Design of a Sustainable, Locally Manufacturable, Agricultural Utility Vehicle for Developing Countries

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Abstract

Many areas of the developing world lack affordable transportation. Habitants spend a significant percentage of their time transporting agricultural products and water manually, over rough terrain and long distances, and it can be difficult to get fresh produce to markets where it can be sold before spoilage occurs. Through a partnership between universities, non-governmental agencies (NGOs), and local partners in Cameroon, a low-cost agricultural utility vehicle was designed and tested. The three-wheel vehicle was designed to use a low cost single cylinder 5-9kW engine, diesel or gas, and carry loads of 600kg at speeds up to 30km/h. The entire vehicle was designed to use locally available materials and resources, allowing for local manufacturing, maintenance, and employment. In 2011, Purdue University students travelled to Bangang, Cameroon and partnered with staff at the African Centre for Renewable Energy and Sustainable Technologies (ACREST) to build and test the basic utility vehicle (BUV). At the conclusion of a three week travel and building phase a working prototype was in operation. The design process, vehicle characteristics and performance, and field test results from the vehicle prototype are presented. The vehicle has a three speed transmission consisting entirely of standard V-belts and pulleys, and chains and sprockets. Maximum speeds are 6, 13, and 27 km/h for the three driveline ratios. Finished vehicle empty mass was measured at 450kg. A limited slip differential was designed using four V-belts with a pair of belt tensioners. A steel truss frame can be constructed from square tubing or angle iron depending on local material availability. A rear trailing arm was designed for the rear suspension. A single airbag, multiple coil springs, or a leaf spring can all be utilized as the primary suspension. The one-piece trailing arm allows full vertical movement combined with very high roll stiffness. Wood is used to construct the cargo bed, engine cover, and seating for three people. The wood cargo bed rests on a steel frame with rear pivot points that allows for dumping the payload. The steering consists of a tiller handle connected to a single front wheel. Required skills for manufacturing the BUV include cutting metal (hacksaw, torch, or grinder), drilling holes, and welding. No machining or high tolerance components need to be fabricated. In summary, a low-cost, locally sustainable agricultural utility vehicle was designed and built, and a prototype constructed and tested in Africa.

Key words: sustainable, developing countries, agriculture, mechanization.

1. Introduction

Water, firewood, and agricultural products are the top three items requiring transport, and taking the most transport time, in rural areas of developing countries (Barwell, 1996). Based on many surveys in sub-Saharan rural Africa, Barwell found that transportation problems cannot be solved simply by improving the roads and that adults on average spend 1.0-2.5 hr/day on transport. Even with adequate roads (not common), affordable transportation is still a problem. Imported Asian motorcycles are becoming more common yet have limited cargo capacity. Cars and trucks are expensive to initially purchase, unable to transverse unimproved roads and trails, and are costly to maintain, especially when parts and maintenance facilities are not locally available (Porter, 2002). Transport time reduces available labor, the principle factor of agricultural production in these areas, and inhibits agricultural productivity and growth. There is a disproportionate, and negative, impact on women in these regions, who contribute to more than 65% of the transport burden (Barwell, 1996; Peters, 2001; Riverson et al., 2006). One study found that women on a main road through a village were able to earn twice the income over women living 90 minutes from the main road (Porter 2002). Leinbach (2000) found that “owner transport and especially affordable and reliable transport services are the essential mechanism”, leading to an increase in agricultural productivity and impact.

Potential solutions are often characterized as Intermediate Means of Transport (IMT), bridging the transportation gap between rural agricultural production and paved roads. IMT options range from human transport (walking with loads on head, back, shoulder, etc.), wheelbarrows and carts, animal drawn carts, bicycles, and small powered vehicles (motorcycles, walk-behind tractors, cars, trikes, and pickup trucks). Starkey (2001) defines IMT’s as filling the gap between walking, carrying, and large scale transport. It should be appropriate, convenient, and affordable. There must be a critical mass that develops to support the infrastructure required for manufacturing and repairs (Starkey, 2001).

