive	Slip-limited	Simple frame	Unstable at low speed on bad roads
Stable vs. 2 wheel	Complex steering	Lightweight	Slip limiting possible	Short drive	Possible high weight	Light for low-load application	Difficult rack interface
Recumbent seating	Long drive train	Short drivetrain	Unfamiliar design	No suspension needed		No suspension needed	
	Suspension needed	No suspension needed					

Table 7: Example of a decision matrix from design refinement process, accompanying plus minus chart in previous Table.

Frame System Decision Matrix

	Frame Weight	Easy to build	Familiar	Durable	Simple/ servicable	Stable	Cost	Added Functionality	Total
Weights	**0.11**	**0.19**	**0.06**	**0.12**	**0.16**	**0.18**	**0.16**	**0.02**	
Frame									
3-wheel tad.	3	3	4	6	2	10	5	0	**4.8**
1-wheel hyb.	7	8	6	9	9	7	7	10	**7.77**
3-wheel tear.	7	8	7	9	9	7	7	5	**7.73**
2-wheel hyb.	10	8	8	6	7	4	9	7	**7.27**

This process was, for the most part, identical to customer-focused design processes commonly used for product development throughout the developed world. The main difference for this project was the criteria and constraints used, and their significance with respect to the product's development. Technical details and concepts (for example, system weight) were weighted according to the design criteria and constraints they related to (for example, weight would affect performance and portability). Also, some decisions had to be made on a basis of cultural differences; the author's previous trips provided the understanding by which such decisions could be made. After several months of development, a final design was created with a combination of several ideas, ready for implementation.

5. FINAL DESIGN

The final design as it was taken on the implementation trip is shown in Figure 27. Because the second assessment trip was taken before conceptual designs had been deeply explored, the design was left in enough of an unfinished state to which necessary changes could be made at the outset of the implementation trip. This is not a recommended circumstance by the final conclusions of this thesis, for reasons to be detailed later in Section 7.

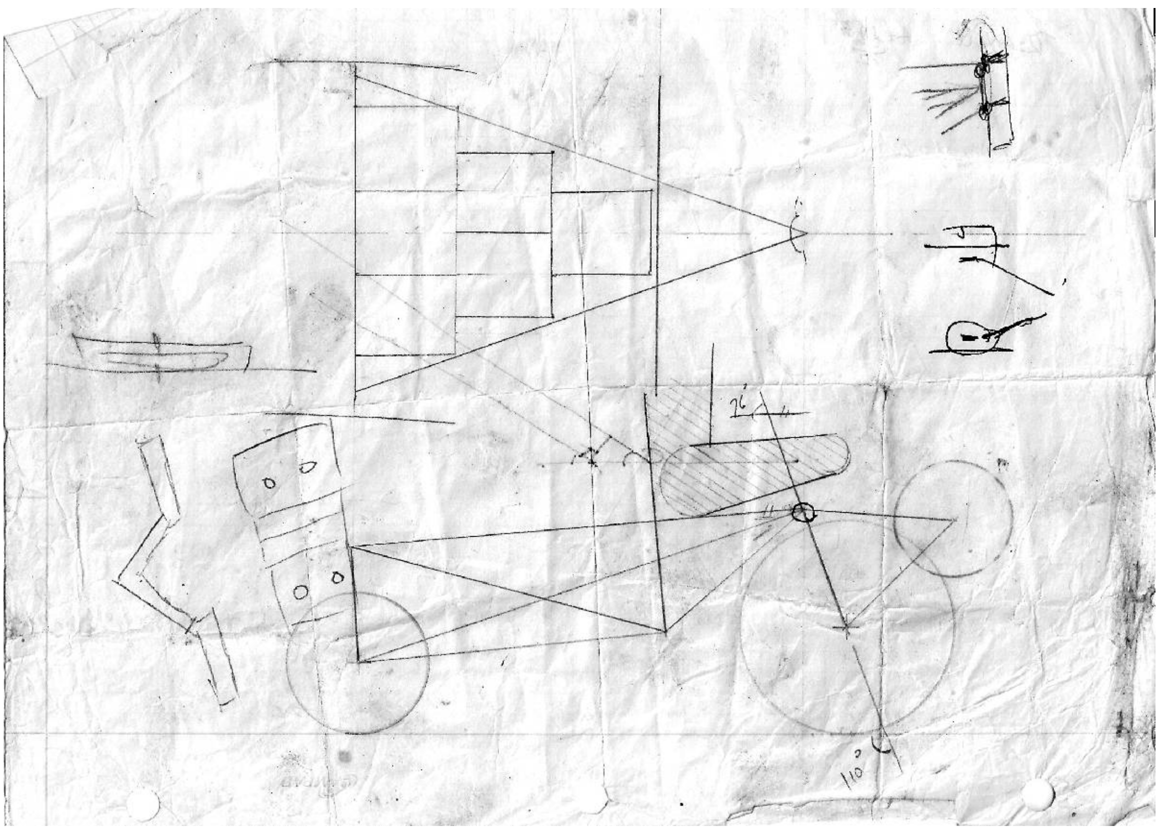

Figure 27: Final design as it was upon leaving for the implementation trip.

The simulations needed to ensure a safe, durable design with sufficient performance to meet specifications were taken on the trip on a portable computer, such that the calculations could be re-evaluated with refined estimates from the extra information needed on available materials and tools. These simulations were written in FreeMat, an open-source analysis program similar to MATLAB, and are available on the FreeMat website http://freemat.sf.net , as well as in Appendix A of this document. Figure 28 shows projected HPUV speeds for different loading conditions and time to exhaustion as functions of input power. These results were calculated using a closed-form solution proposed by Lieh (2006) to the loading case shown previously in Figure 25.

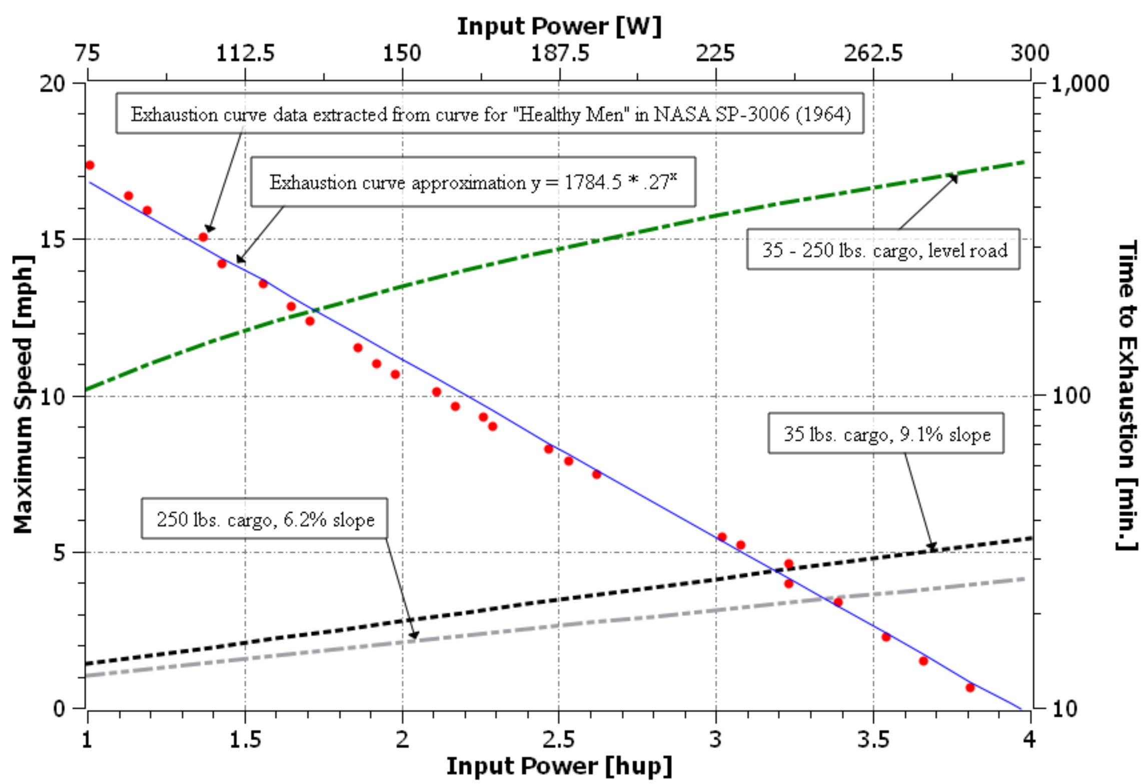

Figure 28: Plots of maximum speed and time to exhaustion for given input powers, based on a solution provided by Lieh (2006).

This final design consists of a three-wheeled vehicle with a detachable rear end that can double as the same cart that is so useful in the rural villages. The front end of the vehicle can also be attached to other objects easily, to apply human power implements such as mills or pumps where electricity is unavailable. This design can be built with two motorcycle wheels, 10 meters of round or square tubular steel and a single, multi-geared bicycle. This is less steel than is already used for a basic push-cart, and represents an actual decrease in cost to build a cart with the same capabilities. A single-geared bicycle could be used, but would have trouble meeting gradeability requirements with the limited torque a single human can produce with the pedals. One advantage to the design for such concerns is a wide rear end, capable of being pushed by other people to move extra-heavy loads, if necessary.

The design has a low enough center of gravity and wide enough half-tread distance to avoid tipping, and enough clearance (9”) for the rough roads common in the intended usage area (like the one shown in Figure 7). Figure 29 shows the results of a simulation of the HPUV's stability in a low-speed, rough-terrain turn. The black lines signify the stable wheelbase of the vehicle, while the different-colored points represent the projection of the center of mass's acceleration onto it with different cargo weights. This simulation assumed a speed of 3.5 mph, a turn radius of 10 feet and a rut depth of 8 inches, as measured from initial benchmarking. The simulation calculated all possible positions of the three different wheels passing through a single rut, hence the multiple points on the graph. So long as the points remain inside the wheelbase projection (as is the case here), the vehicle should not tip under these conditions. The CG diagram used for these calculations is shown in Figure 30.

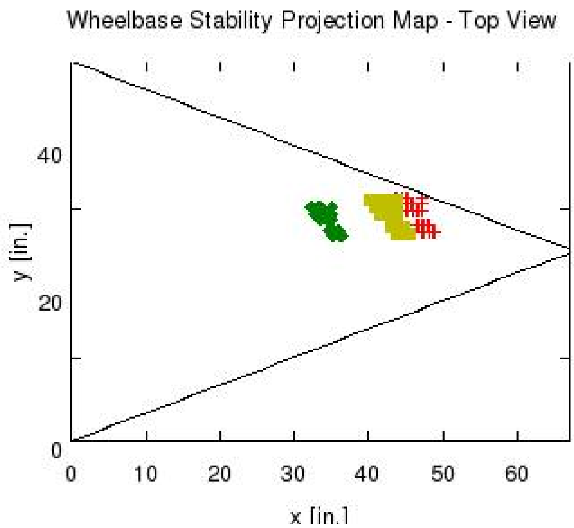

Figure 29: Projection of CG acceleration onto wheelbase in an uneven right-hand turn. Red, yellow and green points represent cargoes of 0, 40 and 250 lbs., respectively.

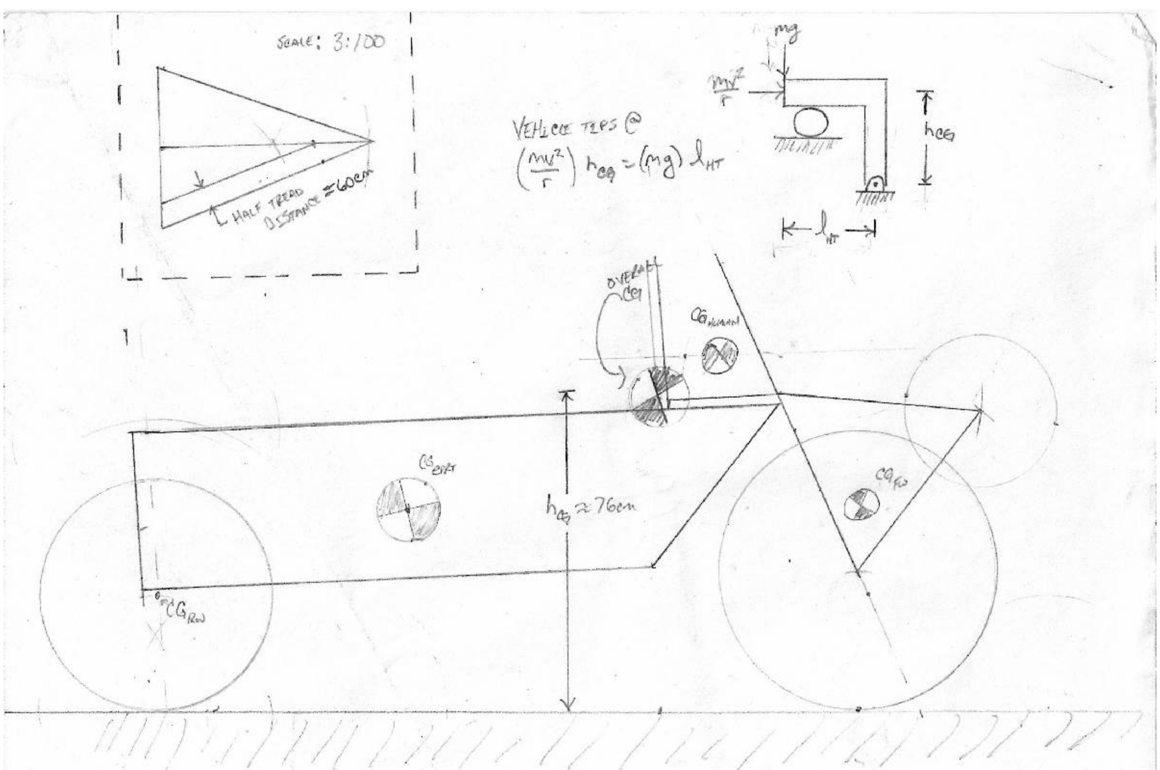

Figure 30: Dimensional sketch showing CG positioning for calculations.

The wide, open area on the back of the vehicle allows for the connection of other implements such as winches, plows and the like, and the bolt-on connection at the front, shown in Figures 31 and 32, allows for connection of the cart to a myriad of different power sources. Mechanical stresses were calculated for various aspects of the bolt-on connection, as shown in Figure 31. Bolt stresses are sufficiently low that four 10mm steel bolts could carry the stress needed for the vehicle's normal operation.

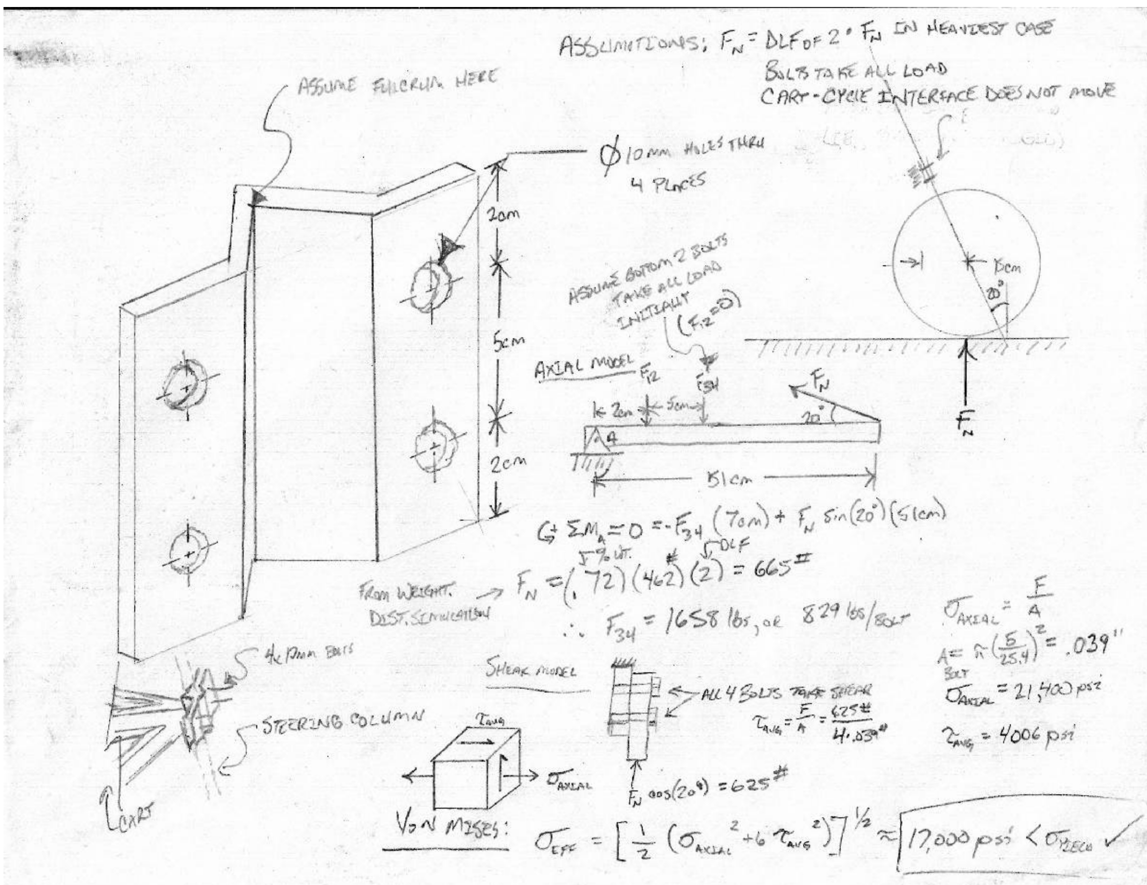

Figure 31: Example of bolt stress calculations for removable interface.

