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PROOF-OF-CONCEPT EVALUATION OF A LOW-COST AND LOW-WEIGHT TRACTOR FOR SMALL-SCALE FARMS

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ABSTRACT

About 80% of farms in India are less than five acres in size and are cultivated by farmers who use bullocks for farming operations. Even the smallest tractors available in the Indian market are too expensive and large, and not designed to meet the unique requirements of these farmers. To address these needs, we have developed a proof-of-concept lightweight (350 kg) tractor in collaboration with Mahindra and Mahindra Limited, an Indian tractor manufacturer. Given the challenges of accurately predicting traction in Indian soils by applying existing terramechanics models, an alternative design approach based on Mohr-Coulomb soil-failure criterion is presented. Analysis of weight, power and drawbar of existing tractors on the market, a single wheel traction test, and a drawbar test of a proof-of-concept small tractor prototype suggest that ~200kg is the maximum drawbar force that could be achieved by a 350kg tractor of conventional design. In order to attain higher drawbar performance of 70% of the tractor weight needed for specific agricultural operations, additional design changes are required. An approach for increasing traction by adding tires is investigated and discussed. Additional research on weight distribution, dynamic drawbar testing and tread design is suggested as future work.

† These authors contributed equally to this work, and are listed in alphabetical order.

INTRODUCTION

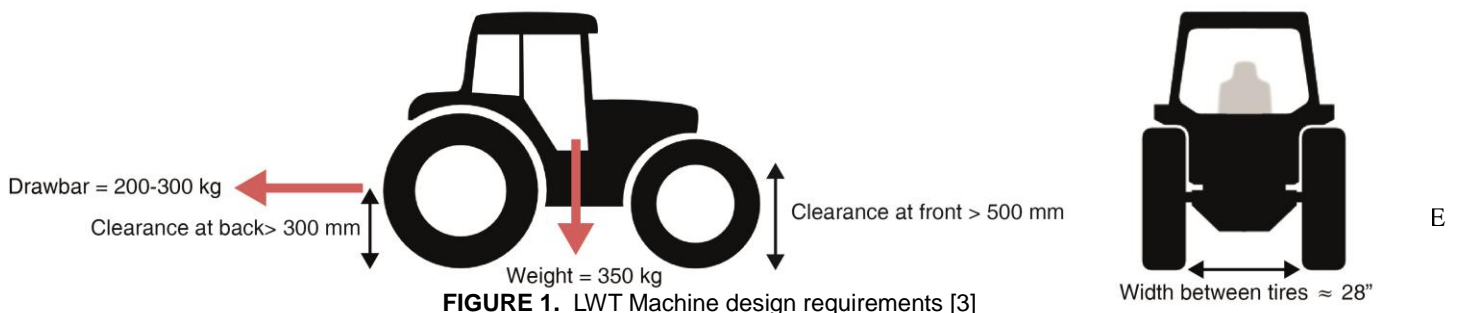
This paper describes the design and performance evaluation of a proof-of-concept prototype of a low-cost and Low-Weight Tractor (LWT) for agricultural use on small farms in India. Agriculture in India plays a pivotal role in the economy, contributing about a sixth of the country's GDP and providing employment to 56% of the Indian workforce. About 80% of the agricultural lands in India consist of small farms of five acres or less [1]. The average size of agricultural holdings in India is about 3.85 acres [2]. Most of these small-scale farmers continue to rely on traditional methods such as using a pair of bullocks to do agriculture work. The smallest tractors available in the Indian market are not only too large to maneuver in small fields, they are also expensive. Mahindra's smallest tractor, the Yuvraj, is designed for use on mid-

sized farms greater than five acres [3]. In addition, the tractors currently on the market are not suitable for the specific needs of small-scale farmers. For example, the average width between the crop rows in small farms is very narrow (less than 30 inches), which requires the width between the tires of the tractor to be equally small. Small-scale farmers also require the tractor to support transportation of their produce for distances of up to 10 km [3].

The motivation behind the design of LWT is to provide small-scale farmers across India with an affordable farming and transportation device that can replace the use of bullocks. Based on cost considerations, compared to Mahindra's smallest tractor, Yuvraj (780 kg - 15 hp), the LWT requires a weight of less than 350 kg and a 10 hp engine [3]. In addition to meeting the size and weight requirements, the tractor should achieve a drawbar pull in the range of 200 kg in agricultural soils, as well as provide a comfortable ride on asphalt at a speed of up to 15 km/h (~4 m/s). A higher drawbar pull of up to 70% of the tractor weight (~300 kg) may also be desired for specific small-scale agricultural operations [3]. The machine design requirements of LWT are summarized in Figure 1.