Providing low cost IMT’s can also provide a source of income beyond farming, and some studies have shown that power tillers initially purchased for farming, were quickly used for transporting goods and people since it was more profitable (Starkey, 2001). Porter (2002) concludes that “programs to develop more sustainable, intermediate transport technologies which can operate over suitable tracks seem to be the most obvious route to improving access in most off-road villages.” Limiting factors identified by Starkey (2001) include lack of “components and raw materials, manufacturing/assembly facilities and skills, designs of vehicles, capital availability and/or marketing systems.” Considerable cost savings are possible through local manufacture and by doing so the vehicle costs can be kept low (Ellis and Hine, 1998; Howe, 2001). The vehicle needs to be flexible and able to haul produce, goods, and people over distances ranging from 10km to 50km. Skills and repair facilities in rural areas are basic, and the infrastructure is very poor hence speeds are usually low.

This paper summarizes a project aiming to improve agricultural production by reducing food waste during and after harvest, freeing time for education and more time for producing crops, and increasing the income of farmers by providing access to new markets and small business opportunities (transport services). The basic utility vehicle (BUV) is designed as an intermediate means of transport (IMT) for rural farmers and villagers that can be constructed locally, economically, maintained with local parts and supplies, haul large loads over unimproved roads, and serve the local needs of farmers in developing regions of the world.

2. Project Background

Since 2001 the Institute for Affordable Transportation (IAT, www.drivebuv.org) has sponsored a student design competition focused on the development of basic utility vehicles for developing countries. Purdue began participating in the competition in April, 2007. In 2008 Purdue University began a partnership with the African Centre for Renewable Energy and Sustainable Technologies (ACREST), a non-governmental organization (NGO) located in Bangang, Cameroon. ACREST is developing appropriate technologies that increase access to energy, food, and clean water, while minimizing environmental impact, and had already purchased an IAT BUV in 2006. This was the beginning of a partnership between Purdue, ACREST, and IAT in developing affordable transportation options for rural villagers in Cameroon. With input from ACREST, Purdue teams have increasingly focused on developing a BUV design that relies completely on local skills and materials, thereby being affordable (<$1800 USD), sustainable, and replicable to other developing regions. Sixty plus students from agriculture, engineering, and technology, have worked on the BUV project since 2009 and twenty-eight of those have traveled to Cameroon to work with our partner (ACREST) to build the prototypes. The students have the opportunity to work with people from diverse backgrounds and cultures. Students experience designing for strict constraints such as very low costs and limited resources (CIA World Factbook, 2011). The limited availability of resources becomes clear during implementation (Lumkes et al., 2011).

Each year the teams have used the feedback from previous teams to improve and optimize the design. Along the way some interesting and innovative ideas were tried. In 2010 the team worked closely with ACREST to develop a new model using locally available parts and materials (wood). A working prototype was tested in the IAT competition (Fig. 1a) and a second built at ACREST (Fig. 1b). It was a drivable vehicle using a wood frame and simple belt transmission, but was more difficult to manufacture than expected, and the belt transmission needed improvement. Many valuable lessons were learned by all involved.

FIGURE 1a. Wood-frame/belt transmission BUV prototype constructed at Purdue (April, 2010)

FIGURE 1b. Prototype BUV reconstructed in Cameroon at ACREST (May, 2010)

The experience gained while building the 2010 BUV in Cameroon was used to further refine the design, and a new prototype was constructed at ACREST in May, 2011. The remainder of this paper summarizes the design process, testing, and results for this BUV.

3. Design, Construction, and Testing of Steel Truss Frame, Belt Transmission, BUV

3.1 Design Constraints and Criteria

The design constraints and criteria (Table 1) were determined through conversations with our partner, contacts at similar NGOs, the literature review summarized in section 1, and successive years of experience working with and building a BUV in Cameroon.

TABLE 1. Top Level Design Constraints and Criteria

Top Level Constraints	Criteria
Must cost less than $1500 USD (ex. Engine)	Cost
Payload capacity greater than 600 kg	Payload
All components and manufacturing skills available locally (Cameroon)	Easy to build/repair
Less than 8km/h max speed in lowest ‘gear’ (engine=3500rpm)	Reliability
Inherently safe operation (stable, brakes, shields, etc.)	Ergonomics
Cargo area greater than $2m^2$	Parts flexibility
Able to use a variety of single cylinder engines (5-9kW)	Empty weight

3.2 Design Approach

Each year the project revisits the constraints and criteria, reviews lessons learned from previous designs (internal and external), and generates a list of alternative solutions. Discussions include frame designs (wood, steel space frame, ladder frame, recycled truck frame, etc.), driveline options (chains, gears, belts, transmissions, hydraulic, etc.), layout (front/rear wheel drive, 3 or 4 wheels, seating, steering, cargo area, etc.), etc., and the alternative designs are evaluated using Table 1.

