Tillers'

Tech*Guide*

Animal-Driven Shaft Power Revisited

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This report is a review of modern and historical options for using animals to create circular or shaft power in response to VITA/s need for low-cost, simply-maintained power for dehulling and grinding sorghum in small villages in the Central American Republic. When animal power was the primary source of farm power in Europe and the United States, animal-driven gear powers were a popular means of generating circular or shaft power for stationary machines. The simplicity of these machines and their use of locally generated animal energy recommends their renewed considerations for rural development projects.

Current literature on the topic is extremely sparse and rather pessimistic. The general consensus of many engineers during the 1960's and '70's has been that the heavy gearing used in historical gear powers was so expensive that it was less expensive in most cases to move directly to internal combustion engines for power, CEEMAT, 1972; Kline, 2-251:1969. They did see some exceptions for operations such as crushing cane that operate at very low RPM's. Nonetheless, there is renewed interest in pursuing several new design concepts and the use of new materials to reduce cost and increase efficiency. If these goals can be met, animal-driven gear powers may be especially attractive in remote areas where supplies of engine parts and fuels are unreliable.

Before describing the varied design options we would like to review the basic characteristics and limitations of animal power and the peculiar challenges posed for designing gear powers.

Characteristics of Animal Power

Oxen can generally generate sustained draft force equal to about $1/8^{th}$ of their body weight at about 2.0 to 2.9 km/h and about $1/10^{th}$ at higher speeds of about 4.0 km/h. They can maintain this level of work for about 3 to 6 hours per day in the tropics. Donkeys can pull $1/6^{th}$ of their weight at about 2.5 to 2.8 km/h for 3 to 3 ½ hours per day. Instantaneous effort is much greater. A donkey can exert a momentary force of twice its weight and an ox can exert two-thirds its weight at working speeds (CEEMAT, 9-29:1972). In teaming animals to gain additional force, getting them to pull together introduces inefficiencies of at least 7.5% for two animals, 15% for three, 22% for four, 30% for five and 37% for six.

Table 1. Estimated Horsepower of Oxen and Donkeys at Low and High Speeds

		Low Speed (2.4km/h)			High Speed (4km/h)		
Animal	Weight	Draft	HP	Kw	Draft	HP	Kw
Donkey							
light	190	30	0.3	.224	19	0.3	.224
heavy	300	48	0.4	.298	30	0.4	.298
Oxen							
light	210	30	0.3	.224	21	0.3	.224
medium	450	64	0.6	.448	45	0.7	.522
heavy	900	129	1.1	.821	90	1.3	.970

Adapted from Goe and McDowell, (38:1980)

The Concept of Power

In 1770 when James Watt invented the steam engine, he also had to define a unit of power so he could describe its power to clients in a meaningful way. He selected a sustainable effort by a horse as his standard, the horsepower. The use of horses by millers to turn millstones provided an opportunity to measure a relatively consistent effort. He defined horsepower in terms of work accomplished in a given time.

Figure 1. An illustration of the definition of horsepower in the milling of flour

WORK = FORCE X DISTANCE TERMS

HORSEPOWER = WORK/TIME Force

1 HP = 33,000 foot-pounds/min
= 550 foot-pounds/sec
= 4,615 meter-kg/min
= 746 joules/sec
= 0.746 kw

pounds
kg f
newton
<u>Work</u>
foot-pounds
joules
(newton-meters)
<u>Power</u>
horsepower
kilowatt
m-kg/sec

If a medium weight ox walking at 4 km/h can produce a 0.7 HP (Table 1), the single Baoule most successfully used in the CAR/GTZ trials was generating more power than should be expected for sustained periods. But we will assume its weight was about 400 kg which its power output implies. The data show that it was producing .63 HP at a speed of 4.4 km/h (2.9 RPM x 60 min x 8 m dia x 3.14 = 4.371 km/h). Not even a large donkey could be expected to generate that much power on a sustained basis. If more power is required to meet the demands of a mill of appropriate size for CAR villages, hitching more animals will most likely meet the need. With proper equalizing of the efforts of two oxen, the loss to inefficiencies should only be about 7.5%. Thus, two oxen (perhaps 400 kg each), that could generate 0.63 HP individually, would generate about 2 x 0.63 – 7.5%, or 1.17 HP, as a team. Further, four such oxen properly hitched could generate 1.97 HP after subtracting a 22% loss of efficiency for the multiple hitch. Thus, up to 2 HP could be obtained from 4 oxen if the situation requires that much power.