Figure 32: Bolt-on interface on final vehicle, allowing for connection to other implements

The HPUV cart uses less tubular steel than the original pousse-pousse design, while increasing its ability to carry weight over rough terrain. It is buildable using only basic technologies, without the need for any advanced machine tools. The design was focused on making construction easy, and accomplishes this with its simple triangular frame. Each of the three sides of the frame can be built on a flat jig, which is easily built with plank wood and pieces of scrap, as shown in Figure 33. Each of these sides can then be put together to easily construct the final 3-dimensional frame.

Figure 33: Jigging being constructed from a cheap plank and small scraps of wood.

With human power, the HPUV produces no emissions in its operation. It can be easily built and repaired in the village using materials that are easily available at the local city-center. The operation of the vehicle is still somewhat labor-intensive, and it can easily be used for many different tasks. The HPUV simulations also show that the design should meet the performance criteria set forward in the initial assessment trips, shown in Table 3. The final design, as presented here, meets the seven appropriate technology criteria listed in the Introduction section for review, and the feasibility calculations in this and the previous section show that it should be able to meet the design criteria and specifications. The actual construction and performance of the vehicle are reviewed in the next section.

6. IMPLEMENTATION

The culmination of this design project was in the implementation and testing of the design in its intended environment. A brief trip log can be found in Appendix B. This section will discuss some of the specific lessons learned from the project, and present the final cost assessment and customer feedback of the design prototype.

6.1 Trip Planning/Scheduling/Budgeting

Planning for the final implementation trip began almost a year beforehand. Currently, travel to most developing countries requires extensive time to acquire visas and vaccinations and to prepare project schedules and budgets. With a travel date in mind, backward scheduling was used to distribute the remaining time available to the different tasks yet to be completed.

Especially useful was a large calendar with deadlines and associated completion goals for the different tasks. For example, visas can take up to a week to process, so including shipping times, it was necessary to have my passport mailed by, at the very latest, two weeks before traveling. This calendar, reproduced in Appendix B, served to keep the design project and trip preparations on task and on-time.

Health

Vaccinations need to begin more than several months before traveling to a country such as Cameroon. Planning should include an investigation into what vaccinations and prophylaxis will be needed on the trip. The United States' Center for Disease Control (CDC) details the different vaccinations and health warnings appropriate for different locations around the world on their website, www.cdc.gov. For this particular trip, vaccinations were needed for typhoid, yellow fever, meningitis, hepatitis A and. B, smallpox, tetanus and rabies. These were all readily available at a local health department for a total of roughly $300. Malaria prophylaxis was also necessary, a common need throughout most of the developing world. Figure 34 shows a map of malaria endemicity from the CDC as of 2003.

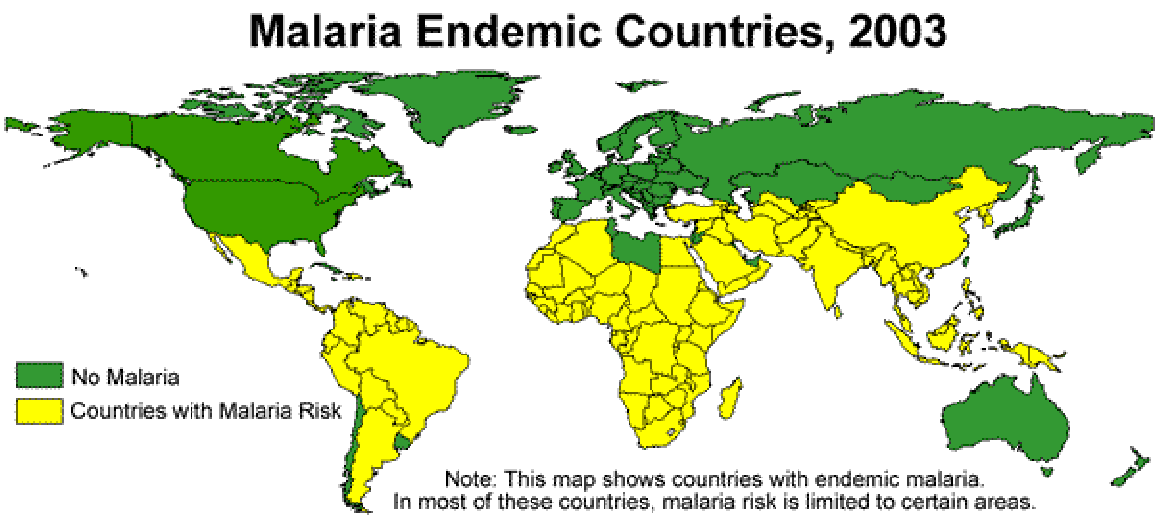

Figure 34: CDC world map of malaria endemicity, from Wikimedia 2008.

Local Contact/NGO Planning

It is essential to communicate with the local contact and NGO during the planning of the implementation trip. The local contact for the HPUV project, a Peace Corps volunteer in Mèri, helped with scheduling train tickets, bus rides, and pricing for the trip budget in general. Contact with the NGO was also established during the planning phase of the trip, to explain the intentions and goals of the project, and to set up a time to present the project results and plans to the NGO's local director.

6.2 Vehicle Construction

Vehicle construction began once the materials for the vehicle were purchased. Due to some scheduling issues, a week of inactivity due to sickness and a week of inactivity from having no electricity, the fabrication phase of the implementation trip started later and took longer than planned. The HPUV was built over the course of four weeks, averaging three days of work per week and totaling 150 man-hours of labor. The final cost to produce the vehicle was near $300, as discussed in detail in Section 6.5. Over the course of the HPUV's construction, both the mechanics and the designer learned some important lessons:

Teamwork

The need for a multi-member, cross-functional engineering team became readily evident over the course of the implementation trip. Because the design was the sole trained engineer working on the project, when his presence was not possible at the build site, the project was stalled. For reasons such as contraction of worms, amoebic dysentery and a severe bacterial infection, as well as issues with transportation to the build site, the need for one specific person wasted several weeks of fabrication time. This resulted in a limited testing phase for the vehicle, as well as an inability to implement additional features to the design. A team whose members are trained in each other's functions could have made up for the absence of a single member would have been able to work around these problems, and could have split up time-consuming tasks such as finding materials and completing documentation. While the HPUV was still finished and tested, the project would have gone more smoothly with a larger team.

Jigging/Fixturing

The concept of building jigging and fixturing seemed foreign to the local workers when it was first suggested. Such construction was deemed a waste of materials, which can often be hard to come by. In a community where hinges are made from nails and scrap sheet metal because $1.00 is too much to spend on a commercially-made item, the idea of using wood that is otherwise perfect for furniture construction as a sacrificial fixture piece to be burned with a welder seemed wasteful at best. The first day of fabrication was spent building nothing but jigging, much to the confusion of the local mechanics. Once welding was underway, however, they quickly came to like the jigs, preferring to use them over their usual methods of tack-welding and adjusting each piece. They seemed to agree that the jigging made the job much easier and faster, and said they were glad the time was invested to build it in the first place. Figure 35 shows one of the jigs as it was being built, while Figure 36 shows a drawing of the jig.

Figure 35: Wooden jigs being built at the outset of fabrication in July.

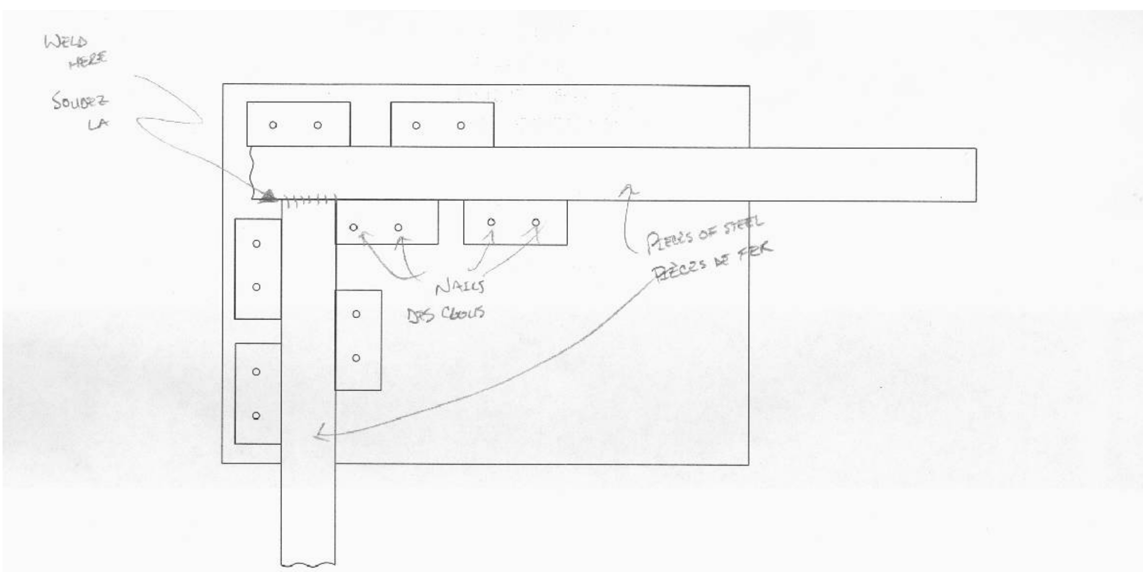

Figure 36: Design drawing of jig structure

Daily Preparation

For roughly the first week of fabrication, ten to twenty awkward minutes began each day as the mechanics waited for instruction. Because specific tasks had not been laid out beforehand by the designer, it took time each day to decide what to do and who should do it. As the fabrication went on, however, more planning took place each night for the next day, planning specific simultaneous tasks to make the most of each labor day. These small planning sessions before meeting with the mechanics made the daily fabrication efforts more comfortable for all involved, as well as more efficient.

Rest and Relaxation

During the third week of fabrication, the local Peace Corps contact suggested purchasing a case of pop for the team of workers in the afternoon heat. Retiring for the day to some cold drinks in the shade allowed for some lively conversation to ensue, during which some of the public's reactions to the project, as well as the opinions of the workers were communicated. Until this point, it was unknown to the local contact or the designer just how widespread news of the vehicle had been, not to mention that the mechanics said they had people asking to purchase the vehicle or a copy of it, before significant fabrication had even taken place. Apparently the public was very excited about the prospects of the design, and were pleased with the design's concept and operating principles. This rest and relaxation time became part of the daily routine, and served as a good time for reflection, communication and relaxed conversation between the team members. Figure 37 shows the team sharing drinks and ideas.

Figure 37: The HPUV fabrication team rests after a day of labor.

6.3 Technology Transfer/Design Dissemination

Technology transfer took place on several levels. First, by the training of the local mechanics during the HPUV fabrication, second, in the presentation of the plans and connection of the NGO Heifer International with the local mechanics who were trained, and finally by the publishing of the final design in several different public venues. This knowledge transfer was a learning experience , because the usual means to transfer and document the details of a design were not as effective as other methods in the rural areas.

Design Documentation

The usual methods for documenting the design for fabricators wasn't effective for several reasons. First, local mechanics are rarely trained to read modern drafting standards. Secondly, the documentation needs to be in a language they understand, which, although the area is Francophonic, is not always French. Local languages do not have a written form, so detailed, obvious graphics need to be used to show the construction patterns for the jigging and the final design. A document packet should include the actual technical drawings for engineers to reference, but should also include such methods to allow the design to transcend language and education barriers. The final drawing packet for this project can be found in Appendix C.

NGO Involvement

The NGO Heifer International became involved with the HPUV project only during the final implementation trip. Contact was first established with them at the beginning of the trip, and they were very interested to see the results and to use the technology in conjunction with their other programs. Upon seeing the basic design sketches and hearing the explanation of the project's goals, they mentioned that it would be immensely useful if the vehicle's rear end could be connected to an animal such as a donkey. Heifer distributes animals and develops technologies to help farmers care for the animals in areas where this is difficult (such as Mèri).

Heifer's interest in the project, as well as their ideas for other people and communities who would be interested to work on it were indicative of a group who would have had some worthwhile input if they had been involved in the design process. In future projects, once a problem statement has been developed, an appropriate NGO should be sought out and involved in the project, possibly even during the first assessment trip. Their input will likely be invaluable. At the end of the implementation trip, the NGO was given the documentation packet, testing and feedback results for the design, as well as price lists and a proposed business plan.

6.4 Vehicle Testing/Design Feedback

Construction of the HPUV was finished two days before the end of the implementation trip, allowing only for a day of testing and feedback. Before the vehicle was even ready to operate, six excited children climbed onto the machine at the same time, severely straining the welds on the vehicle-cart interface. This was repaired, and the vehicle finally brought to a state ready for testing. The final product is shown in Figure 38.

Figure 38: The finished HPUV prototype with the local mechanics and author.

With respect to the initial customer specifications for load capacity and gradeability, the HPUV is a successful design. With little effort, it was possible to carry two of the mechanics over level ground (well over 250 lbs.). The gearing made negotiating the outlined grades of 6.2% and 9.1% with the different loads possible, although strenuous. An additional torque converter, possibly in the form of the CVT mentioned in the product benchmarking section, could reduce cost, while reducing the torque necessary for the ascension of steep grades.

The prototype also remained stable over rough terrain, and capably traversed ruts as deep as the rear wheels would allow (greater than 9 inches). The trail on the front wheel, however, was too great, resulting in significant side-loading of the wheel in a turn when the vehicle carried high loads. This could be avoided by centralizing higher loads near the back end of the vehicle, but reducing the trail is the better solution for the long-term.

Initial customer feedback on actually driving the vehicle showed a liking to the vehicle's operation, although several noted the learning curve with the new cycling position. Steering the drive wheel with one's feet on the pedals seemed odd at first, and some instruction was required to help the local customers effectively pilot the vehicle.

The customers were surprised at how few *people* the vehicle could carry (small children were disappointed when they learned that no more than 4 or 5 of them could get on at a time), but in terms of transporting goods or one person at a time, they were impressed with the ability to move loads. It is easy to forget how dense people are – almost five times as dense as a sack of millet. The original 6 young men who wanted to get on at the same time would have weighed well over a half ton, and likely would have broken the vehicle frame.

All together, customer feedback on the design was positive, especially with respect to the usability of the rear end of the vehicle as a cheaper, more effective cart, and the fact that it was human-powered. The new riding position was strange to most people at first, but the learning curve was shallow enough for most people to use the vehicle quickly. Design revision and further testing is required for the front wheel trail, but beyond that, the design was an overall success.

6.5 Final Cost Assessment

Table 8 details the actual costs of the project in terms of material, tooling and labor. The final cost of the vehicle is $319, approximately 50% of the projected cost from the initial assessment. According to the methods used in the Feasibility Analysis in Section 4, this results in a rate of return of 47%. Similarly, the vehicle would recoup its cost over its two year life at a rental rate of around 300 CFA (roughly $0.68) per day, which is roughly the same cost of renting a simple pousse-pousse like the one in Figure 2. This is easily affordable for regular use, but the up-front costs to purchase an entire vehicle are almost prohibitive for most families in communities such as Mèri. An NGO, however, can easily afford the initial investment with the prospect of such returns. A new pousse-pousse costs 60,000 CFA; for the cost of two of these simple carts, a multi-use vehicle with the same useful, detachable cart can be built. Also, the mechanics who built the first prototype had cost-saving measures that could further significantly decrease the cost of the vehicle by producing the front end from raw materials rather than purchasing an entire bicycle at the market. Cost reductions based on their suggestions would amount to roughly 30% of the total cost of the HPUV, increasing accessibility to more people.

Table 8: Actual material, tooling and labor prices for final vehicle construction.