The lineup of Mahindra tractors arranged by engine power and weight is shown in Figure 2 [4]. Figure 3 shows the drawbar pull and weight of a selection of John Deere tractors [4]. These plots suggests that a small tractor of 350 kg should be able to produce a drawbar load of at least 200 kg, if current tractors scale linearly.

In this paper we discuss the science of traction on soil, implement a single-wheel traction test to further estimate traction, and design and evaluate a proof-of-concept prototype of the LWT. This study provides an insight in to the technical feasibility of the LWT as an actual product to meet small-farmers' needs. The study intends to be a proof-of-concept tool to inform further detailed product design.

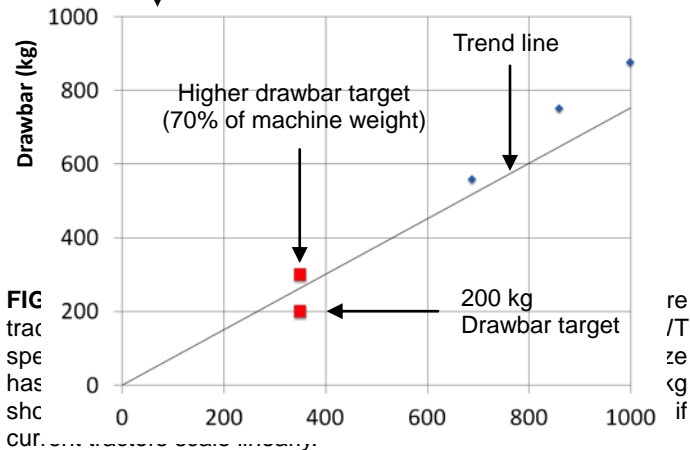
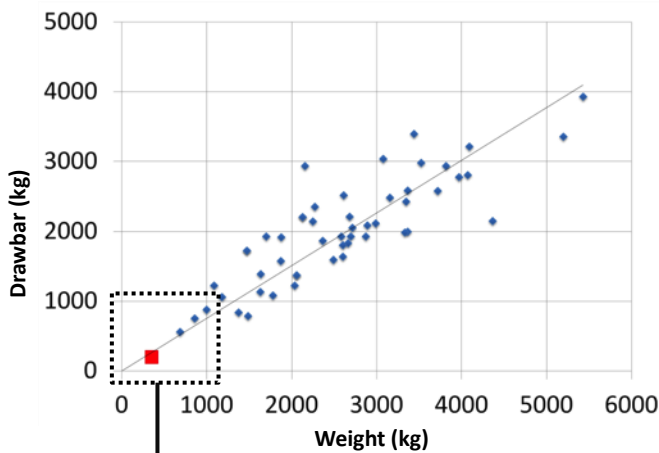


$$F = [cbL + W \tan \phi] \left[1 - \frac{K}{iL} \left(1 - e^{-\frac{iL}{K}} \right) \right] \quad (1)$$

where cohesion, c , angle of shearing resistance ϕ , and shear deformation parameter of terrain, K , are properties of the soil, and i is the slip factor [7].

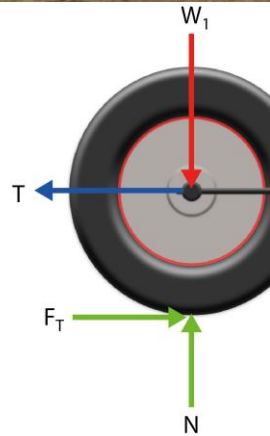
In designing a tractor, the parameters that we have control over in order to affect the tractive force are the geometry of the tractor wheels (parameters b and L) and the weight distribution of the tractor (i.e. the magnitude of W). Conventional agricultural tractors have a rear wheel drive layout with front/rear weight distributions ranging from 35/65 to 25/75 [6], where the front tires are steering tires and the rear tires are traction tires. For the design of LWT, which is a rear wheel drive machine with a weight distribution of 25/75 (front/rear), we can expect a load of 166 kg on each drive tire, including an operator weight of ~70 kg located over the rear tires.

FIGURE 2. Weight and engine power of current Mahindra tractors [4]. The red point represents the LWT.