Table 2. GTZ/project Consult Observations of Oxen in CAR

Breed	Weight	Force	Speed		Power	Time	
		kg	RPM	km/h	HP	Kw	min
1 Baoule – (taurine)	?	40 kgf	2.9	4.37	.65	487	107
2 Baoule – yoked	?	45 kgf	2.9	4.37	.73/b	548	12
1 M'Bororo – (zebu)	?	25 kgf/a	2.2	3.32	.31	231	32
2 M'Bororo – yoked	?	45 kgf	2.1	3.16	.53	397	36

a/ After two weeks they decided that the M'Bororo tired quickly and were too weak so they continued working only with the Baoules.
b/ The report implies that there were problems getting the second animal to work well.

Historically, large 14-horse gear-powers drove threshers and other large machines with an effective power to the gear power of 60% or less. Despite that loss, they did aggregate about 8.4 HP. While that is more power than should be needed for this VITA/CAR project, many aspects of the old gear powers such as the equalizing systems are instructive and could be helpful.

Figure 2. Top view of a 14-horse gear power showing bracing, the equalizing system, and one set of double trees.

Basic Considerations for Animal-Driven Shaft Power Design

In the past, animal powers (sweeps, gear powers, treadmills, capstans, manege, etc.) were used when other forms of wind or water power were not available or reliable. They have been replaced in many parts of the world as engine power has become more efficient and convenient. They are still used in a number of developing countries as reliable means of crushing sugar cane or lifting water. Indeed, the tasks that continue to be powered by animals can be done at low RPMs.

However, the sorghum mill used in the VITA/CAR project required substantial speed for the desired output. In the trials the mill operated at about 200 RPM and VITA is interested in options for increasing that to as much as 500 RPM. The challenge is finding a low-cost and efficient means of gearing up the plodding 2 to 3 circles per minute that oxen can make around a 4-meter radius.

The principal technical design challenges are:

1. Increasing speeds from animal inputs of 2-3 rpm to the desired speeds of 200 to 800 rpm, ratios of 1:100 to 1:250.

2. Minimizing inefficiencies in transmission of power.

3. Protecting the mechanism from the tremendous instantaneous force and torque that animals can exert (2/3 the weight of oxen times the length of the beam or about 5 times normal operating forces).

4. Equalizing the efforts of multiple animals so they are all contributing a maximum sustainable force.

5. Increasing the versatility of both stationary and mobile shaft power units.

6. Keeping costs substantially below those of engine power.

Figure 3. A Small Traditional Gear Power

Types of Animal Powers

<u>Gear Powers.</u>

Traditional European and American gear powers used large diameter pinion gears to make the first step up in speed as in Figure . Other gearing would then increase the 2 to `3 RPMs of the animals by a factor of 30 or even 100. If that 60 to 300 RPMs was not sufficient, then a speed jack (an additional gear box) was placed in the line to increase the RPMs by an additional factor of 3 to 10. This allowed them to drive machines at speeds of up to 1075 RPMs. Unlike the GTZ model tested in the CAR, this gear power was separate from the machine being powered. Because it could be hooked to a number of stationary machines with a drive shaft or belt, its usefulness was multiplied.

David Kemp of AFRC Engineering (formerly the National Institute of Agricultural Engineering of the U.K.) says that traditional gear powers are still manufactured in Poland and East Germany. He agreed to look through his files to find the names of the manufacturers. Given wage rate differences, the practicality of importing many of these into the CAR is doubtful. A 1975 publication of the UN Division of Narcotic Drugs advocated the use of such maneges for a number of stationary farm tasks. Somewhat optimistically they suggest that any developing country could manufacture them since the traditional models did not have precision bearings or ground gears. They recommend casting heavy gears in sand molds and using them without finishing. Without an established demand, setting up such an operation in CAR is probably not wise. Whether the UN group tested the efficiency of power transmission for these gear powers is unclear. Tillers also has some of these early gear powers for demonstration use. While we know they are substantially more difficult to turn than units with modern bearings, we have not had the time to do input and output engineering tests to determine their efficiency.