Item	Qty.	Price [CFA]	Ext. Price[CFA]	Ext. Price [$]
Materials				
Rear Wheel Innertubes	2	1000	2000	$4.76
Rear Wheel Tires	2	3500	7000	$16.67
Rear Wheel Spoke Sets	2	500	1000	$2.38
Rear Wheel Hubs	2	2500	5000	$11.90
Rear wheel Rims	2	3500	7000	$16.67
Rear Wheel Mounting Plates	4	250	1000	$2.38
Square Tube, 30mm x 1mm x 5m	2	4500	9000	$21.43
Mountain Bike (velo)	1	70000	70000	$166.67
Steel Angle, 30mm x 2mm x 150mm	1	500	500	$1.19
Bolts, 10mm w/ nuts	4	100	400	$0.95
Mat'l Transport from Maroua	1	2000	2000	$4.76
Tooling				
Welding Rod, 2.5mm x 1kg	1	900	900	$2.14
Hacksaw Blade, 8mm x 250mm	1	500	500	$1.19
Grinding Wheel	1	800	800	$1.90
Labor				
Skilled Man-Hours	180	150	27000	$64.29
		Total	**107100**	**$319.29**

Another important assessment is that of the project costs, in human as well as physical capital. There is a significant investment of time and money for travel, supplies and communication. The many costs incurred over the course of such a project are quite significant. Table 9 itemizes the costs of this project, from the initial assessment trips to the final implementation, and Table 10 estimates engineering time and resources spent over the course of the design process, between the first assessment trip and the final implementation. The costs in Table 9 are greatly simplified and combined to enhance readability; the actual cost breakdown of expenditures over the three trips is quite large. A fully-detailed budget for the implementation trip can be found in Appendix B.

When considering the cost to develop new technologies, it is important to understand the resources that will be necessary. Table 10 shows the scale of investment in the development of the HPUV: just under 3 man-months, and just over $14,000. The man-hours put into the project could have likely been reduced by the involvement of more people in the design and report generation. Splitting up tasks can speed them up, and teams with multi-functional roles tend to have more diverse ideas for concept generation, resulting in more innovative designs. Such a team could have improved the HPUV by providing it with additional simple features, or by further optimizing its design.

Table 9: Actual project trip costs for assessment and implementation.

Item	Qty.	Price [USD]	Ext. Price [USD]
Initial Assessment Trip			
Vaccinations, total	1	$310.00	$310.00
Malaria prophylaxis, 9 weeks	1	$150.00	$150.00
Airfare, JFK-NDJ round-trip	1	$2,900.00	$2,900.00
Hotel in N'Djamena, per night	1	$205.00	$205.00
Car from N'Djamena to Meri, round-trip	1	$300.00	$300.00
Groceries, per week	3	$20.00	$60.00
Rent/utilities for homestay, entire trip	1	$40.00	$40.00
Motorcycle trip to Maroua, one way	2	$6.00	$12.00
Hotel in Maroua, per night	2	$30.00	$60.00
Visa fees, long stay, multiple visit	1	$460.00	$460.00
Misc. expenditures	1	$80.00	$80.00
Secondary Assessment Trip			
Vaccinations, total	1	$95.00	$95.00
Malaria prophylaxis, 12 weeks	1	$195.00	$195.00
Airfare, JFK-NDJ round-trip	1	$3,100.00	$3,100.00
Hotel in N'Djamena, per night	1	$205.00	$205.00
Car from N'Djamena to Meri, round-trip	1	$150.00	$150.00
Groceries, per week	6	$20.00	$120.00
Rent/utilities for homestay, entire trip	1	$75.00	$75.00
Motorcycle trip to Maroua, one way	4	$6.00	$24.00
Hotel in Maroua, per night	4	$30.00	$120.00
Misc. expenditures	1	$150.00	$150.00
Implementation Trip			
Malaria prophylaxis, 16 weeks	1	$260.00	$260.00
Airfare, DTW-YAO, round-trip	1	$2,983.00	$2,983.00
Cameroon visa fee, short stay, single visit	1	$115.00	$115.00
Transport, Yaounde to village, round-trip	1	$350.00	$350.00
Food for trip to village, one way	2	$30.00	$60.00
Hotel stays from Yaounde to village, one way	2	$140.00	$280.00
Transport to Maroua, round-trip	8	$12.00	$96.00
Hotel stays in Maroua, per night	6	$22.00	$132.00
Project mat'l and labor costs	1	$350.00	$350.00
Rent/utilities, per month	3	$50.00	$150.00
Groceries, per week	12	$20.00	$240.00
Communication/Internet cafe time	7	$1.50	$10.50
		Total	**$13,837.50**

Even for this small project, significant resources, human and capital, were required to make the design a success. Most of the cost is from the assessment and implementation trips: 63% of the final $14,000 investment is in airfare alone. The need to travel to the site and understand the problem, however, is the most important element in developing an effective solution. The many resources to develop these technologies outlines the need for a good design process with feasibility analysis and direct involvement of the customer and local volunteering professionals. While such oversight in the process does not guarantee the success of a design, it works to significantly decrease its chances of complete failure, protecting such a large investment.

Table 10: Man-hours spent and capital invested in various aspects of the HPUV project.

Item	Man-Hours Spent	Money Spent [USD]
Trip research/planning	40	
Communication with int'l contact	5	$81.00
Background search/benchmarking	75	
Assessment trips (assume 40 hr. weeks)	360	$8,815.00
Concept generation/refinement	80	
Financial planning/grant proposal	150	
Design/analysis	270	
Pre-implementation fabrication	30	$264.00
Implementation trip	480	$4,884.50
Design fabrication/testing	220	
Final report generation	320	
Design documentation/drafting	35	
Final communication/document publishing	15	$30.00
Total	**2080**	**$14,074.50**

Larger development projects will require even more investment of time and money. The cost of moving a whole team of engineers to a location such as Mèri would be in the tens of thousands of dollars for a single trip. As the developing world becomes more accessible to transportation and flights in and out of the major cities become more common, these prices will likely fall, allowing for a rather significant reduction in the capital involved. The man-hours for such a project, however, will likely remain high when operating in a different country and culture. It is necessary to spend significant time in the community, getting to understand the people, the problems, and the world surrounding them. This time investment provides an education for the engineer that no amount of reading or speaking with a local contact can, and such an education is crucial for the success of any technical project in the long-term.

7. CONCLUSIONS

Over the course of the conceptual design and implementation, key design criteria and design process steps for appropriate technology development were examined. The effectiveness of these criteria and process steps in developing useful, sustainable designs can now be discussed, along with recommendations for revision for future projects and lessons learned.

7.1 Evaluation of Appropriate Technology Criteria

Most of the common literature on the subject of appropriate technology, as has been discussed previously, is around three decades old at the time of this writing. The HPUV was designed to fulfill the criteria found in this literature, such that their effectiveness could be examined. The following is an evaluation of the seven criteria mentioned in the Introduction section of this thesis by the experience and feedback from this project.

1.) Appropriate technology should require only small-scale capital investment

Extreme poverty is often a major inhibitor to development, and is therefore present in most developing areas. It is difficult for such people and communities to make large investments in new technologies, so there is a perceived need for designs to require only very small amounts of capital for their production. In many cases, a machine's effectiveness or profitability can be significantly increased by implementing slightly more expensive features. So long as a feasible business plan is developed, such that the machine's operating cost is affordable to the end user, the machine will retain its usefulness.

In this project, a type of bicycle (referred to as a 'velo' in local French, as opposed to a 'bicyclette') was used that is commonly available in markets, but rarely purchased by farmers and other villagers. The two different types of bicycle are shown in Figures 39 and 40. Investing the extra capital for the “velo” was necessary for the ability of the vehicle to transport heavy loads, but this represents a large amount of capital not commonly available to local people. It is, however, affordably covered in operating costs as outlined in the Final Cost Assessment of the Implementation section. The use of the more expensive bicycle is essential to the design's operation and is still affordable to common people, but requires a significant initial investment of capital in local terms.

Figure 39: Mountain bike with different speeds, known as a "velo".

Figure 40: Local mechanics fix a Nigerian-made "bicyclette".

2.) Appropriate technology should be buildable and maintainable using locally available materials and technologies.

This criterion is of utmost importance. Figure 41 shows a pump in Maase-Offinso, Ghana that was originally installed in 1986. Since then, it has failed multiple times, each time leaving the community without sanitary means for water retrieval for months. This is due to the expensive and difficult process of having the motor repaired or replaced, neither of which can be done in the village. The model used for this project was one that considered a production area at the local city center (Maroua), and a usage area of more rural locations (Meri). This allowed more availability of materials, so long as there were repair and maintenance capabilities in the usage area. To achieve this end, FMEA should be used to ensure high-risk failure modes are either repairable or replaceable on-site.

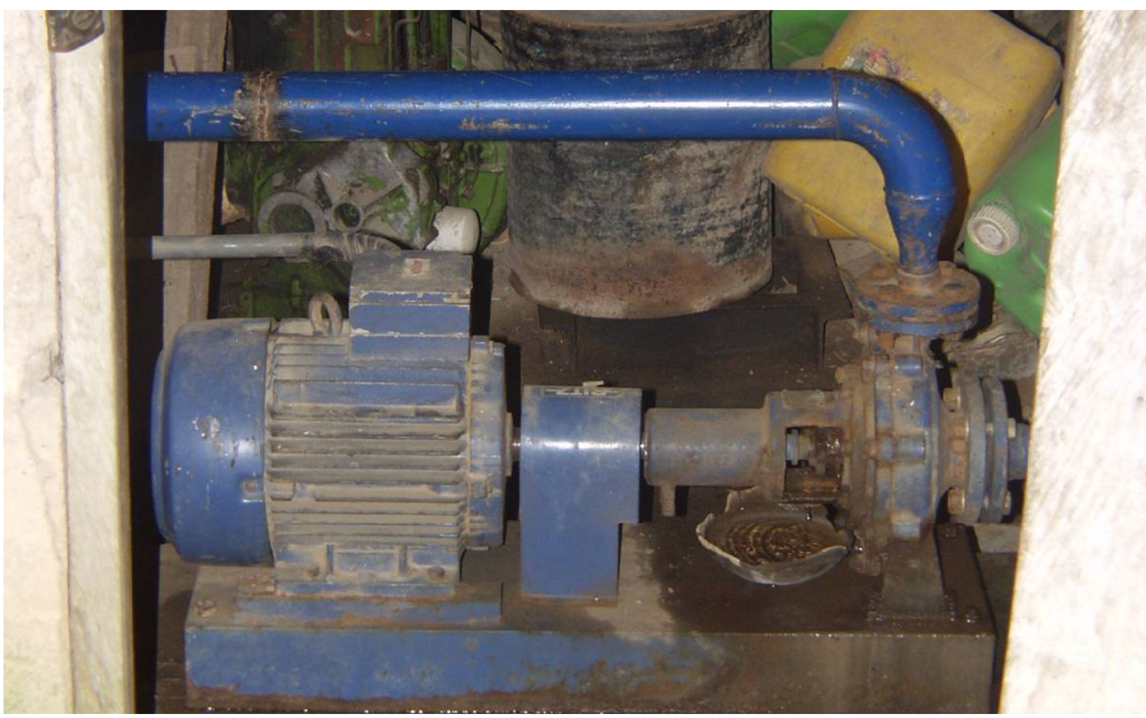

Figure 41: Centrifugal pump driven by electric motor in Maase-Offinso, Ghana.

Initial assessment of available materials on-site and at local-city centers can be difficult, because it is unknown at first what specific materials will be needed. For this reason, it is important to conduct at least one assessment trip after design concepts have been generated, allowing for revision to ideas, and refined product searches for more specific materials. In this project, a true second assessment trip couldn't be fully conducted, so some of the final design decisions and drafting had to be left to the last minute. This, in turn, delayed the construction of the vehicle, and made the project rushed at the end of the trip, and limited the amount of testing that could be conducted. To this end, it is again useful to have a contact in-country if a second trip proves infeasible.

3.)Appropriate technology should be labor-intensive in its operation.

The need for labor-intensity in the operation of appropriate technology designs is outlined in many sources, but it is not necessary. This perceived need is due to the additional employment opportunities seemingly thereby created. One must keep in mind, however, that technology serves to enable people to extend their skills, and this often involves the elimination of menial tasks. One technology that does this is a hand-cranked water pump, such as the one shown in Figure 42. Usually, water is retrieved by the women of a household by walking to wells that can be up to 2 miles from their home. This technology significantly eliminates labor intensity in the need to travel to wells far from the village, making water more accessible to more people.

Figure 42: Hand-operated water pump that improves water retrieval.

Using the HPUV project as an example, labor-intense technologies already exist for moving crops from one place to another. Whether by cart, bicycle or by hand, the crops can possibly be moved to other markets, and indeed, this is currently done to some extent, as shown in Figure 43. The problem, however, is that there is too much labor-intensity for the task, due both to unreliability in the machines in use (bicycles often break when overloaded with heavy loads), and an inability of the current machinery to easily accommodate the loads a human is capable of moving. This design removes such intensity, and is much to the farmer's advantage. The cart pusher, cyclist or carrier can still perform his or her task using the new vehicle, without fear of a lack of goods to transport. Now, however, instead of the single *tasse* (one bunch) of wood, the HPUV enables a single cyclist to move up to 6 *tasses* at a time, safely and reliably.

Figure 43: A cyclist transports a tasse of wood to the local city center by bicycle.

A significant role of technology is allowing people to use their minds and bodies in more productive ways. By reducing the labor intensity of tasks such as transportation, small-scale village economies benefit from the increased availability of goods and services. Perhaps a better criterion would be “Appropriate technology should be an enabling technology by stimulating economic freedom.”

4.) Appropriate technology should be affordable to the local populace.

Economic benchmarking is usually the most difficult for projects in developing communities. Poverty has proven difficult to succinctly define, much less measure. A design's affordability to the customer is integral to the design's success, so specific understanding of their purchasing power. This must be commensurate with the cost to the end-user as outlined in the business plan.

The design, however, does not need to be affordable to a single person or family to be effective. The new face of development lies with small companies and NGOs, which tend to have considerable buying power in rural markets, so long as their business plans are, in the end, profitable. The HPUV, for example, costs approximately 90,000 CFA to produce. An average family in the intended usage area can reasonably expect to have a yearly surplus of roughly 10,000 CFA for spending. Thus, such a vehicle would need to be subsidized by eight other families harvest weeks. An NGO, on the other hand, provides the up-front capital, such that a more effective machine, cheap in its operational cost, can be easily subsidized by dozens of families without difficulties scheduling usage. This is a common mode of business throughout much of West Africa, and is effective in the distribution of the otherwise unaffordable cost of many machines.

5.)Appropriate technology should be understandable to local people for construction, maintenance and modification.

It is essential that a design be buildable and maintainable locally, and this is only possible if some of the local people can understand how to do so. It is not, however, necessary for everyone to understand precisely how the technology works, although this can be a good feature. Much like the developed world, where people routinely take their automobiles to mechanics, there are local people in these rural locations who are usually good at fixing things and solving problems. So long as these people can understand how to maintain or fix the vehicle, it will be possible to operate the vehicle sustainably in the village.

It is important that the construction of the vehicle be feasible with local technical workers. It is important that these workers have a fundamental understanding of the machine's operation and limitations, and what can be safely modified, because modification in areas with such diverse problem sets is inevitable. For example, one adaptation of the pousse-pousse shown in Figure 2 is capable of carrying much heavier loads that would otherwise break the wheels of a normal pousse-pousse. To counter this, the spokes of the wheel have been replaced with solid steel rebar, which can be an effective solution. Such modification is common with the many other machines found in these areas.

To this end, the designer or design team should prepare a document package such as the one for this project found in Appendix C, and must fulfill the needs of technology transfer, as will be discussed in detail in Section 7.2. This will enable the continuing dissemination of knowledge in communities even beyond the ones involved in the implementation trip. This step will sometimes require a significant investment of time during the secondary assessment and final implementation trips. The NGO and local contact play a critical role in this transfer, providing translation and education where necessary, and distributing the knowledge to new workers in different villages even after the engineering team has left.

6.) Appropriate technology should be adaptable for different uses, locations and circumstances.

The wide range of problems one encounters in the developing world is astounding. An MIT Focus group who runs the International Development Design Summit dedicated to developing appropriate technologies for developing communities has produced numerous designs and still finds plenty of work (IDDS 2008). Even over the course of this implementation project, applications and modification ideas for the vehicle surfaced that went unconsidered throughout the design process. This does not necessarily signify a failure in the process, but highlights the need for final designs to include adaptability and robustness in their criteria. Like the heavily-loaded bicycle previously shown in Figure 43, when machines are in short supply, they are often used to complete a rather diverse selection of tasks.

One group expressed the need for the vehicle to be adaptable for use with animals, as animals are available in the southern region of Cameroon. This would transform the human-powered cart into something capable of moving even heavier loads, for possibly a marginal extra cost. The idea that the cart be capable of standing alone was a feature included in the design by way of the removable drive mechanism. Other problems experienced during the power outages throughout the project made clear the usefulness of attaching a v-belt sheave or generator to the drive mechanism to power equipment such as mills and pumps. There was not sufficient time to incorporate such a feature on the implementation trip due to scheduling problems, but such modification is well within the skill sets of the local mechanics trained to construct the vehicle, and the design is robust and simplified enough to allow such modification.

7.) Appropriate technology should be environmentally friendly and sustainable.