Once the system level design concept is understood, various design tools are utilized, in parallel, to model and simulate the design. As data is collected the design is refined and optimized. 3D modeling is used to generate concept sketches, support finite element stress/strain analyses (FEA), and evaluate ergonomics, packaging, manufacturing, bill of material, component and vehicle weight, etc. Mathematical simulations are done for driveline ratios, tractive forces, roll stiffness, roll-over angles, speed in each ‘gear’ ratio, etc. The goal is to have the BUV completely modeled and simulated before construction begins.

At the conclusion of the modeling and simulation the team decided on a truss frame, three wheels with tiller steering, a three-speed belt and chain transmission, dump-bed, seating for three, and component flexibility with wheels, suspension components, engines, etc.

3.3 Frame

The frame (Fig. 2) was designed to use straight pieces of square tubing or angle iron, depending on material availability and cost. Although the previous design (Fig. 1) used wood (which in some locations would be very low cost), concerns over durability, problems with deforestation in other areas of Africa (Tutu and Akol, 2009), and construction time led the team to migrate to simple steel frame. All major external loads are applied at nodes in the frame, and the layout of the frame was optimized for placement and spacing of the driveline components. FEA was used to optimize the frame load paths. The rear trailing arm used two diagonal members in bending to provide chassis role stiffness. This stabilizes the vehicle, but also allows a wide variety of rear suspension components to be used. Shown in Fig. 2 is an air bag, but a larger leaf spring can be transversely mounted across the rear, multiple coil springs can be mounted across the back to achieve the desired load capacity, or in extreme locations, ‘donuts’ from old tires can be cut and stacked to provide a basic suspension.

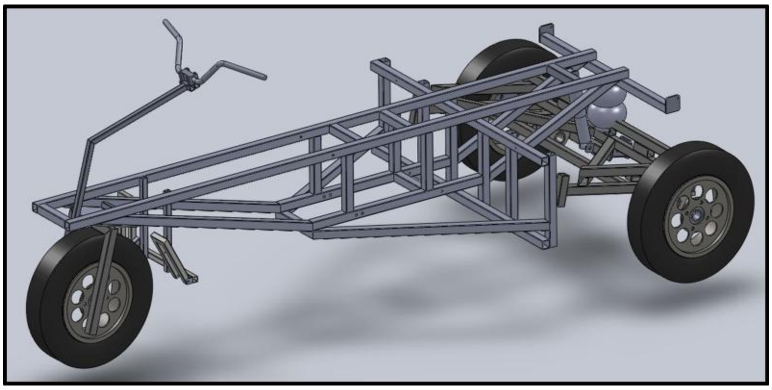
FIGURE 2. Truss Frame and Rear Trailing Arm Design

Using the rear trailing arm to add role stiffness is important in a three-wheel vehicle since the single front wheel does not prevent roll, especially with heavy loads while turning or traversing slopes. Benefits however, of a single front wheel are that the frame torsional loads are significantly reduced relative to 4-wheel layouts, and rear tire contact forces are almost always equal. In uneven terrain—common on rural African roads—a 4-wheel vehicle frame experiences significant torsional loads, even lifting a rear tire in extreme cases. If this occurs on a rear tire and an open differential is used, the vehicle becomes stuck. The frame design, built at Purdue using square tubing and in Cameroon using angle iron, has proven itself to be lightweight, durable, and working as designed. Both BUVs are still running strong after one year of use (significant use in the case of the Cameroon prototype).

3.4 Driveline

Since belts, pulleys, and chains are common in many parts of the world, easy to maintain with simple tools, and reliable; a three-speed driveline was designed using standard size B V-belts and two chain and sprocket reductions. A pedal-actuated belt tensioner acted as the vehicle clutch, and three belt/pulley combinations, connected between two parallel shafts, acted as the three speed transmission. Left and right belt/pulley sets, two belts on each side, acted as a limited slip differential. The final reduction to the rear axles was provided by a set (left and right) of chains and sprockets. Figure 3 illustrates the ratios and the physical layout for the driveline. With slight variations for tire sizes, the three selectable belt/pulley ratios resulted in maximum speeds of 6, 13, and 28 km/h, respectively, in 1^{st}, 2^{nd}, and 3^{rd} ‘gear’. Three over-center lever selectors (Fig. 3b) were used to tension one of three belts between shafts S1 and S2 (Fig. 3b), and sheet-metal guards were used to both protect operators from inadvertent contact with the belts, and to keep the un-tensioned belts from touching the pulleys. Spring loaded idlers on the differential belts allowed one tire to rotate faster than the other during a turn, while providing limited-slip differential operation. Brake rotors and calipers were mounted inboard on each S3 shaft. The vehicle speed was measured using GPS and correlated very well with simulated data. The vehicles were powered with single cylinder 6.8kW diesel engines available in Cameroon for approximately $500 USD.