In Botswana, the Rural Industries Promotion (RIP) has built several gear powers for pumping water. The unit is made with gears manufactured for mining operations. They use several large gears to increase ROMs by a factor of 300 to 400 to provide an output of 800 RPMs. They power it with 6 donkeys according to illustrations. While they are working on a less expensive model, AT International people who have worked with RIP on the project say present costs are $4,000 to $6,000. We have not found input and output measurements for comparisons. The costs imply that they are working toward high efficiency from a traditional design with precision gears and bearings. We look forward to learning of their test results, but the price is an obvious problem that they are attempting to address.

AFRC Engineering tried a cost reduction approach to the traditional design. The idea of using the gearing from a cement mixer is one that we had mentioned to Carl Lindblad in earlier discussions, so it was particularly interesting to learn that they had actually put the idea to the test. Costs could be substantially reduced by finding a good production source for the large pinion gear that makes the first step up in speed and takes the high torque of the animals' slow but powerful movement. This gear converts the vertical axis of the power input into a horizontal axis for further gearing and output. These gears will increase the input RPMs by a factor of 6 to 10 which can be supplemented by lighter gears or sprockets. The pinion gear needs to be stabilized by substantial bearings. AFRC

Engineering tried using oil-soaked wood bearings to minimize costs, but found major efficiency losses. They were more satisfied with ball bearings that cost them about $200. They have apparently not published results of these trials though David Kemp said he would send us the notes that he took on their tests.

This approach offers considerable promise since cement mixers operate in the horsepower ranges that are comparable to those needed for operating grinders and other small stationary farm machines. However, these pinions need to be protected from the enormous torque of about 4 times operating levels that animals can create on an instantaneous basis. Some input clutch or shear pin arrangement is needed. To the extent that gears were obtained from models marketed in a country, replacement parts would be relatively accessible.

Borge Bunger and associates developed an animal powered pumping system in Sri Lanka from which the capstan or gear power can be detached to mill rice. With this gear power a small pair of oxen can lift 50 tons of water 4 meters in a day or dehull 75 kg of paddy rice per hour (Tanish et al, 58:83). A model capable of lifting 100 tons of water is being proposed for the Sudan (Bunger, 26:1986). Mr. Bunger refused to give more input or output details over the telephone supposedly to protect his design investment. We have sent a written request for performance data, gear ratios, and prices.

Other animal driven gear powers are apparently being used in Mali to power sorghum dehullers designed by AT International. They do not have any available written material describing the power units, and we have failed to find the researchers at the office to discuss details (AT International, 26 & 34:1986).

Tillers has been working on a version of the gear power design that uses a rear differential from a light truck as the first step of gearing. Practicality of this design is dependent on the availability of used differentials. The design attempts to maximize versatility by incorporating the gear power into a cart. The differential is used as an axle in the cart mode. When it is needed as a gear power the cart box can be lifted off and the cart set on its side so the axle is vertical. The tongue is detached from the cart frame and reattached to the upper wheel as a sweep beam onto which a team of animals can be hitched. The lower tire is set in a 25 cm deep hole and staked to keep it from turning. (A light stake can serve as a shear pin to protect against surges in torque.) Two poles are laid on the ground and fastened to the cart frame with guy wires to stabilize it. A large sprocket is mounted on the drive shaft mount of the differential. By a roller chain it powers a smaller sprocket at ground level.

The 1971 Datsun differential that we use provides a 1:2 ratio and the sprockets a 1:7 ratio. We attach an extended drive shaft from the small sprocket out beyond the path of the animals to the transmission with a maximum 1:4 ratio. Multiplying these ratios times the 2.5 RPMs of the oxen yields about 140 ROMs. This can be adjusted by factors of 1 to 6 with pulley sizes off the transmission. While we have not been able to test this arrangement for efficiency, we know it turn significantly more easily than the traditional models that we have in our collection.

The advantage of the cart/gear power design is the multiple uses that it offers to a farmer for transport, stationary power, and mobile power. The unit could be used to power implements like field mowers.