The impacts of technology on the environment have, in recent years, come to the forefront of worldwide societal issues. From production of food an electricity to transportation of people and goods, many technologies supporting our worldwide needs today are proving environmentally harmful and unsustainable. In some cases, it may soon be necessary to abandon infrastructures built around such technologies in favor of more sustainable methods, at great cost. The developing world presents a chance both to avoid such problems through foresight in design, and to serve as an effective demonstration of sustainable technologies to other societies who are not so quick to adopt new methods.

Long-term environmental impacts, while sometimes difficult to assess, must be weighed in the conceptual design selection, with the understanding that it may rule out otherwise promising or advantageous designs. For example, many developing countries lack the emissions standards commonly found in more developed urban areas. Because of this, it is often easy to operate cheaper vehicles with cheaper fuel in the developing country, much to an economic advantage. Many visitors have noted, however, the air quality problems also common in such areas, to the extent that large cities in China today require the use of masks to protect one's lungs from the outside air.

Some balance must be struck between the design criteria, and this one must not be ignored. This project, while a poor case study for trading off performance or other advantages in the name of the environment, represents an effective combination that simultaneously meets the different criteria for performance, economy, environmental-friendliness and sustainability. Such synergies must be pursued in future designs to ensure development will not one day create worse problems than it solves.

Sustainability is also important. Many large-scale infrastructure problems in the developed world today, such as urban sprawl and the elimination of light rail in the United States stem from a lack of sustainability in infrastructure planning and design. As these lessons are being highlighted by the contemporary problems they cause, it becomes clear that the stewards of new development must learn from the shortcomings of past designs. It was mentioned in Section 1 that the introduction of technologies into a society not ready to support them can cause more harm than good. Figure 44 shows a typical paved road in rural Ghana. The road is visibly in disrepair, due to a lack of funding to upkeep the road. The adoption of vehicles designed for a more developed road infrastructure has caused these developing governments to invest in a road structure that is, in their terms, not sustainable. This investment represents money that likely could have been more effectively used to the public's good, as the pavement reaches the end of its useful life.

Figure 44: A typical paved road in disrepair between Offinso and Kumasi, Ghana.

Human or animal power can be clean and reliable, and provides energy independence. Some of the most population-dense areas in the developed world use human power for transport extensively, simultaneously addressing environmental, public health and sustainability issues commonly associated with other forms of personal transport. This project has shown that human power combined with effective design can meet needs a community previously thought impossible. The concept that one could, under their own power, affordably move two sacks of millet to the local city center was unheard of. Now it is a reality, and that capability will be relatively unaffected by fluctuations in road quality or the availability of gasoline or livestock. It is this feature that seems to appeal to the end customers the most, and it is also this feature that makes the design an effective long-term solution.

7.2 Key Process Steps

Initial Assessment

This step can easily become overwhelming. The two important outcomes of this first trip are a refined problem statement and an understanding of some of the surrounding cultural and infrastructural constraints, sufficient that conceptual designs can be generated. It is important to become familiar with local customs and culture, to the extent that one will need specific training or instruction on local customs and language, and should have a local resource as discussed in Section 6.1. Living in the community under study for a period of at least a few weeks is important to this end.

Developing a single, effective problem statement can be difficult because of the problem-rich environment found in these communities. Long hours of discussion with one's local resource can be a good starting point; NGOs and volunteers who have spent time in the area are likely acquainted with the local problems better than most. While many end-customers may not truly understand their problems (e.g.: in the village of Tourou, it is commonly believed that malaria can be caused by rain), these professionals are usually trained to understand the underlying causes enough to know They understand their needs in an end-based capacity better than anyone, and significant discussions and interviews with them can prove invaluable. It is the engineer's task, thereafter, to process the likely deluge of problems into a concise statement that can be realistically addressed with a design. This statement can be further revised after some benchmarking, as will be discussed in the next section.

Based on an initial feeling for the problem to be addressed, as much assessment as possible pertaining to that area of infrastructure should be conducted on the initial trip. Common questions of available materials and fabrication technologies should be answered in a significant appraisal of industrial technology in the village and at the local city center. Local resources can help locate technical workers and acquire accurate pricing information for goods and services. In order to generate feasible conceptual designs, it is important to have a good understanding for what materials and technologies are available. Also, based on this initial problem statement, an appropriate NGO should be selected to work closely with for the remainder of the project.

Probably the most challenging assessment is economic. Measuring poverty is difficult, as is understanding what is affordable in developing communities, given the nature of the subject. In many cultures, it is not appropriate to directly ask how much a person makes, what they can afford, or how much they can save. Even then, direct answers on the subject may prove dubious. Again, the most reliable resources are local volunteering professionals, NGOs and one's own experience with the current costs of local goods and services. It is thus useful to keep an accurate log of as many prices as possible for the different materials and items encountered over the course of the trip.

Not all questions can be answered on this trip. It is necessary to perform some benchmarking and to generate a refined set of directed questions from conceptual designs. These questions can then be answered on a second assessment trip, as will be discussed in the following sections.

Background Search

The main goals of the background search are threefold: to benchmark existing designs and solutions, to frame the problem with available background information, and to generate concepts to start the conceptual design process. This search should include the Internet, libraries, literature associated with intermediate and appropriate technology, and other development groups' websites and background literature. Good starting points include studies by the World Bank, the United Nations' development programs, and library sections on the developing or “third” world. Continued contact with the local resources from the first trip may also point to other beneficial sources of information.

Most of the problems in the developing world are not new. What generally makes them unique is the constraint set surrounding them, which can be quite severe. A lot of problems in northern Cameroonian farming, for instance, were also experienced by small-scale American farmers a hundred years ago. The problems (and, therefore, the solutions) for Cameroonians are different due to differences in the available materials and animals, climate, terrain and culture. It is therefore important, before starting design efforts anew, to search for existing technologies, ideas and designs that may help solve the problem.

For example, the bicycle trailers shown in Figures 11 and 12 were found by a simple Google Internet search for load carrying bicycles. These would not solve the transport needs of farmers in Mèri well, because they cannot carry enough load, are too expensive to buy directly, and are not necessarily compatible with the bicycles found in this community. The idea of connecting a bicycle drive to a removable trailer that can double as a cart, however, played an integral role in the design of the HPUV, as can be seen in the final design.

The ever-important understanding of the culture, economics and history of the region is also a key component of the background search. Prior assessments of the region's demographics, economics and present state of development are readily available from the World Bank's Development Indicators and other sources. There are many library volumes about the experiences of development workers in many parts of the world, and while many of these studies are old, they can still prove useful. In this respect, library books and online publications provided more information than technical journals for the HPUV project. This research serves to frame the problem in its unique context, and provides some more objective understanding of the social, economic and cultural climate surrounding the design effort.

As ideas are aggregated and studied, different conceptual designs should be generated as was done for this project, detailed in section 4. The concepts should be refined enough that basic sketches and descriptions can detail the proposed machine's operation, and how it could address different criteria and constraints. Decision matrices, plus-minus charts and basic simulation models are useful tools to filter many ideas into a reasonably refined concept, as was done in the Concept Selection stage of this project. Several concepts should be sufficiently explored that they can be taken on the second assessment trip to be reviewed with the customer, and the specific information needed to complete the design can be found and recorded. Once the concepts have been advanced to this level, the design team is ready for the second assessment trip.

Secondary Assessment

Design projects involve many questions, which must often be answered to know which questions to ask next. Because of this delayed response in information gathering, a second assessment trip is essential to developing a good design. This assessment trip should take place well after the first trip, such that conceptual designs can be well-explored and assessed for their feasibility as solutions to the problem under study. Product benchmarking and background searching should be complete, so the designers have in mind the various tools available to them for improvement on their design concepts over the course of the trip.

There are three main goals of this process step. First, this is a chance to take the conceptual designs back to the people in the village, as well as the local contacts and NGOs for their review. This allows them to input their ideas, which can serve to better tailor the design to their needs, and to revise the problem statement if needed. Providing the customer and local volunteering professionals with a fundamental understanding of the design being undertaken, its scope and its proposed methods allows them to see problems with both the stated problem and the proposed solutions the designers would not otherwise foresee.

For example, during the first assessment trip of the HPUV project, a group of engineers from a university in the United States was implementing a water filter design on their third and final trip to the nearby village of Tourou. They had taken two assessment trips, for roughly the same amount of time spent in-country as the HPUV project, but hadn't generated concepts before their second trip. Because of this, their local contact could not warn them of some obvious problems with their final solution. The team of engineers had developed an entire technology without any in-process feedback, resulting in a rather complete design and manufacturing plan, invested with the same magnitude of human and capital investment, but which was, in the end, unusable by the local population. Direct contact and involvement with the customer is one of the best tools available to improve the final success of the design.

Secondly, this trip allows further development of the conceptual design by answering otherwise unanswerable questions. A significant list of questions about each concept should be written before the trip, along with pictures and explanations of the different concepts. Over the course of the second trip, the designers should gather information pertaining to the specific needs of the different concepts including material and labor cost and availability, available tooling and any information needed to refine the feasibility assessments of the different concepts.

The second assessment trip of the HPUV project succeeded and failed at different aspects of this second goal. Some rough conceptual designs had been explored, but not in the depth needed to answer all the second-round questions. Product benchmarking and a background search were in-process, resulting in missed opportunities to present ideas such as the winch shown in Figure 15 to the customers. These two failures resulted in extra time being taken at the beginning of the implementation trip to actually locate the materials for the project, and missed opportunities with implements that would have significantly augmented the usefulness of the vehicle. This was due to both the reduced weighting of the additional implements' importance in the implementation trip schedule and the rushed final weeks of the implementation project.

The HPUV project found success with this second goal, however, in the gathering of the useful information and understanding needed to proceed with the conceptual design process. The conceptual design, at this point, was refined enough that customers could understand some of the possible pitfalls, and identify them early. Long conversations with local contacts and several customers in particular resulted in a solid establishment of the main criteria important to the end customers. The specific information gathered on available materials and local geography was sufficient to develop accurate simulation of the vehicle's strength and performance capability during the design process. These successes, combined with continued contact with the local volunteering professionals provided the means to develop a good final design, albeit with project planning problems in the final implementation trip.

The third and final goal of this step is to increase exposure to the end customer. Before the HPUV project's final implementation trip, five young men were already interested in becoming involved with the fabrication. Farmers up to 5 miles away had heard about the project's goals, and by the third week of the fabrication process, people were already asking the technical workers involved in the project if they could buy an HPUV. Figure 45 shows the entrance to the garage during the fourth day of fabrication. It was abnormal through the entire process to have less than five or six people watching the construction and asking questions about the design.

Figure 45: Local people watch the fabrication of the HPUV.

This exposure goes both ways in that the second exposure to the community garners more experience for the designers with the culture, the language, the customers and their surroundings. More time spent in the village generally equates to a better understanding of the environment into which the design is being placed, given that the right questions are asked and answered. The HPUV project taught local workers in Mèri and Douvangar how to build a vehicle, and some basics of its underlying mechanics. The engineer, however, likely learned more in interacting with the mechanics, watching them add their own touches to the final design and hearing them suggest uses and changes to the ideas being used.

Technology Transfer

One of the most essential elements to be addressed in development projects is technology transfer. The most effective problem solving can be accomplished by those who live the problems' realities day in and day out. Thus, it is not sufficient to transfer simply design drawings or specifications, nor is it sufficient to transfer them only to a few local people; the greatest gains for development come from the transfer of fundamental knowledge crucial to the design's physical limitations and performance to agents capable of redistribution of this knowledge.

In this project, for example, we designed a human-powered utility vehicle. Throughout the design process, many ideas were considered and filtered according to their projected effectiveness in fulfilling design constraints and criteria. Simply teaching the local mechanics the final design plans would skip much of this knowledge and understanding, which is necessary for the successful modification and improvement of the design in the future. In the spirit of transferring technology to spawn development, this knowledge and understanding must be disseminated to ensure the continuing fruitfulness of the project. Therefore, throughout the vehicle construction, the mechanics were taught the concepts of slip and torque limiting, how to calculate the balance of the vehicle, frame reinforcement techniques, and basic knowledge about structures and strength of materials. Most of this knowledge was anecdotal or greatly simplified, but in such a way that they would likely find it more useful than concepts they wouldn't likely understand without an accompanying engineering education.

The design was also presented to a local NGO. NGOs are playing an increasingly important role in worldwide development efforts in local capacities, serving as effective vehicles of technology distribution in rural areas. The NGO collaborated with over the course of this project, Heifer International, was excited to accept the design and establish contact with the local mechanics who were specifically trained in the construction of the vehicle. Their continuing exposure to different communities' needs in the region will likely provide other opportunities to apply the technology where it is needed, without the need for a professionally-trained engineer to revisit the problem.

A third venue in which the design will and should certainly be disseminated is the internet. Society has never before had such access to international communication as is enjoyed today. This communication provides a means to distribute knowledge and understanding throughout the world, and will be key in fueling international development efforts in even the most rural areas. Publishing plans, pictures and even commentaries from previous design projects provides significant guidance to future efforts in the same vein.

Another important subject in the transfer of knowledge is the way in which the information is presented. Modern drafting standards cannot effectively communicate designs to people who are not instructed how to read them. An example of such a technical drawing is shown in Figure 46. While such technical documents should be included in the drawing package for mass distribution, it is also useful to use other drafting methods to demonstrate the construction of the vehicle, such as color-coding, part numbering, and sequential, graphic-based assembly instructions. Such instructions should focus on the use of pictures instead of language when possible, and include any of the different translations that could be needed in the area. Such a document from this project is shown in Figure 47. These drawings were developed with the help of the mechanics working on this project, such that the end product would be something they would be able to easily understand. The entire drawing package can be found in Appendix C.

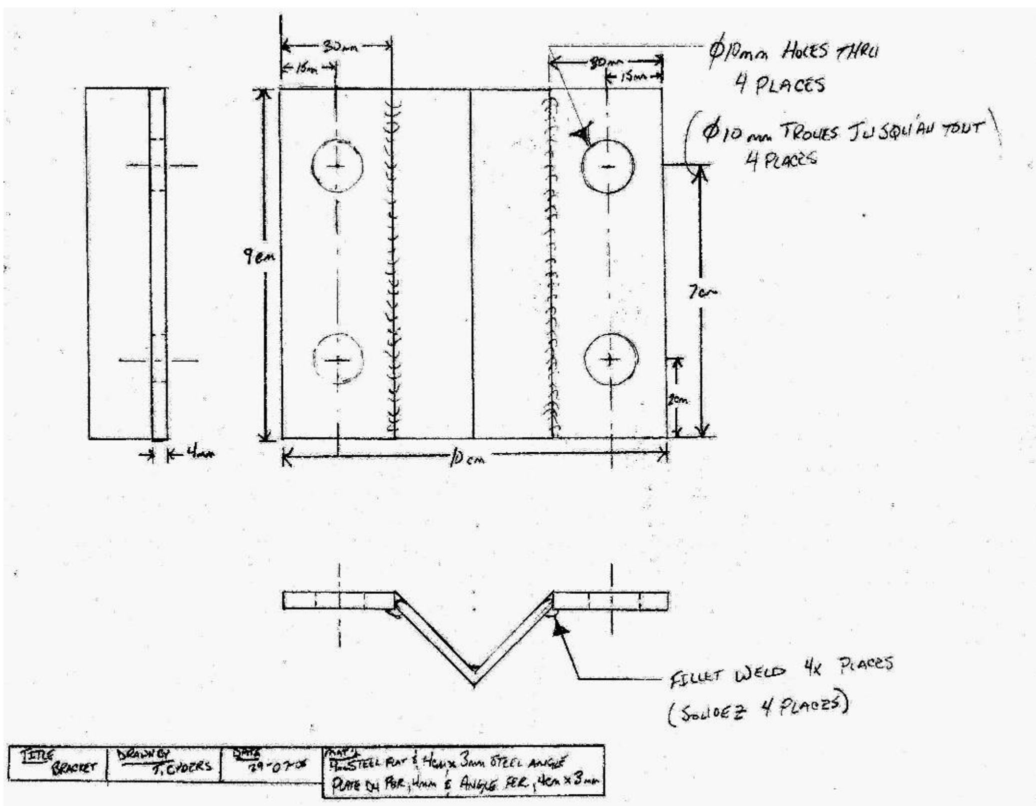

Figure 46: Technical drawing produced by modern drafting standards.