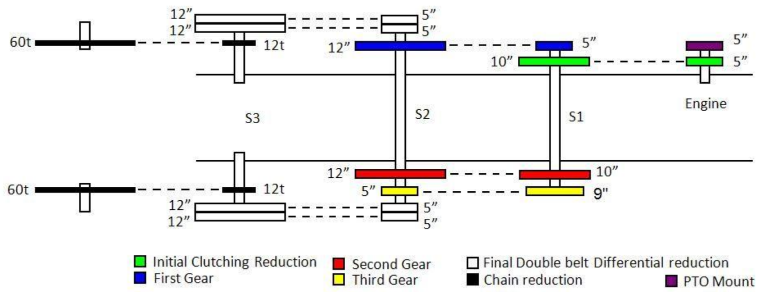

FIGURE 3a. Driveline reductions from engine to rear axles

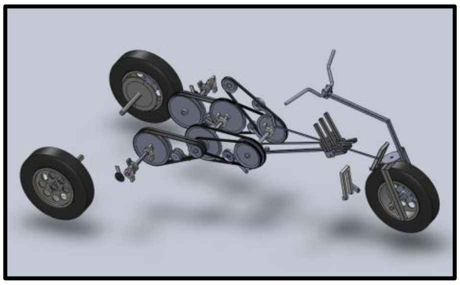

FIGURE 3b. 3D Model of driveline components

3.5 Cargo Bed and Ergonomics

The cargo bed, three seats, driveline shielding, and engine cover were integrated using a wood structure. This allowed easy maintenance when the bed was lifted for dumping (Fig. 4). The sides of the cargo bed were removable to allow operation as a flat bed. A steel frame mounted under the wood supported the dump mechanism.

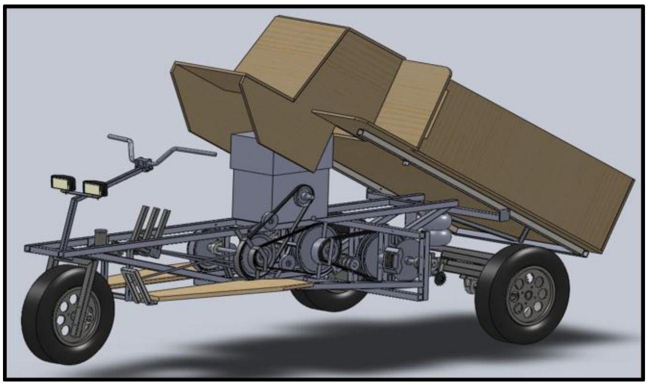

FIGURE 4. Cargo Bed, Seating, Dump Bed

3.6 Final Vehicle Specifications

Capacity:	600+ kg
Speeds:	6, 13, 28 km/h
Cost:	$1800USD w/engine
Empty Mass:	450 kg (measured)
Req'd Tools:	Metal saw, drill, welder

4. Conclusion and Future Goals

Purdue students on the Global Design Team travelled to ACREST for three weeks in May 2011. This provided enough time to build the BUV, providing ACREST with a prototype that has been tested over the past 12 months. The BUV has performed very well with no major problems reported. The Purdue and ACREST prototypes are shown in Figures 2a and 2b.

Figure 5a. BUV prototype built at Purdue

Figure 5b. BUV reconstructed in Cameroon

As a result of this partnership between Purdue and ACREST, additional projects, including hydroelectric and wind power, biomass fuels, and water pumping have been addressed. Students get to see real impact, apply their skills in challenging situations, learn valuable indigenous and cultural knowledge from our partners, and have an international design and travel experience (Lumkes, 2012).

FIGURE 6. ACREST BUV in use

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