TRACTION IN SOIL AND DESIGN PARAMETERS

The most commonly used traction models are the Wismer-Luth traction model [5] and the Brixius traction model [6]. These models use the Buckingham pi theorem to fit empirical soil data to curves. However, applying these theorems to agricultural tires often yields errors of $\pm 30\%$ in Indian soil conditions [3]. Instead of relying on these models based on empirical soil data, we investigated the parameters involved in the Mohr-Coulomb failure criterion for soil, which we could vary with the design of the tractor. The tractive force achieved by a wheeled vehicle in soils is determined by the size and shape of its wheels, weight distribution of the vehicle and soil properties. For a wheel (Fig. 4) transmitting a weight, W to the ground with contact patch length, L , and contact patch width, b , the tractive force achieved, F , is



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FIGURE 5. A single wheel traction test set-up and corresponding free body diagram of the single wheel test. Weight applied at the axle is W_1 , weight applied to the lever arms is W_2 , normal reaction force at the contact patch is N , cable tension is T and tractive force denoted by F_T .

smaller than the 8-18 R1 tires used on Mahindra's smallest tractor, was mounted to its rim and attached to a steel fixture through its center of rotation. In this tire designation system, the first number is the nominal tire width in inches. The number after the hyphen is the nominal rim diameter in inches, and the letter and number designate the tread pattern. R1 tread pattern is a common tire tread for agricultural use [8].

Weights were attached to load the wheel to ~170 kg. Lever arms of 0.7 m were mounted through the center of rotation, which facilitated easy application of specific torques. A spring scale connected to cables between the wheel fixture and a stationary object, allowed us to measure the tension in the horizontal cable generated by the loaded wheel.

During the test, weights were moved from the axle to the end of the lever arms to generate a torque on the wheel. The lever arms were measured with a torpedo level to ensure that they were parallel to the ground and that the load vector was perpendicular to the lever arm. The spring scale reading was then recorded to calculate the tractive force generated by the wheel. As seen from the free body diagram in Figure 5, rearrangement of the weights allows the force at the contact patch to remain constant while different torques are applied. In addition, there are only two horizontal forces acting on the system, thus the spring scale reading is a direct measurement of the tractive force.

A maximum torque of 435 Nm was applied during the test, which generated a tractive force of 125 kg on a single wheel, equivalent to 250 kg if the results are extrapolated to a two-wheeled rear drive system. Moving more weights to the lever arms caused the wheel to slip. Given the large increments of torque adjustment during the test, the actual maximum tractive force that could be generated by the tire was likely to be slightly higher. This test indicated that the required tractive force of at least 200 kg required for the LWT could be achieved with normal agricultural tires. As seen in Figure 5, the tire was tested in soil at a planter, close to the base of a tree. Qualitatively, the soil used in the test was fairly compact and moist.

FULL TRACTOR PROTOTYPE

A prototype of the full LWT was devised by modifying a 13 hp, 250 kg Craftsman riding lawn mower (Model No. 917.257631), roughly the desired size for the LWT. The rear wheels of this lawn mower were replaced with two 8-16 R1 agriculture tires (Fig. 6). A flanged coupling was manufactured to allow the wheel to be mounted to the splined axle (Fig. 7). Weights were added to the lawn mower to bring its total weight up to 325 kg, and four force plates were used to ensure a front/rear weight distribution of 25/75. Including the operator, the weight of the tractor was ~400 kg.

In order to evaluate the prototype, tests were performed in agricultural soil and on asphalt. In agricultural soil, the tractive force was tested with spring scales anchored to a rigid support, as shown in Figure 8. In lowest gear, the LWT was used to pull against the anchor. The maximum drawbar measured during the test, before the torque lifted up the front wheels of the LWT, was 210 kg.



FIGURE 6. LWT Proof of concept prototype

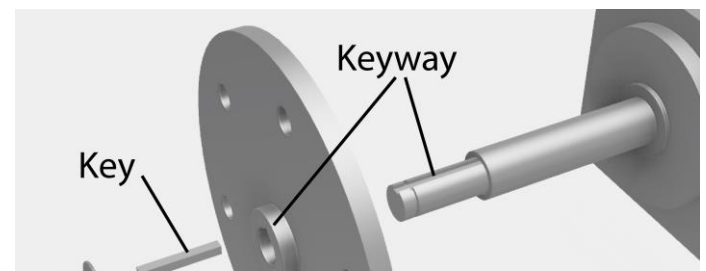


FIGURE 7. Coupling used to mount the agricultural wheel



INCREASING TRACTION

The drawbar testing of the prototype recorded a 210 kg pull, which was 70% of the maximum target of 300 kg. Hence, the test indicated that the basic traction requirement of 200 kg could be fulfilled. Methods to further increase traction were also investigated. Based on Equation 1, we decided to investigate the effect on traction by increasing the contact patch area, by adding more tires to the driving axle (Fig. 9).