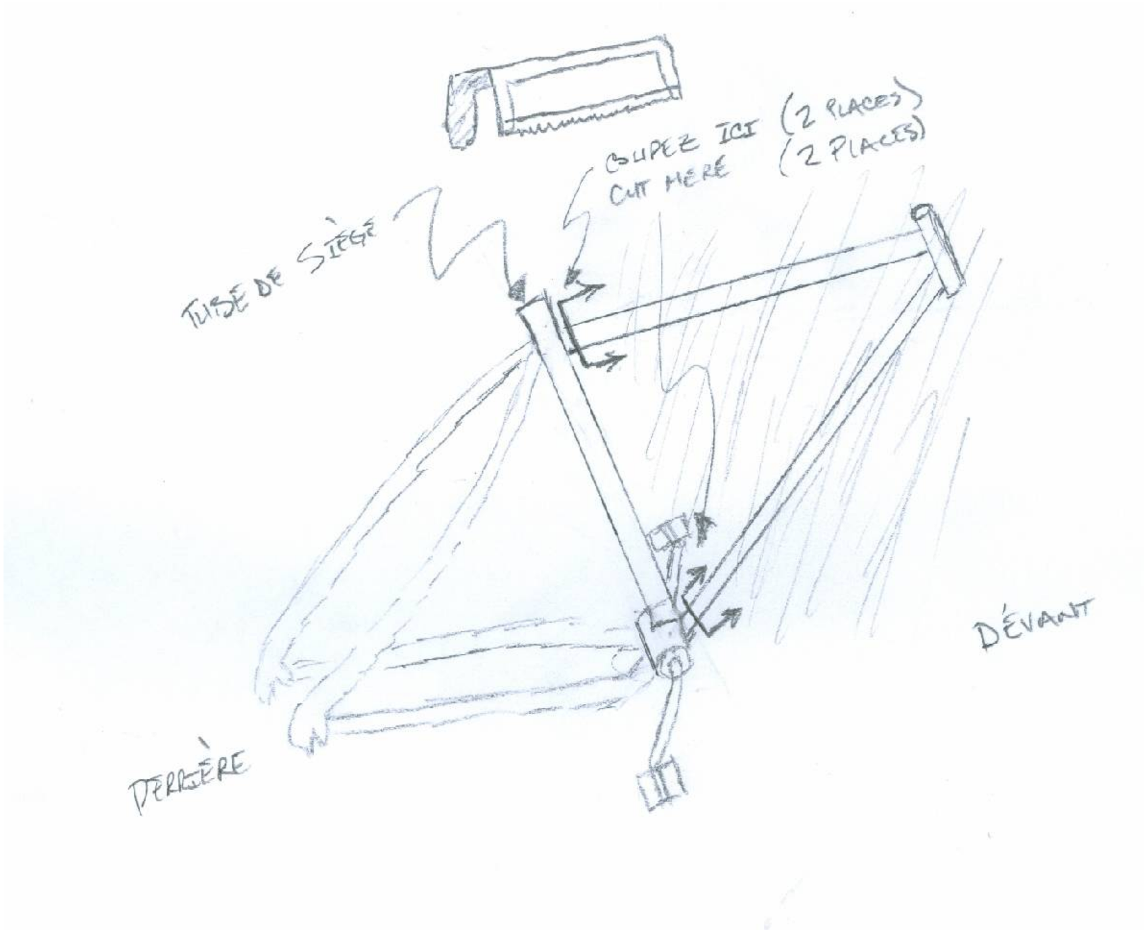

Figure 47: Instructional diagram to illustrate steps which are difficult to visualize

7.3 Essential Tools and Skills

From analysis software and design methods to drafting implements and hand tools, there are many different implements and skills used over the course of the design process. During this project, several of these tools and skills were indispensable, and bear mentioning here.

Foreign-Language Communication

In areas where English is not spoken, it can be difficult for American engineers to communicate with the local people. While the local resources can generally be of significant help with translation, it is much more effective if some form of communication can take place directly from the engineer. Spending time in the region is one way to get some immersion experience in the language. Taking a class in a language that is commonly spoken in the area can also augment the engineer's skills.

For this trip, the most powerful tool to improve language skill was regular conversation in the language. Getting used to using the words one knows to get around phrases that are unknown is essential unless one is fluent in all the technical language needed locally. This vocabulary is also essential to producing useful documentation for the design. Before the second meeting with the local mechanics a list of unknown objects such as tools and materials were drawn pictorially, such that their French names could be written down and practiced before needing to use them on a regular basis. This, along with the routine use of the words during the construction phase, was instrumental in remembering local words for the different objects and actions associated with the project, knowledge that was useful when creating the design documentation.

It is also surprising how much communication can be effected using just basic words and a lot of hand motions. Because the engineer's technical French skills were so limited at the outset of the project, it was necessary to resort to a lot of finger pointing, drawing and long explanations for otherwise simple concepts. This, however, still gets the job done, and although frustrating, can transcend even some of the most severe language barriers. It can be easy to practice this even before the trip, by communicating with team members using no words. Getting around language problems is an essential skill for technology transfer, especially in the form of the final documentation to distribute the design. Pictures, arrows, numbers and illustrations are generally universally understandable, and played a vital role in the documentation included with the HPUV design, as can be seen in Appendix C.

Open Source Software

Open Source Software (OSS) is software whose source-code is open to the public. Usually, this means that OSS programs are free in terms of money in addition to always being free in terms of use. The main idea behind OSS is that open-sourcing a program, or releasing the source code to the public, results in a much wider user-base, and a communal sense of innovation. It is in the same spirit as the HPUV project, in the releasing of the design and the work behind it such that further modification and optimization is possible, by anyone who wishes to do so. OSS packages range from office suites like OpenOffice.org to entire operating systems, such as Linux.

OSS presents some compelling opportunities for the developing world. In addition to being “free as in freedom”, most OSS is also free to download. Many Internet cafés in Maroua, in fact, run OSS operating systems and software to reduce startup and maintenance costs, as well as susceptibility to viruses. The main advantage to OSS is its wide user base, and their ability to report and solve problems directly. Along these lines, development of OSS for development-specific needs can best be achieved by using such software to complete development projects. The easiest way to spot problems or possible augmentations of a program's usefulness is for the customer to explore the program and use it for his or her needs, as is done in beta testing today. For this reason, this project was completed using only open-source software packages. Software used included the following (listed with the packages' functions)

OpenOffice.org – full-featured office suite for thesis/article composition and spreadsheet applications. Includes applications similar in scope and capability to Microsoft Office. http://www.openoffice.org

FreeMat **–** analysis/programming environment very similar in nature to MATLAB. Used here for analysis, gathering and processing of GPS data and vehicle simulation. http://freemat.sf.net

QtiPlot **–** plotting program similar to the commercial package Origin. Used to create some plots with dual axes. http://soft.proindependent.com/qtiplot.html

GIMP – image manipulation program for editing photographs. Used for transferring and editing figures for this document. http://www.gimp.org/

QcaD Community Edition – Computer-Aided Drafting program similar to early versions of AutoCAD. Used to create technical drafts of the vehicle for final drawing packet. http://www.ribbonsoft.com

Scribus – desktop publishing application, similar to Microsoft Publisher. Used for this project to create the design packet layouts and pamphlets in Appendix C. http://www.scribus.net

GanttProject – project management and scheduling application for creating calendars and Gantt charts. Used to generate project schedule and lay out tasks on the implementation trip.

Ubuntu Linux – Linux-based operating system used throughout project. Includes software repositories containing hundreds of thousands of tested, compatible programs. http://www.ubuntu.com

Drafting

Drafting is an ability essential to producing usable design documentation. During an implementation project, it is likely that changes will be made to the design during fabrication, and that the documentation will need to reflect these changes, as well as possibly different needs for illustration of the design's construction. Combined with this, CAD systems and plotters will likely not be found in the area. As such, it is important to take tools necessary for manual drafting, including a scale, straightedge, protractor and compass as well as pencils, erasers and graph paper. These simple tools, with a photocopier, which is commonly found in internet cafes, can be used to produce drawings and sketches of professional quality without the need for computer-based systems. This however, requires some prior training, and can be time consuming if the draftsman is out of practice.

Figure 48 shows one of the hand-drafts of the HPUV that was used extensively during the construction phase of the implementation project. This drawing and the ability to read scaled measurements from it were instrumental in the fabrication of the vehicle. At the outset of the project, the drawing was also useful to give an initial feeling for the appearance of the design to the worker who would be building it.

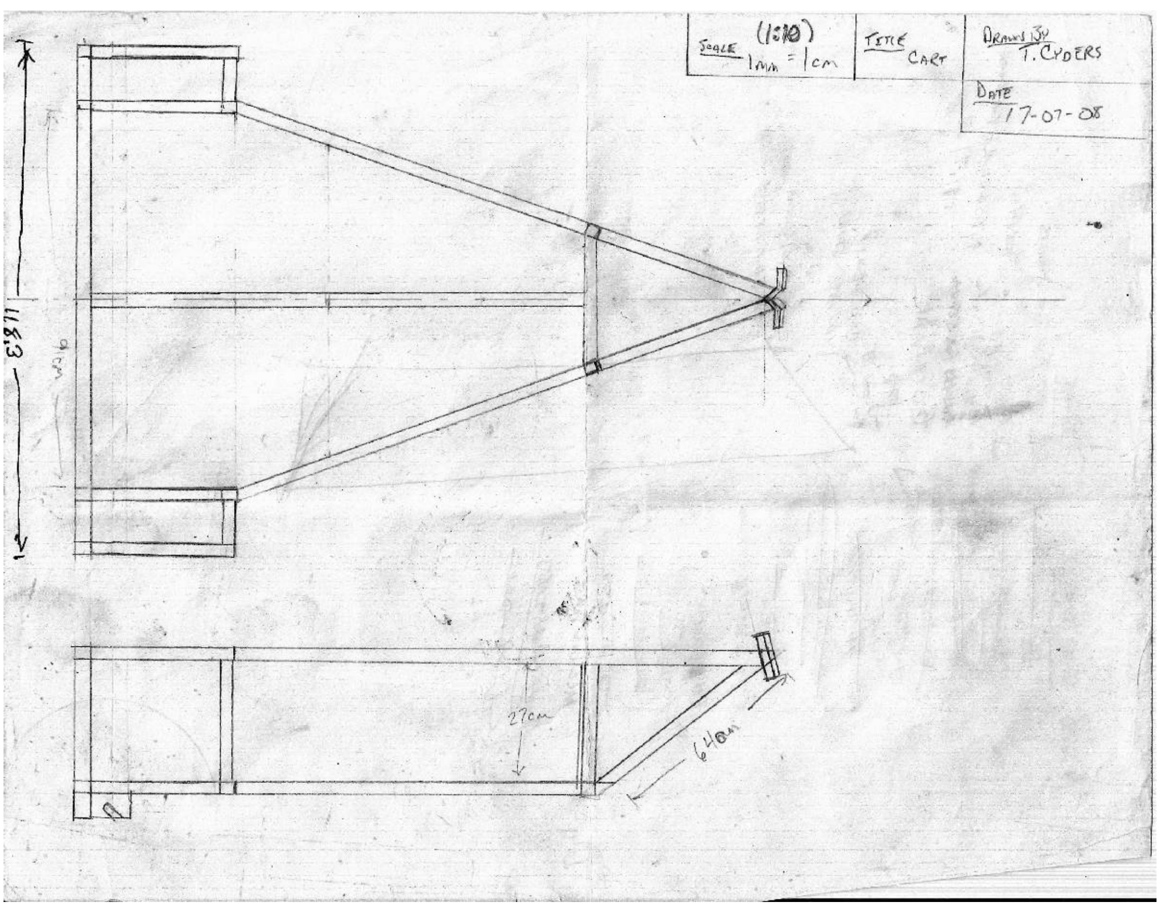

Figure 48: Hand-drafted scale drawing used during the implementation trip.

7.4 Final Notes

This project has simultaneously met the needs of many different people and provided an extraordinary educational experience for the author. Criteria for appropriate technology were reviewed and revised according to the needs of the communities studied, and recommendations for useful tools and future work have been presented. The design of the HPUV was successful both in terms of provision of a useful tool for developing communities, as well as a significant case study in the area of appropriate design.

As the world's population continues to grow, development will become an even more important issue. Studies such as this to refine the design process and thus, our ability to develop sustainable technologies for the people who need them most are and will continue to be necessary as the developing world evolves. There exist already some international bodies, such as the International Developing Technology Group and Practical Action, attempting to gather appropriate designs and make them available to the people who need them. Such bodies are instrumental in world development, as are the efforts of engineers and the use of tools and methods described in this thesis.

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APPENDIX A – INITIAL ASSESSMENT AND DESIGN

Sample GPS Raw Data

Latitude	Longitude	Altitude [m]	Speed [km/hr]	Course	Slope	Distance [m]
10.7725883	14.1194701	539.0				0
10.7727814	14.1200280	539.0	4.4	70.6	0.7	64.6
10.7729316	14.1202211	539.4	4.8	51.6	1.5	91.5
10.7729745	14.1204357	537.5	4.3	78.5	0	115.5
10.7729316	14.1205215	537.5	2.4	117	5.7	126
10.7729316	14.1205215	539.4	0		11.4	126
10.7729530	14.1205215	538.5	0.4	0		128.4
10.7729530	14.1205215	538.0	0		11.4	128.4
10.7729745	14.1205215	537.5	0.1	0		130.7
10.7729745	14.1205215	538.0	0		16	130.7
10.7729745	14.1205430	540.4	0.2	90	11.4	133.1
10.7729959	14.1205430	536.6	0.2	0		135.5
10.7729959	14.1205215	537.5	0.1	270		137.8
10.7729745	14.1205215	537.5	0.1	180		140.2
10.7729959	14.1205215	537.5	0.2	0	0	142.5
10.7729959	14.1205215	539.9	0		11.6	142.5
10.7730174	14.1205215	537.5	0.1	0		144.9
10.7729959	14.1205001	537.0	0.4	224.5	10.3	148.3
10.7729745	14.1205001	537.0	0.3	180		150.6
10.7729745	14.1205001	538.5	0			150.6
10.7729959	14.1205215	539.0	0.4	44.5	0	154
10.7729959	14.1205215	539.9	0			154
10.7729959	14.1205215	538.5	0			154
10.7729959	14.1205215	538.5	0			154
10.7729959	14.1205215	538.0	0			154
10.7729959	14.1205215	537.0	0		0	154
10.7729959	14.1205215	537.5	0		16	154
10.7729745	14.1205001	538.0	0.4	224.5	4.1	157.3
10.7729745	14.1205001	538.0	0		1.3	157.3
10.7732320	14.1203284	539.9	11.2	326.8	0.8	191.4
10.7742190	14.1200066	541.4	29.6	342.2	0.2	306.1
10.7755280	14.1197920	542.3	33.2	350.9	0.7	452.8
10.7773304	14.1198564	538.5	38	2	1.1	652.3
10.7787037	14.1198349	535.6	32.3	359.1	1.4	804.2
10.7790041	14.1198993	534.6	11.2	11.9	1.6	838.2
10.7793260	14.1201138	533.2	14	33.2	1.1	880.8
10.7796693	14.1203499	532.2	11.8	34	0.4	926.8
10.7797337	14.1203713	532.7	9	18.1	0	934.3
10.7797980	14.1204572	532.7	8.5	52.6	1.9	946
10.7798195	14.1204572	532.2	4.3	0	1.6	948.4
10.7799268	14.1205430	531.7	13.6	38.2	0.9	963.5
10.7801628	14.1207576	531.3	11.5	41.8	0.8	998.6

Source Code for Simulations

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Title: hpvsim3.m
% Function: Analyzes human-powered vehicle stability and performance
given inputs and terrain data
%          Program outputs plots of power, speed, acceleration and
other relevant info
% Inputs: Maximum power in HP, cargo in lbs, constant slope [in
sin(theta)], distance vector, altitude vector
% Author: Timothy Cyders
% Date Originated: 09/08/2007
% Date Modified: 01/18/2008
%
% Copyright (c) 2008 Timothy Cyders
% Licensed under the GPL
%
% Program also available at oak.cats.ohiou.edu/~tc285202/hpvsim3.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function hpvsim3 (maxp,cargo,x,y)

%%% Vehicle Parameter Definition - warning, square pupils ahead! %%%

   ratio_f = [2 1.33 1.17 1 .98 .88 .82 .77 .66 .65 .63 .58 .54 .5 .47
.42 .35 .31 .27 .2];  %% vector of gear ratios
   numgears = length (ratio_f) ; %% number of defined gears

   %%% ---Environment Constants--- %%%
   g = 32.2; %% Gravity [ft/s]
   mu_road = .6; %% coefficient of friction for drive wheel
   cd = 1.2; %% coefficient of drag
   cr = .1; %% coefficient of rolling resistance
   a = 8.2; %% frontal area [ft^2]
   rho =  .075/32.2; %% air density in [slug/ft^3]

   %%% ---Vehicle Dimensions--- %%%
   radius_wheel = 14/12; %% wheel radius [ft]
   radius_pedal = (170/25.4)/12; %% pedal radius [ft]
   wheelbase = 170/2.54; %% front-rear wheelbase [in.]
   rearwidth = 130/2.54; %% rear wheelbase width [in.]