<u>Gristmills.</u>

Prior to the availability of gearing that would increase speeds to higher RPMs, animal power was effectively used by designing machines to operate at very low RPMs. That possibility should be carefully examined before investing in the complexity and expense of gear powers. Operations like pressing sugar or sorghum cane and milling flour in a gristmill were mechanized to the speed of the animals. We should re-examine those options before going through the inefficiencies of gearing up animal power to be compatible with machines that have been redesigned to meet the needs of high-speed engine power.

The gristmill, as illustrated in Figure 1, was designed to operate at very slow RPMs. That is not to say that it ground proportionately less flour. As compared to a 1 HP engine powered burr mill, its capacity is increased by having a mill stone of about 1 meter diameter as compared to the plates of about 25 cm in the burr mill. Given the greater radius of the millstone, the surface speed at the outer edge would be 4 times greater than that of the burr mill if operated at the same RPMs. Also, the grinding surface of the millstone would be 7,850 square centimeters as compared to 490 square centimeters for the burr mill. That is 16 times more grinding surface.

The old Pompeian donkey mill described by L.A. Moritz (74-90:1958) increased the grinding surface by making the surface conical, rather than flat, and by increasing the RPMs by reducing the radius of the donkey's path to less than 1.3 meters. Thus, the donkey could make nearly three times as many revolutions as the horse in Figure 1 which has a radius of about 4 meters though turning sharply certainly reduced the donkeys effective power. These design accommodations of early mills to low RPMs recommends careful consideration of the use of millstones. Perhaps these could be cast of special concrete aggregates to facilitate the controlled aggregates to facilitate the controlled flow of grain and flour. While our task is not to discuss mills, the interaction of power characteristics and machine design should not go unnoticed.

Figure 4. Pompeian Donkey Mill

Figure 5. Endless chain treadmill driving a thresher

<u>Treadmills.</u>

The design concept of the treadmill gets a jump on the problem of low RPMs and high torque by converting the motion of animals' feet more directly to shaft power. Distance traveled is a basic element of power. The treadmill takes advantage of the fact that there is much more surface that passes under the feet of animals in a unit of time than there is surface of a pinion gear that passes a given point. Thus, by rigging a moving apron powered directly by the feet of the animal, the first shaft in a treadmill revolves much more rapidly than the first gear in a gear power. If the apron chains of a treadmill turn its drive sprockets at the circumference surface speed of 180 feet per minute and the circumference of the sprockets is about 6 feet, the treadmill will be starting at 30 RPM rather than the 2 ½ RPM's of the miller's horse in Figure 1. That is a marked input advantage over the gear power that allows lighter and less additional gearing. Assuming efficiency of the treads in moving power, this strategy also avoids the potential inefficiencies and cost of several gears.

No literature or information could be found on current designs of treadmills for generating power, even though design improvements have been made for their use in training horses and new materials have been used in human exercise treadmills. Nonetheless, the strength of materials needed to support the weight of the animals makes it unlikely that an inexpensive and practical model will be forthcoming for use in developing countries.

<u>GTZ Drive-wheel Sweep</u>.

The conceptual advantage of the treadmill should not escape our consideration. Indeed, it is the genius of the GTZ design tried in the CAR. In spite of that power's shortcomings, its engineering concept does answer many of the challenges of creating high RPM power with animals. Instead of gearing up the slow surface movement at the center of a sweep beam, it picks up the much faster surface movement next to the animal. In one minute the sweep was turned 2.9 times by reports. The tire track has a radius of about 3.25 meters and has a circumference surface of 20.4 meters. Thus, the tire covers 59.2 meters of surface/minute. If the tire has a diameter of about 64 cm, it will have a circumference of 2 meters and will turn about 30 RPMs, or 10 times faster than the sweep itself. As with the treadmill, this design avoids the inefficiencies of gearing slower speeds back up, as well as the high torque problems of the very low speeds. Further, the possibility of the tire slipping on the track if the machine is overloaded or jammed is an excellent safety clutch.

Figure 6. a) GTZ Wheel Sweep view of beam and drive wheel, b) top view showing placement of single ox

These advantages would be enhanced perhaps if we had comparative efficiency rates for this and other machines. While we have observations indicating how much power the animals transferred to the sweep, we do not know how much power arrived at the mill and how much was lost in transmission through the sweep and its bearings.