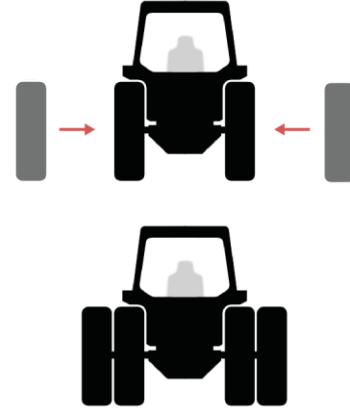


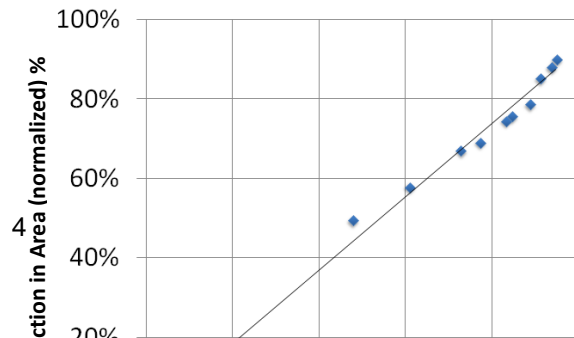
FIGURE 9. Additional tire concept for increasing traction

Preliminary testing was completed to understand how force was distributed over the tires and contact patch area. As more tires are added to the machine, the force per tire and contact area per tire decreases. The testing sought to determine if total contact area would increase with more tires. The test set-up is shown in Figure 10. A force plate was placed under a bicycle's front wheel, and the contact patch area was measured as weight was added.



FIGURE 10. Contact patch area test set-up

From data obtained through the test described above, the effect of adding additional tires to support a constant machine weight could be extrapolated. The reduction in force and area per tire was normalized by the initial unloaded case (Fig. 11). The reduction in force can be calculated by assuming that the machine weight is equally distributed among the new number of tires. A new value for the contact area can be calculated to estimate the reduction in contact patch area per tire. The total contact patch area, as a percentage of the original contact patch area, when additional tires are added is listed in Table 1. These results show that additional tires have a weak effect on the contact patch area. For instance, increasing the number of tires by a factor of 10 increases the total contact patch area by only 70%.



Reduction in Force (normalized) %

FIGURE 11. Reduction in contact patch area per tire as force per tire is reduced due to additional tires.

TABLE 1. Total contact patch area for additional tires

Number of Tires	1	2	4	10
Contact Area	100%	108%	123%	170%

RESULTS AND CONCLUSIONS

This paper presents a proof of concept design and evaluation of a low weight tractor to meet the needs of small-scale farmers in India. The single wheel traction test and testing of the full tractor prototype indicates that the LWT would be able to achieve expected drawbar pull based on the scale down trend of larger existing tractors. However, to achieve the higher drawbar target of up to 70% of vehicle weight that Mahindra would like, additional methods for increasing drawbar pull would be required. Methods to enhance traction were also investigated as a part of this study. Adding tires to a machine without adding ballast is expected to marginally increase contact area and accordingly slightly increase traction. Qualitatively, vehicle speed tests and rider comfort tests on roads indicated satisfactory performance. On asphalt, the tractor was able to achieve a speed of 13 km/h (~3.6 m/s). The heavily protruded tread pattern of the agricultural tires did not cause any rider discomfort.

This result implies that the LWT with a simple scaled down design would be able to deliver satisfactory transportation performance without any major rider discomfort on roads.

In the future, testing should be conducted on the effect of weight distribution on drawbar pull of the machine. Dynamic towing capacity should also be tested. In a dynamic towing test, the moving test machine drags a towed vehicle that increases its resistance by applying its brakes. This test is more analogous to how a tractor loses traction in actual usage. Other design concepts for improving traction should also be pursued. Research into the optimization of tread patterns for agricultural tires to achieve better traction may yield new methods resulting in higher drawbar within the cost constraints of the LWT. Development of fundamental understanding of the influence of tire tread profiles on tractive force in realistic and variable agricultural soil conditions can facilitate new design concepts that could achieve the desired tractive force. For example, external modular attachments over the tire's contact surface to change the tread profiles based on specific requirement may be considered within the cost constraints of the LWT. Alternatively, completely different systems can be imagined such as a winching system, which could pull the machine along instead of relying on traction-based driving. Finally, the maximum drawbar requirement, currently at 70% of machine weight, should be critically examined to determine if there are other ways to meet the needs of small-scale farmers, besides increasing the machine towing capacity.

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