   %%% ---CG positions and weights--- %%%
   h_cgrearwheel = 10; %% rear wheel radius [in.]
   x_cgrearwheel = 0;
   w_rearwheels = 6; %% weight of rear wheels, [lbs.]

   w_rider = 195; %% weight of rider, [lbs.]
   h_cgrider = 86/2.54; %% cg height of rider [in.]
   x_cgrider = 129/2.54; %% horizontal distance between rear wheel
center and rider cg [in.]
```

```
   w_cart = 28; %% weight of cart w/o wheels or cargo, [lbs.]
   h_cgcart = 48/2.54; %% cg height of cart [in.]
   x_cgcart = 60/2.54; %% horizontal distance from rear wheel axle to
cart cg

   w_cargo = cargo; %% cargo weight [lbs.]
   h_cgcargo = 48/2.54; %% cg height of cargo [in.]
   x_cgcargo = 60/2.54; %% horizontal distance from rear wheel axle to
cart cg

   w_frontwheelassembly = 10; %% weight of front wheel assembly, [lbs.]
   h_cgfrontwheelassembly = 15.5; %% height of front wheel assembly cg
[in.]
   x_cgfrontwheelassembly = 175/2.54; %% horizontal distance from rear
wheel axle to front wheel assembly cg

   m =  (w_rider + w_cart + w_rearwheels + w_frontwheelassembly +
w_cargo) / g; %% total mass (rider, vehicle and cargo)
   h_cg = (w_rider*h_cgrider + w_cart*h_cgcart +
w_rearwheels*h_cgrearwheel +
w_frontwheelassembly*h_cgfrontwheelassembly + w_cargo*h_cgcargo)/(m*g);
   x_cg = (w_rider*x_cgrider + w_cart*x_cgcart +
w_rearwheels*x_cgrearwheel +
w_frontwheelassembly*x_cgfrontwheelassembly + w_cargo*x_cgcargo)/(m*g);

%%% Set-up simulation environment (finally!) %%%
   q = 1; %% start in first gear
   roady = y*32.2/9.81; %real(csvread('altinterp.csv')); %% reads road
elevation data from file
   roadx = x*32.2/9.81; %real(csvread('distinterp.csv')); %% reads road
distance data from file
   slopecounter = 2;

   roadslope = [0 0]; xtot = 0; t = 0; f = 0; x = 0; dx = 0; ddx = 0;
omega = 0; torque_act = 0; gear = 0; %% sets up useable variables
   t_f = 3600;
   dt = .75;


%%% Stability Calculations %%%

   %%% ---Cornering--- %%%
   %% calculates cornering envelope based on half tread and cg height
   halftread = sind(atand(wheelbase/(rearwidth/2))-atand(x_cg/
(rearwidth/2)))*sqrt((rearwidth/2)^2 + x_cg^2); %% calculates half-
tread for three-wheeled vehicle
   v = linspace(.1,15*5280/3600,100); %% velocity vector for cornering
calcs, [ft/sec]
   r = (halftread*g/(h_cg*v.^2))^-1; %% calculates minimum turning
radius for cornering calcs, [ft]

   %%% ---Static Side Tipping--- %%%
```

```
   maxtilt = atand(halftread/h_cg); %% maximum tilt until static
tipping
   tiltheight = sind(maxtilt)*rearwidth; %% maximum elevation
difference in rear wheels

   %%% ---Rut Traversal--- %%%
   %% determines rut traversal capability during a right turn at
defined speed and radius
   %% negative x direction to vehicle's direct left, positive y
straight ahead, positive z upward against gravity
   tiprad = 10; %% assumed turn radius for tipping calculation
   tipvel = 3.5*5280/3600; %% assumed velocity during turn (walking
speed meets criteria)
   rutdepth = input('Input rut depth to simulate: '); %% depth of rut
to be simulated (negative means down) [in.]
   rutres = rutdepth/5; %% resolution for rut traversal calculations
[in.]

   %%% ---Tilt vehicle to worst case scenario--- %%%
   for rearleftdrop = 0:rutres:rutdepth;
       for frontdrop = 0:rutres:rutdepth;
          theta(int32((frontdrop/rutres)
+1),int32((rearleftdrop/rutres))+1) = asind(((rearleftdrop/2)-
frontdrop)/wheelbase); %% calculates vehicle pitch [deg]
       end
       phi(int32((rearleftdrop/rutres)+1)) =
asind(rearleftdrop/rearwidth); %% calculates vehicle roll (assumed to
left) [deg.]
   end

   %% calculate cg position and wheelbase outline assuming right wheel
doesn't drop
   for j = 1:length(phi)
      for i = 1:length(theta);
         phi_cg = phi(j) + atand((tipvel^2/tiprad)/g); %% calculates
phi angle for stationary wheelbase
         theta_cg = theta(j,i); %% copies theta angle, assumes all
centripetal acceleration directly outward
         cg_projectionx(j,i) = (rearwidth/2)-h_cg*sind(phi_cg);
         cg_projectiony(j,i) = x_cg + h_cg*sind(theta_cg);
      end
   end

   %%% ---Output stability results--- %%%
   wheelbasex = linspace(0,rearwidth,100);
   wheelbasey = [linspace(0,wheelbase,50) linspace(wheelbase,0,50)];
   figure;
plot(cg_projectionx,cg_projectiony,'.b',wheelbasex,wheelbasey,'-k');
   grid off; axis equal; axis maximal; title('CG Projection Through Rut
Traversal');
   figure;plot(v,r); grid on; xlabel('Speed [ft/s]'); ylabel('Minimum
Turning Radius [ft.]');title('Cornering Chart');
```

```
   printf('\nHPUV can withstand %.3f degrees of roll.\nThis is an
elevation difference of %.3f [in.] between rear
wheels\n',maxtilt,tiltheight)


%%% Begin Drive Simulation %%%

for n = 1:t_f/dt
   t(n) = dt*n;

if n > 2
   if xtot(n-1) < max(roadx)
      roadslope(n) = sin(atan((roady(slopecounter)-roady(slopecounter-
1))/(roadx(slopecounter)-roadx(slopecounter-1))));
   else
      roadslope(n) = slope;
   end

   if roadslope(n-1) - roadslope(n) > epsilon %% if slope changes
significantly, recalculate weight distribution and slip limit
      weight_dist = (x_cg-(h_cg-
radius_wheel+x_cg*sin(roadslope(n))*sin(roadslope(n)))/wheelbase; %%
calculates percent of weight on drive wheel
      sliplimit = m*g*mu_road*weight_dist; %% calculates maximum tire-
road couple force
      sliptorque = sliplimit*radius_wheel; %% calculates maximum torque
applicable to wheel before slipping
   end

end

      if n <2
         f(n) = (30*radius_pedal)*ratio_f(q)/radius_wheel; %% initial
force of 30 lbs (to avoid instantaneous jump at start)
         ddx(n) = (f(n) - (m * g * roadslope(n)))/m;

   %%% ---Match performance to basic constant-power torque-speed curve
with max. torque--- %%%
      else
         dx(n) = (ddx(n-1) * dt) + dx(n-1); %% current speed is
acceleration of last iteration times dt plus previous speed
         omega (n) = dx(n)*ratio_f(q)/radius_wheel; %% pedal rotation
speed [rad/s]

         if omega (n) > (maxp*550/(170*radius_pedal))
            torque_act(n) = maxp*550/omega(n); %% input torque = max
power [hp] * 550 ft-lbs/sec / pedal speed [rad/s] - assumes constant
max power capability
         else
            torque_act(n) = 170*radius_pedal*1.5; %% max input torque =
rider weight * pedal crank arm length
         end
```

```
   %%% ---Test for Slip Limiting--- %%%
         if sliptorque < torque_act(n)
            torque_act(n) = sliptorque;
         end


   %%% ---Switch gears if pedaling too fast or too slow for comfort---
%%%
         if n > 5 & omega (n) > 9.3 & q < numgears & gear(n-5:n-1) ==
gear(n-1)  %% gear switching program

               q = q + 1; %% increase gear at omega > 9.3 rad/s

         else if n > 20 & q > 3 & omega(n-20)-omega(n) > .1 & gear(n-
20:n-1) == gear(n-1) & omega(n) < 6
                     q = q-1;
              end
         end

         f(n) = torque_act(n) * ratio_f(q) / radius_wheel; %% wheel
force [lbs]
         ddx(n) = (f(n)  - m*g*(roadslope(n)+cr) -
(rho)*(dx(n)^2)*cd*a)/m; %% acceleration = wheel force - drag force -
parallel force / mass
         gear(n) = q;
         xtot(n) =(dx(n) * dt) + xtot(n-1);

         if xtot(n) < max(roadx)
            if slopecounter < length(roadx)
               slopecounter = min(find(roadx>xtot(n)));
            end
         end

      end
   end

      smph = dx*3600/5280;

%%% Generate Plots and Output Files %%%
      plot (xtot,dx); xlabel('Dist. [ft.]'); ylabel('Speed [ft/s]');
      figure;

      plot(t,roadslope); xlabel('Time [sec.]'); ylabel('Slope');
      figure;

      plot (roadx,roady); xlabel('Dist. [ft.]'); ylabel('Elevation
[ft]');
      figure;

      plot (xtot,smph); xlabel('Dist. [ft.]'); ylabel('Speed [mph]');
      figure;
```

```
    plot (omega, torque_act, 'ro'); xlabel('omega [rad/s]');
ylabel('torque [ft-lbs]');
    figure;

    plot(t,dx); xlabel('time [s]'); ylabel('speed [ft/s]');
    figure;

    plot(t,smph); xlabel('time [s]'); ylabel('speed [mph]');
    figure;

    plot (t,gear); xlabel ('time [s]'); ylabel ('gear #');
    figure;

    plot (t,omega); xlabel ('time [s]'); ylabel ('omega [rad/s]');