Of course this design innovation also has its disadvantages which should be considered in comparing it to other designs. First, a concrete tire track and a beam structure strong enough to support a mill are expensive to construct. Having the power available on the beam limits the sweeps versatility since its power output is not truly stationary. Thus, it does not have the multipurpose capability of the traditional gear power with its central gear box. On the other hand, while it has the components of a cart, it does not have the mobility of wheel-driven units like the Reed's PTO forecart. Thus, it is not suited to multiple field applications of power. These multipurpose considerations are not as important if the machine can be used on a full-time basis for its specific function.

Some modifications should be considered. The RPMs should be increased by a factor of 2.5 to meet the mill expert's desire to have 500 RPMs. Then, the use of more animals should be perfected. A team of two oxen should be able to work together with only a slight inefficiency, but nearly doubling their output to over 1 HP given what the single Baoule ox did. If there is the demand for milling described, the economics of having two teams that can be exchanged should be calculated. Having two teams would allow 8 hours of work per day. Working a mill at 1 HP for 8 hours per day should about triple daily output. The most important questions are (1) whether the beam structure of the GTZ sweep is designed for 1 HP of sustained effort and the possible peaks of instantaneous torque, and (2) whether the problem with hitching the second Baoule was peculiar to that animal or was a problem in the hitching arrangement?

Possible hitching arrangement considerations are: offsetting the hitch point from the center of the yoke to compensate for the roughly 20% extra distance the outside animal has to travel, extending the hitch point on the beam beyond the center of the animals path so the inward angle of the chain will be parallel to the circumference of the path at the point where the chain attaches to the yoke, and attaching a pole forward from the beam to a short rope off the halter of the inside ox to help guide it around the path. The problem with the garrot bar that was apparently tried is that it conceals unequal performance by a lazy member of a pair. If adjusted to the circle, a yoke should be far superior in getting the animals to work together even though it does not hold them to the path as nicely as the fixed bar.

Ground-driven Cart Wheel.

By using a ground-driven wheel, ground surface speed has historically been utilized to gain revolving force to power moving machinery, much as the GTZ sweep used the tire on the track. This design concept was used to drive broadcast seeders. A large sprocket and drive chain were attached to a wagon or cart wheel and led to the seeder that was placed in the cart. It was a very inexpensive way to make double use of a cart.

Figure 7. Cart wheel-driven broadcart seeder

Depending on their diameter, cart wheels turn at 17 to 34 RPMs (2-4m circumference wheels pulled at 4km/h). A couple 1:6 steps will increase that to 204 to 408 RPMs. If carts with pneumatic tires are used by farmers in the area, a sprocket could be attached to the inside of the hub as GTZ attached the sprocket to their drive wheel (Figure 8). From there, it would be a simple matter of a couple pillow block bearings, a small sprocket, a short shaft, V-belt, and a pair of pulleys to power the unit. The retrofitting of carts would be simple and inexpensive. This option seems to address the cost and RPM challenges as well as any option.

Figure 8. Mounting of sprocket on pneumatic tire

One concern is adding the task of powering a mill or other machine to that of pulling the cart. The rolling resistance of a cart on a hard surface is nominal. M. Goe (16:1983) gives the coefficient of rolling resistance as j0.01 on a hard surface and 0.40 on wet or sandy ground. Thus, if the equipped cart with operator weighed 500 kg, its rolling resistance would be 5 kg on a hard surface but 200 kg on a soft surface. As with the GTZ model, a hard surface would be important, but a laterite gravel track would probably suffice. This track could be laid out in a substantially larger circle (a 5 or 6 meter radius) if they were to be guided by a turn style to save labor. However, as the radius is reduced, the cart tongue may have to be angled to the inside and the length of the yoke beam extended to keep the tongue from pushing against the inside animal.

This system effectively limits damage from instantaneous peaks of torque through tire slippage, as with the GTZ model. Indeed, if a 1 HP mill is used there may be a problem of loss of traction on loose soil or in wet grass. Some simple tests would need to be run to understand this problem. Another problem would be the downward pressure on the tongue that machine resistance would create. Shifting weight to the back of the cart or adding a third wheel under the tongue would relieve this problem. Also, taking the power from just one wheel will tend to pull the cart tongue in that direction.