    csvwrite('time.csv',t); csvwrite('speed.csv',smph);
end
```

APPENDIX B – IMPLEMENTATION AND TESTING

Project Schedule

June – Dec. 2007: Final Assessment trip to Ghana and Cameroon. Return in Aug, compile assessment information, develop project framework and conceptual designs. Complete feasibility analysis and thesis proposal by mid-January 2008.

Jan. - Feb. 2008: Submit thesis proposal, funding proposals, and initial concept to advisor.

Jan.-June 2008: Weekly design reviews/input with thesis committee

Feb. - May 2008: Design/filtering/analysis from concept to final design. Finish machine prints/manufacturing plan by end of April

Feb. - April 2008: Modeling/Finite Element Analysis of system and subsystem components over development of specific design.

April – June 2008: Finish FEA/DFMA for design, order mat'ls. Fabricate special parts to eliminate long lead-times for project. Finish fabrication/specific material plan by June.

June – July 2008: Travel to Cameroon, brief local machinists and purchase remaining materials in local markets. Fabricate jigging and vehicle with local machinists, and disseminate design/manufacturing plans

July – Aug. 2008: Test vehicle in different areas and tasks around the community – gather feedback and measure performance. By mid-Aug., present NGO with design and manufacturing plan.

Aug. - Oct. 2008: Complete evaluation of design from qualitative and quantitative feedback – provide design revisions if needed, and submit thesis for final defense.

Implementation Trip Budget

Item #	Description	Price
	Travel/Lodging	
1.)	Cameroonian Visa	$196.00
2.)	Airline Ticket (round-trip Cincinnati to Yaounde, Cameroon)	$2,983.00
3.)	Hotel stay in Yaounde (2 nights)	$75.00
4.)	Two one-way train tickets, Yaounde to Ngoundere and return	$250.00
5.)	Two one-way bus tickets, Ngoundere to Garoua and return	$35.00
6.)	Hotel in Garoua (2 nights)	$50.00
7.)	Two one-way bus tickets, Garoua to Maroua and return	$30.00
8.)	Car from Maroua to Mèri	$10.00
9.)	Hotel in Maroua, Cameroon (three trips)	$60.00
10.)	Food for trip from Yaounde to Meri (round-trip)	$150.00
11.)	Rent/Utilities ($50/month)	$150.00
	Project Costs	
12.)	Bicycle parts (derailleur, pedals/cranks, etc.)	$80.00
13.)	Cargo transport from production site to village (by car)	$10.00
14.)	Steel for frame (tubular steel)	$60.00
15.)	Wheels (2 moto wheels, 1 bicycle wheel)	$75.00
16.)	Seat material (fabric, webbing, etc.)	$10.00
17.)	Gearing material	$25.00
18.)	Winch cable	$32.00
19.)	Labor (1000 CFA/hour for 200 man-hours)	$365.00
20.)	Misc. Expenses (extra parts, etc.)	$300.00
21.)	Tooling for Custom Parts (jigging materials, mills, etc.)	$175.00
	Other Expenses	
22.)	Food ($2/day for approx. 68 days)	$136.00
23.)	Internet Café for Correspondence	$15.00
24.)	Water Treatment Tabs (for travel)	$12.00
	Total	**$5,284.00**

Trip Log

June 7 - 13

Arrived in Yaoundé June 7. My bags were held back for extra security checking (because of the weird-looking contents), and as a result, we couldn't leave Yaounde until the 10th. Even then, parts of the ergometer were missing, and my calculator is destroyed. I'm not sure if I'll be able to repair the ergometer or not. We traveled by train from Yaounde to Ngoundere, bus from Ngoundere to Garoua, stayed the night in Garoua, then by bus to Maroua, stayed overnight in Maroua, and took the bush taxi to Mèri. To boot, we got stopped by gendarmes between Maroua and Mèri demanding money even after they saw all my valid documents, including vaccination records and plane tickets. Ridiculous. Arrived in Mèri the 13th, to find that the power was out.

June 14 - 20

We settled in and got the house straightened up, stocked the refrigerator, etc. This week, we did 'protocol', or visiting with all the local officials and important people, such as the mayor, the local gendarme commandant, the sous-prefet (a military attaché), other officials and some friends in-village. This process usually takes 4-5 days, and this week was no exception. Lots of hours spent saying 'Hi, how are you? How is your family? How is your health? My family is good!", etc., ad infinitum. At the end of the week, I met with Père Roger at the Catholic mission in Douvangar who said he had some young men interested in working with me. We had dinner with the Père and met the young men, explaining the concept of the project to them. They seemed very interested! The power was still out at the end of this week, totaling 12 days since the village last had power.

June 21 – 27

The power finally came back on! Apparently one of the nuns at the Catholic mission in Douvangar had had enough of Sonel's (the electric company) procrastination, and wrote a Had the first meeting with the young men around halfway through the week. They rode to Mèri from Douvangar (around 4 miles) on their bicycles, and the local contact was doig her own work, meaning I had no translator. Despite this, everything seemed to go well, although I hadn't done a good job of planning the meeting. I asked some specific questions about some materials we would need and how much they should cost, where I could find them in the market, etc. They were very helpful, and I got a lot of information I needed. The men are going into their final exam week at school, so we'll meet again in two weeks. The local contact has to make a trip to Maroua this weekend and I can look at buying (or at least pricing) a bike with changeable speeds there.

June 28 - July 4

The trip to Garoua was fruitless in term of buying a bike, but I got an idea for how much they should cost. Jess and I stopped in Maroua on the way back long enough to meet with the director of the local Heifer International office, to talk about the project and their involvement. Oliver (thankfully an Anglophone – technical explanations are still a bit difficult in French for me) was very excited once we explained the design to him, and he wondered if it would be possible to hook the back up to a donkey. He suggested some other people to send copies of the design to, and agreed that it would be a great idea to collaborate with him and the local mechanics to distribute the technology and train new workers in its construction. We'll schedule a final presentation with them when the vehicle is done and tested.

I took a trip with a local friend, Issau, to Maroua on my own to get replacement parts for the ergometer. Issau seems to know quite a bit about the industrial workings of the local village, and was quick to invite me to come to Maroua with him on his moto. We had a productive day, and I got some nuts and bolts that may enable me to reconstruct the ergometer, and he also showed e the different parts of the market where they sold items I might need for the HPUV. Standard parts are out, though – everything is metric. We'll see if I can make it work. Our friend Jamie came down from Tokèmbère with one of her friends, Matthias, who I got to talk to about the project and hear his opinions. He really liked the idea, and thought it was a really appropriate solution. We have a July 4 celebration this weekend in Tokèmbère, and Jess and I are riding our bikes there, then on to Maroua for a going-away party for an NGO worker I contacted about the project earlier.

July 5 – 11

The July 4th party in Tokèmbère was excellent. I realized I haven't been in the United States for July 4 for four years now, pretty sad. We sang The Star-Spangled Banner and ate roasted pork (hard to come by in areas as heavily Muslim as this), watched some classic American movies, and had a relaxing evening. Jess, Jamie and I rode to Maroua the next day, and then Jess and I back to Meri the next morning – a total of 102 km for Jess and I for the weekend. When we finally got back home after a long, hot ride, we came to find that the power was out yet again, and would be for another week.

To make matters worse, I awoke Monday morning to find I had some pretty serious diarrhea – about every 15 minutes. I didn't have a fever or other symptoms, so Jess took a stool sample to the hospital on her bike to have it checked out. She came back with the wonderful news that I had both amoebas and worms – I must have somehow contracted them on the way up, because they have an incubation period of at least 30 days. I spent most of the rest of the week on my back thanks to the extremely potent medicine that it takes to get rid of worms. One day, however, I was feeling good enough to travel with Père Roger to Maroua to pick up most of the materials for the HPUV – tube steel, wheels, etc. Issau helped us bargain for good prices, and arranged for the materials to be delivered where the Père could pick us and them up in his pickup-truck. We had a flat tire on the way home, but aside from that, the day was uneventful. Hell of a week.

July 12 – 18

I rode to Douvangar Monday to meet with the young men and set up a time to start building the HPUV. I've given up efforts to try and fix the ergometer, because the standard (instead of metric) parts I need are simply not available here, and I can't substitute – the problem is with the pedal shaft, and that it's completely custom-made. Lesson learned.

When I got home from Douvangar, Jess was headed to a meeting for the evening. I noticed I was really tired, and within an hour, confirmed with a thermometer that I had a pretty serious fever. I started to get the severe muscle aches I recognized from the last tie I had an acute bacterial infection and before the evening was out, I was freezing cold in 100 degree heat. I immediately started to take the Cipro I brought for just this reason, and within 12 hours felt fine. This means that I got it all – worms, amoebas and bacteria at the same time. Awesome.

Thursday and Friday I met with the guys out at Douvangar again (Wednesdays are out because that is their market day, and they have other work to do), and we started to build the vehicle! We're just cutting pieces and disassembling the bike for now, but things are finally starting to get done. By the end of the week, we were ready to begin welding the cart frame together, but the power was out AGAIN. I'm getting sick of this.

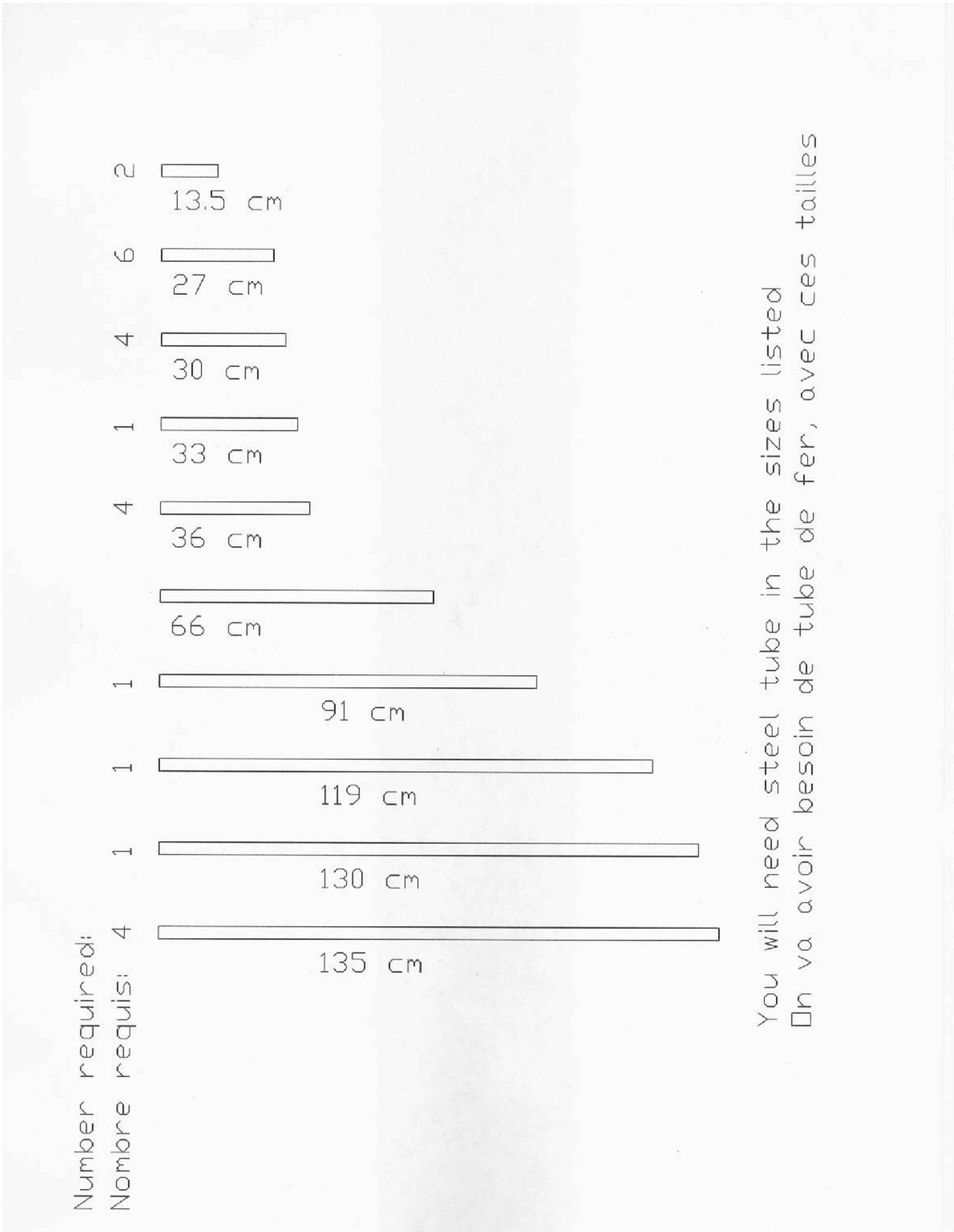
July 19 – 25

The power came back on at the beginning of the week, and we got right to work welding the frame together. We worked four days this week, and made a lot of progress – we got the jigging built for the entire rear cart, and constructed almost the entire thing, wheels and all! Jess and I took the guys out for a case of Coke and Fanta after the third morning of work, and found that the rest and relaxation was a nie atmosphere to get to know the workers a bit more. They talked about other things they're working on, and the general reactions to the project. Apparently, multiple people have been asking to buy copies of the vehicle since we started building it! This is awesome! They really like the idea of the vehicle's operation and adaptability mostly because it an be used at extremely little cost. The cart part of the frame is turning out to be lighter and cheaper to construct than a pousse-pousse. The workers were also excited to hear that we'd given an NGO their contact information, and that the NGO was likely going to be interested to talk to them about building more, and training new people to build it. This has been a very exciting week!

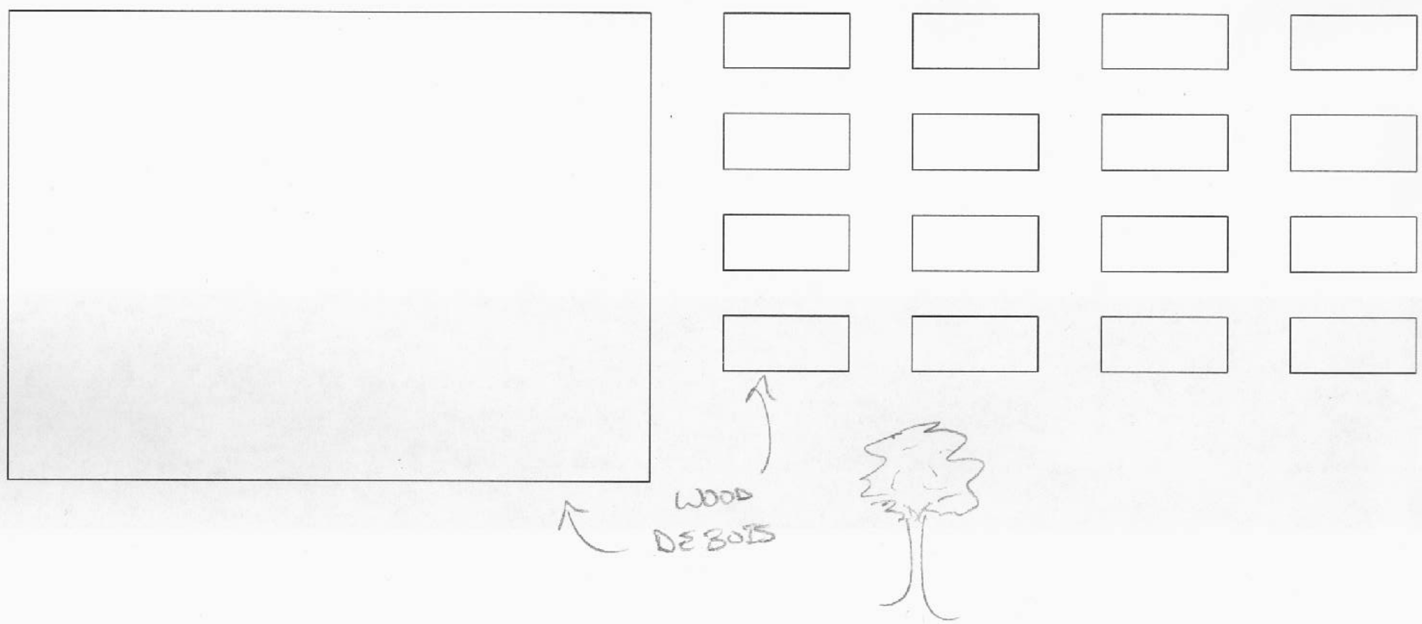
July 26 – Aug. 1

The 26th, Jess started to feel pretty sick, and began to throw up repeatedly. In a wonderfully stressful test of my French skills I rode my bike between the hospital and the village a total of 5 times over the next two days to find she had the exact same infections I had had two weeks ago, and to get the medication needed. She was sick the rest of the weekend, but back on her feet in time to come help me when production was to continue Monday morning. That morning, however, the power was out, so I spent the day working on the thesis and working on the design documentation packet. I had to go to Maroua to pick up some final materials for the bolt-on interface for the cart, so we left Tuesday and came back Wednesday.

APPENDIX C – FINAL DESIGN DOCUMENTATION

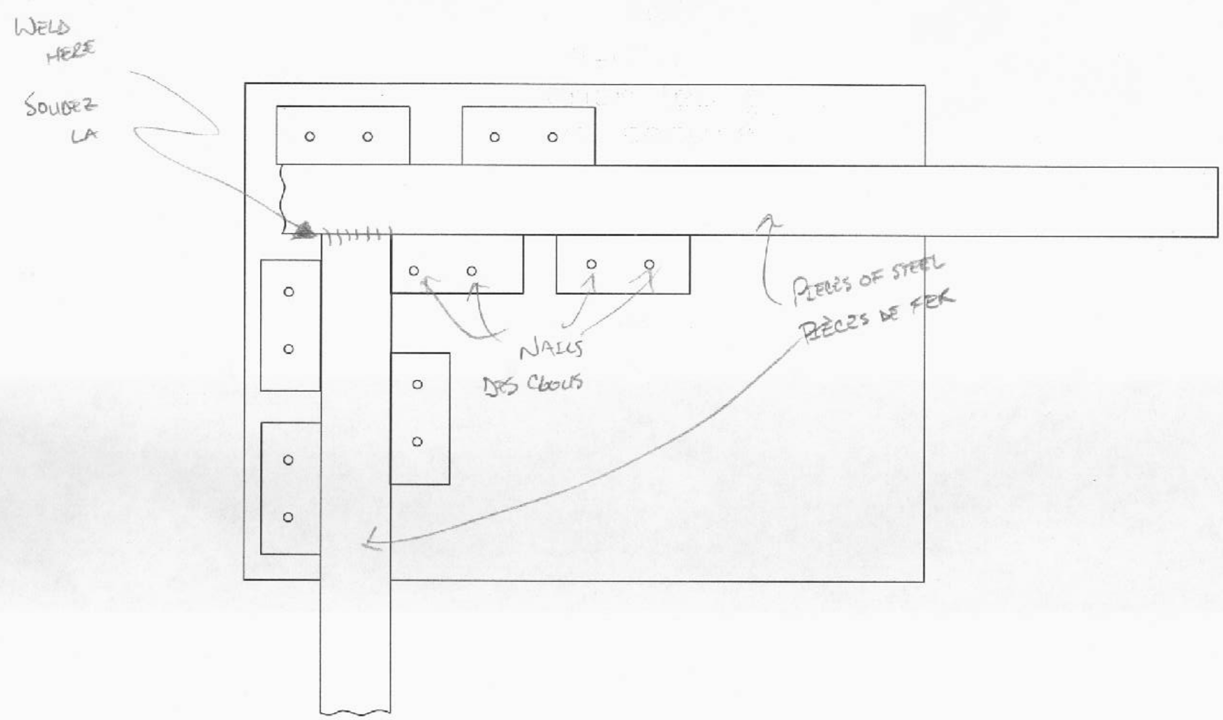


Begin with 30mm square steel tube
On va avoir besoin de tube de fer, 30 mm x 30mm



You will also need a flat piece of wood, and 16 thick pieces, and some nails

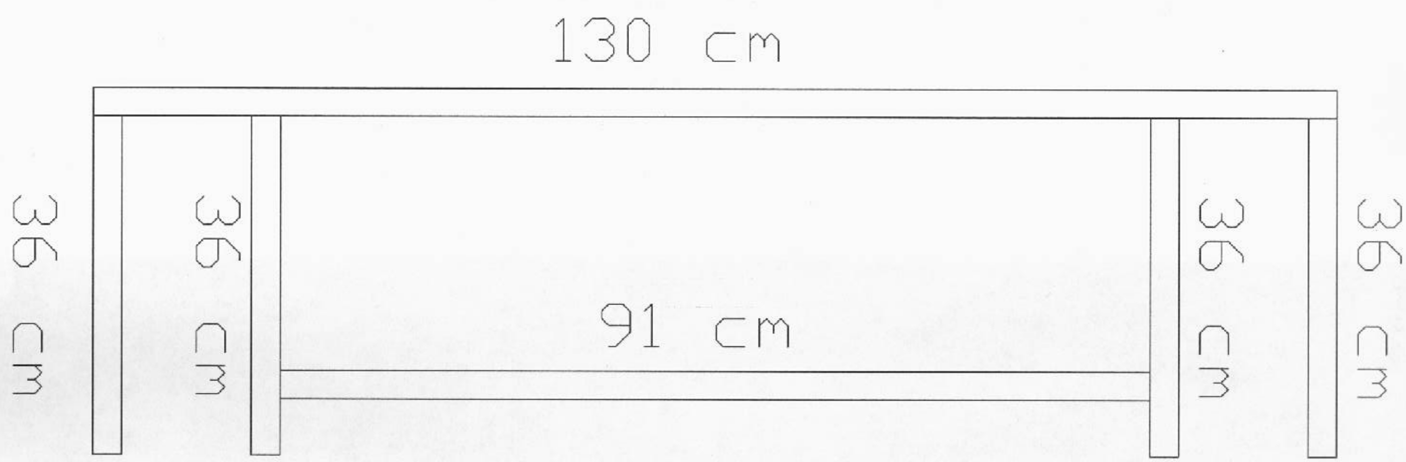
En plus, on va avoir besoin de un contreplacard, et 16 pieces de bois gros, et des clous



Nail the thick pieces of wood to the plank as shown in the picture, so the steel fits tightly in between the pieces

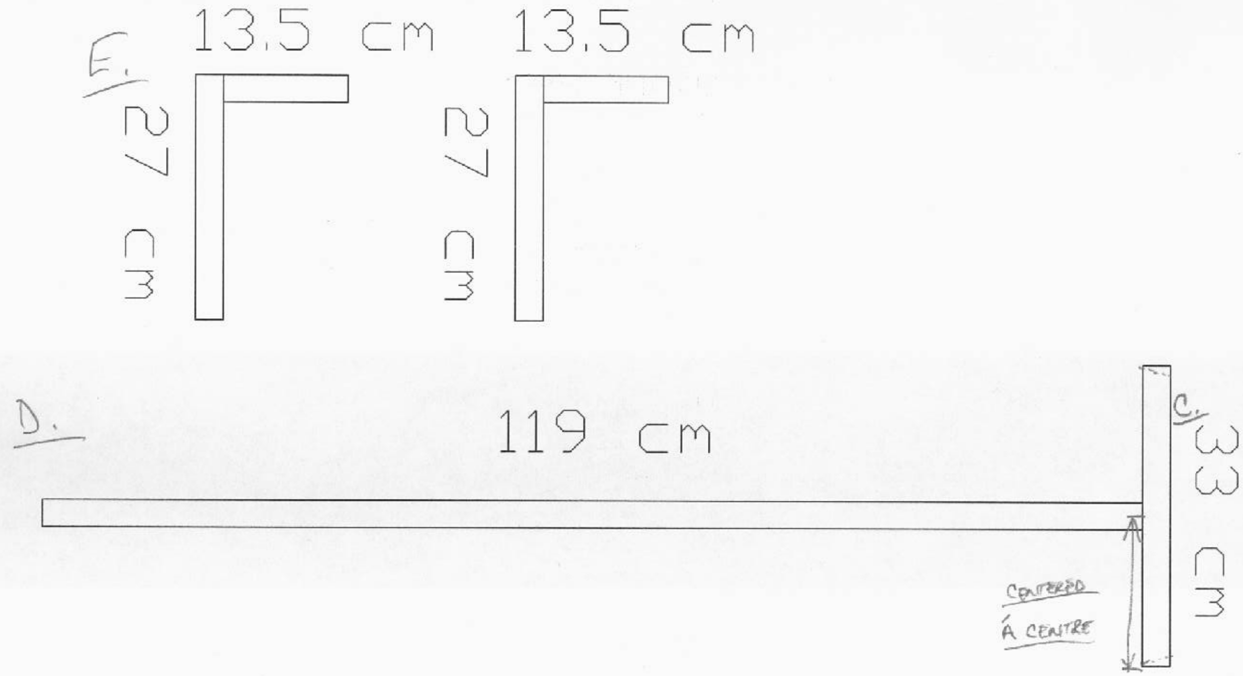
Utilise les clous pour attacher les gros pieces a le contreplacard. Le tube de fer devrait etre secure entre les pieces comme la figure.

A.



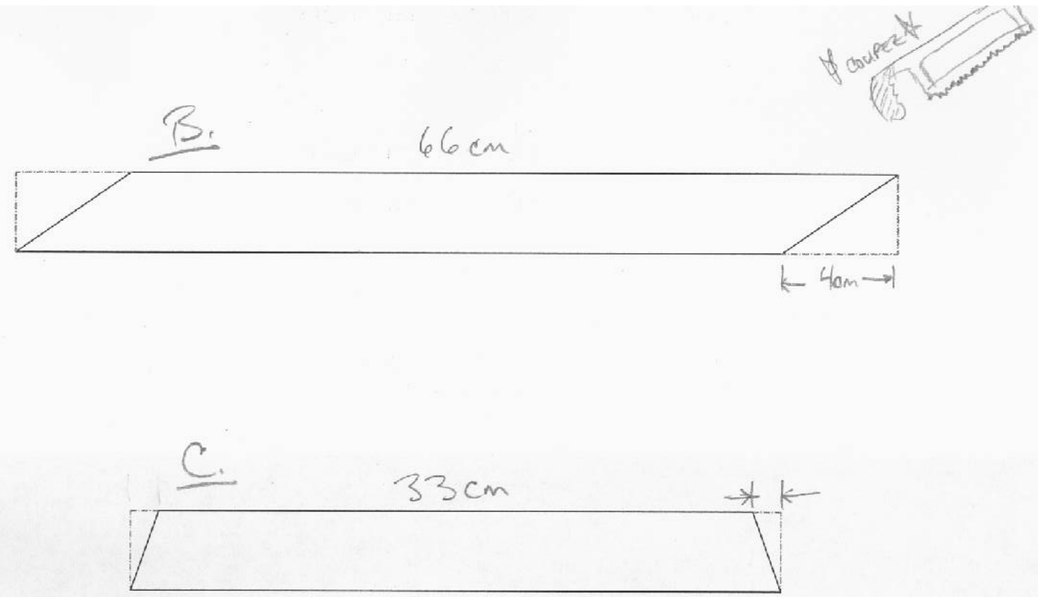
Using the fixture you just built, weld tubes together to make the shape shown

Utilise le fixture vous avez faire pour garde le fer quand vous soudez the construction en le figure



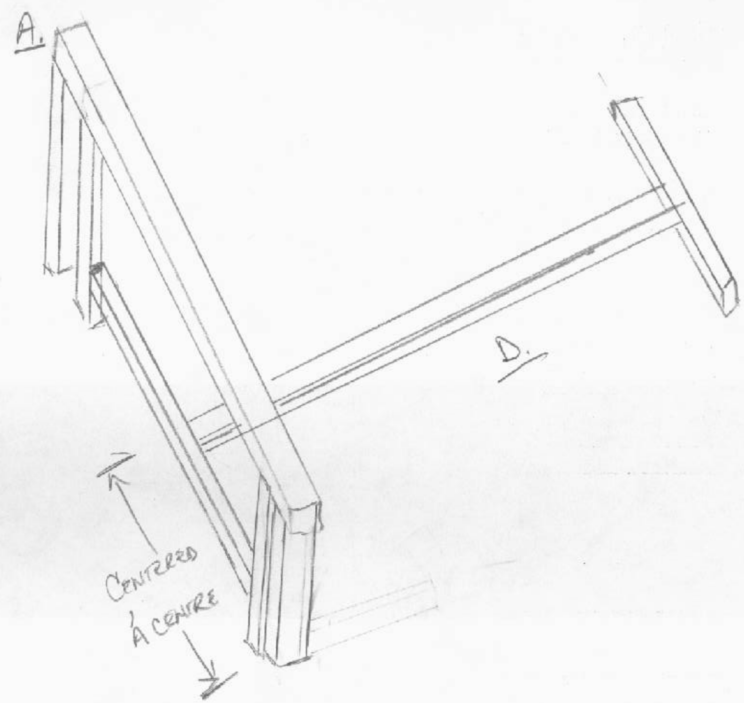
Next, weld the following shapes, again using the fixture.

Prochainement, soudez ces figures tandis que utilise la fixture.



Use a saw to cut angles on the ends of these steel pieces

Utilise une scie pour couper le bord de le fer a l'angle en la figure

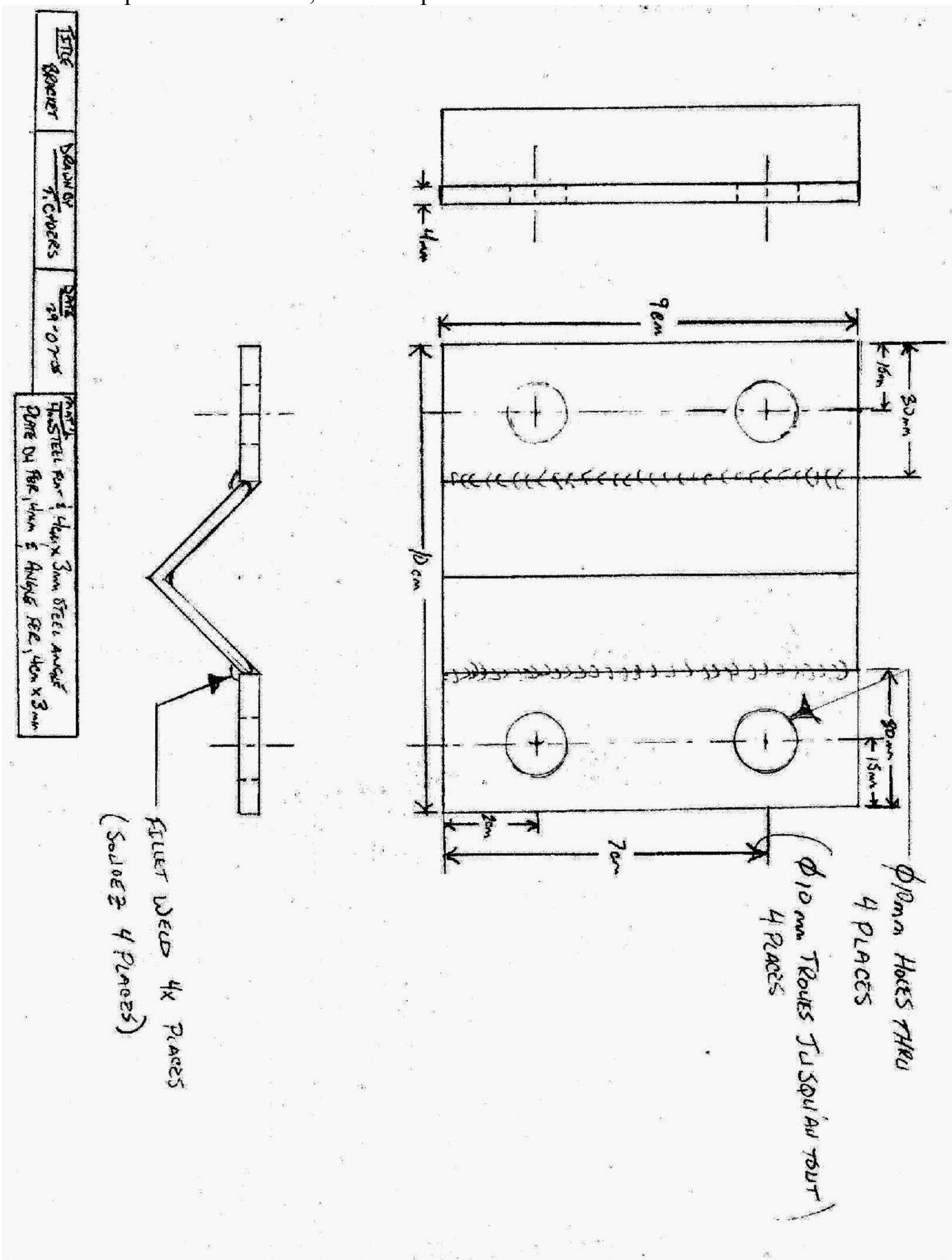


Next, use the piece you just made to weld this shape

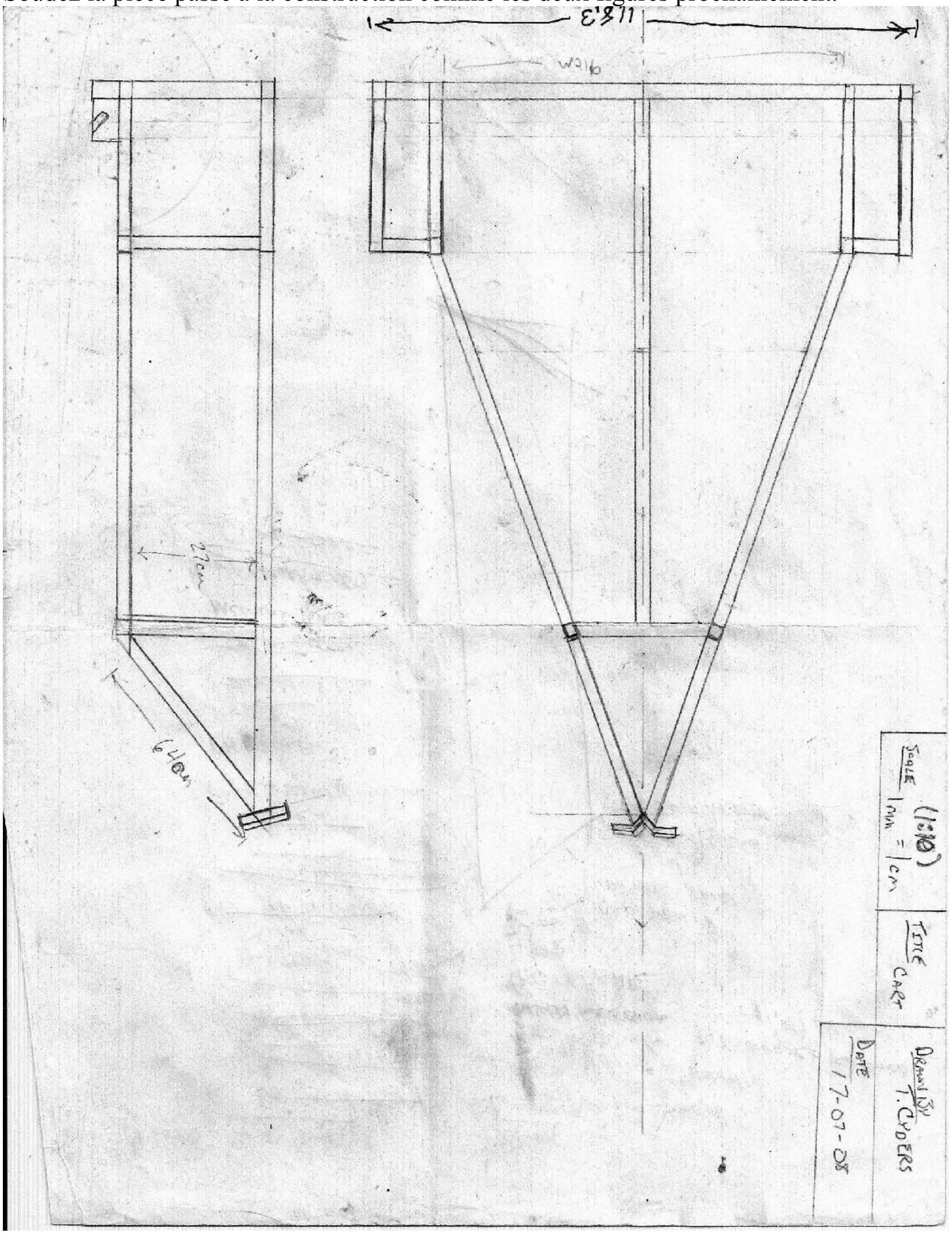
Prochainement, utilise le piece vous avez juste fait pour faire ce figure.

Weld the remaining pieces as shown. Soudez la reste des pieces que la figure.

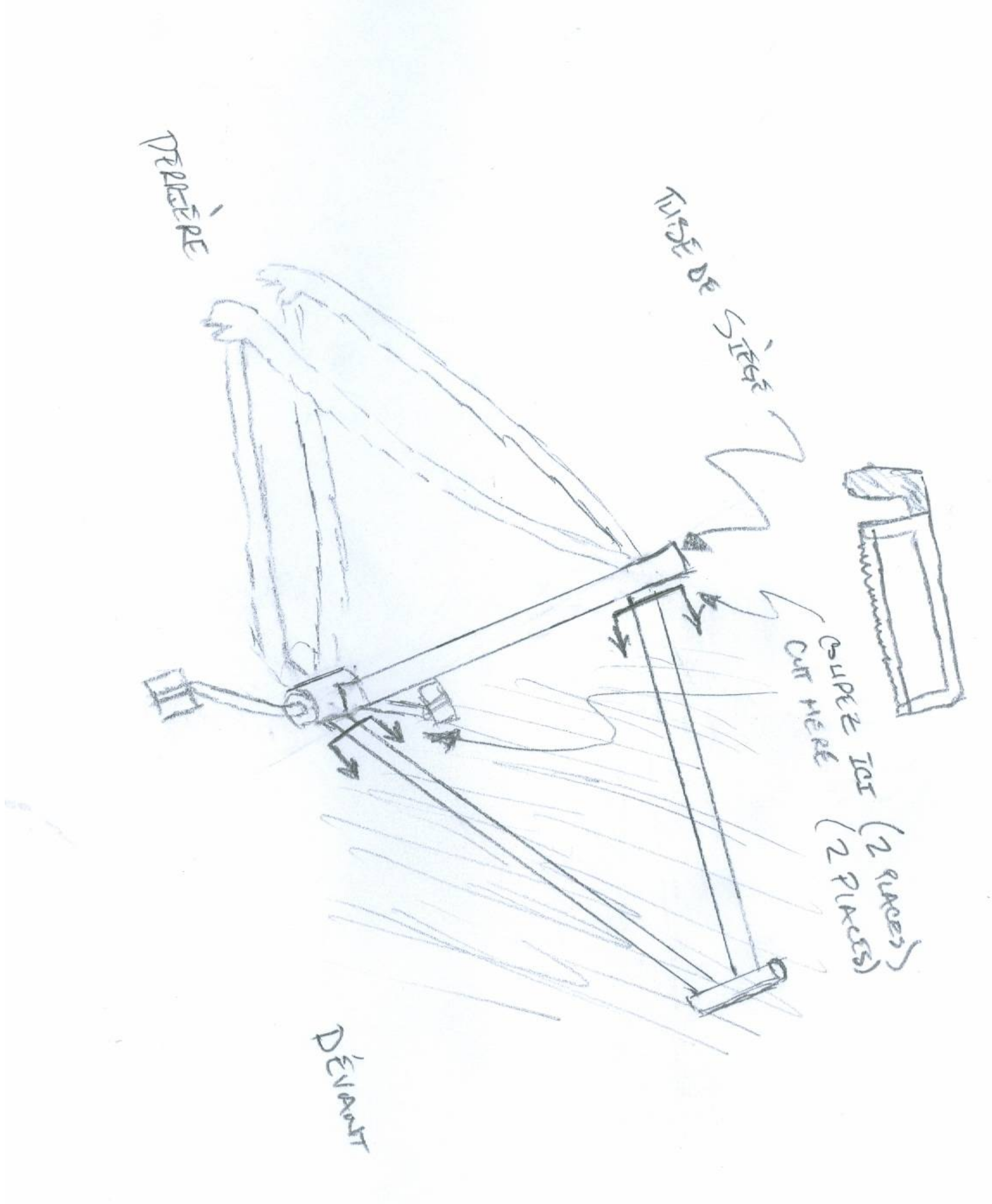
With steel flat and steel angle, make 2 copies of this piece
Avec le fer plat et la corniere, fait cette piece en deux



Weld the bolt interface you just made to the construction as shown in the next two figures
Soudez la piece passé a la construction comme les deux figures prochainement.



Next, cut the bicycle as shown here to create the front of the vehicle.
Prochainement, coupez le velo comme la figure pour faire le devant de la vehicule.



Weld the newly cut piece to a front fork assembly as shown in this picture
Soudez la piece nouveau a l'assembly devant comme la figure

Finish the vehicle by building a seat, and ride as shown in this picture.
Accomplissez la vehicule avec une siege, et roule avec le vehicule comme la figure.

For updated plans, extra interactive tools and contact info for the designer, please visit http://oak.cats.ohiou.edu/~tc285202/HPUV/