Again, angling the tongue may compensate for the problem. Since this system would be added to an existing tool, there would be no problem assuring multiple use. The basic investment could be used as a cart or for powered field operations such as mowing forage as the farming system develops. It obviously could not be used for stationary power requirements like pumping water.

There is a modern ground-driven power unit that has been developed in Kentucky by Elmo Reed over the last few years. It is a versatile 3-point hitch cart pulled by draft horses that also has a PTO output of 540 RPMs. With the 3-point hitch any portable tool can be attached very rapidly. It has a third wheel under the tongue so the resistance of added PTO machines will not throw extra weight onto the tongue and the necks of the animals. While it should be quite efficient given that it is made of high quality new parts, input and output engineering research has not been done to determine its efficiency. It is probably a little over-sized for a pair of African oxen, and its price of $3,000 is as much as a motorized sorghum mill. While a patent is pending on design, Mr. Reed is interested in both down-sizing it and licensing its production. More engineering research on this design would educate us on the future potential of draft power.

Table 3. Summary of Advantages

		Effic.	Torque	Equal	Multipurpose		Cost
	RPMs	Trans.	Protect	Draft	Stat	Mobile	Min
Gear powers							

Traditional	High	Poor	Over design	Good	Best	No	High
Botswana RIP	Best	Good?	Over Design ?	Poor?	Yes	No	High
Bunger Entrp.	Med?	?	?	?	Yes	No	?
Cement mixer	Good	Good?	?	?	Yes	No	Med.
Rear diff.	Good	Good?	Some	Good	Yes	Yes	Low
ATI/Mali	?	?	?	?	Yes	?	?
Gristmills	Low	Good	N/A	Good	None	None	Low
Treadmills	Good	Med.	Med.	Good	Good	None	High
GTS Wheeldrive	Med	Good?	Best	Med?	Limited	None	Mod?
Ground Drive							
Cart-mounted	Good	Good	Good	Good	Limited	Good	Med
Reed PTO	Good	Good	Good	Good	Limited	Good	High

Recommendations

From this review and the summary in Table 3, several priorities emerge. First, a program of further testing for the GTZ model to get it up to 1 HP output should be devised. That would focus on efficiently hitching two animals with effective equalizing systems. Also its RPMs could be adjusted to meet the specifications of the milling expert.

Second, simple trials of the low-cost, cart-wheel power should be conducted. The cost of this adaptation is very attractive. Simple tests could be run to determine its effectiveness in a circular path with a turn-style to guide the animals. These tests would show if minor adjustments could correct problems. For the longer term development of wheel-driven shaft power, the work of Elmo Reed on his PTO forecart needs to be analyzed and encouraged.

Third, design and trials of true stationary gear powers built with a pinion gear from a cement mixer should be sponsored. The gear power has a lot of versatility for stationary se that none of the other options can meet. Testing a couple simple designs would direct further development.

The Tillers cart/gear power that is based on the rear differential of a light truck is another option for areas where small shops can find truck parts and adapt them into useful implements. Our prototype is nearly complete and needs only testing and minor refinements to judge its merit.

At this point, it could probably go without saying, but all systems need to be better refined and understood before placing them with farmers or in villages. We need to develop simple quantitative tests and data to replace and supplement the subjective data in Table 3. Until we have such tests of efficiency, research needs to be done near engineering labs rather than in the field. That will limit the development of on-site expertise and the effective adaptation to local skills and materials, but it would be better than the present blundering with non-quantitative data.

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Sources of Information

Search.

Recent material on animal-driven shaft power is very scarce. We spent four days search the collections of Michigan State University, the University of Michigan, and the American Society of Agricultural Engineers for relevant material. In the end, resorting to telephone conversations with people working with animal power was more productive. While we cannot claim to have made an exhaustive survey in the 7 days that we had for this project, we can say that very little is being done in the field of animal-driven shaft power though there is renewed interest and some interesting new ideas. Thus, VITA's work in the CAR may have pioneering importance. Secondly, the information that we have been able to find does not include objective data on efficiencies and output. If we are to address the lack of information, we need to work harder toward simple, but useful comparative data.
s and output. If we are to address the lack of information, we need to work harder toward simple, but useful comparative data.

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