Tractor design for small farms in resource limited markets

by

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Abstract

This thesis describes the design of a tractor for small farms (<2 ha) in resource limited markets, particularly India, and the analytical framework used to arrive at the design. Indian smallholder farmers typically rely on draft animals, which compared to tractors are more expensive to maintain, more exhausting to use, slower, and incompatible with many modern farming tools and methods. These disadvantages are detrimental to the farmer's income and crop yields. However, existing small tractors are too large and expensive to directly replace draft animals. The presented tractor design is unique in its ability to compete with draft animals' physical dimensions, pulling performance, and sale price, while retaining key tractor advantages like compatibility with modern tools, low maintenance costs, and reduced drudgery. This tractor features motorcycle-like controls and seating, inline drive wheels, stabilization via an outrigger arm or a specially-developed balance board attachment, and the ability to attach implements ahead or behind the rear axle. The design was created to satisfy unmet farmer requirements identified during on-site interviews with Indian farming stakeholders.

Before deviating from the conventional tractor design, a comprehensive description, from a historical and physical perspective, of why the conventional tractor came to be was elucidated. Then, the proposed tractor design was conceived by leveraging historical, physics-based, and user-focused insights. Experimental results with an instrumented proof-of-physics prototype validated the new tractor could produce traction forces as predicted by the analytical framework used to create the design, as well as meet or exceed the maximum pulling forces generated by draft animals.

A functional prototype of the tractor was built, and its ability to complete key farming operations was demonstrated on a Massachusetts farm. The vehicle was able to complete plowing, disc harrowing, rotary tilling, planting, cultivating, spraying, and towing of a trailer per Indian industry specifications. A study was conducted to assess whether the vehicle would meet the needs of small and marginal farmers in India through on-site, one-on-one interviews with 24 farmers in Karnataka, Gujarat, and Tamil Nadu. Farmers generally reported that the prototype tractor would meet their needs, with an average likelihood of 4.8/5 that they would use the vehicle for planting, inter-cultivation, and spraying, and an average likelihood of 3.8/5 that they would use the tractor for primary or secondary tillage.

Thesis Supervisor: Amos G. Winter, V
Title: Associate Professor

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Chapter 1

Introduction

This thesis proposes a small tractor concept, called Bullkey, specifically designed for small farms in low resource settings - particularly in rural India. The chapters move from a review of the evolution of the conventional tractor (Ch. 2), to the implementation and testing of a tractor layout with a high drawbar pull to mass ratio (Ch. 3), to the creation of a Bullkey prototype and an evaluation of its ability to satisfy the needs of Indian farmers (Ch. 4). The socioeconomic research and evaluation of conventional tractors that motivated this research are summarized here in Chapter 1.

1.1 The need for mechanization in farms

Tractors are an icon of industrialized, modern farming and their presence has been noted as a differentiator between farming in developed vs. developing countries [39] [32]. In 1950, the USA Census Bureau stated the benefits of mechanizing American agriculture [98]:

> *The increased use of mechanical power on farms has influenced agriculture more than any other factor during the present century. The changes from horses and mules to tractors for farm work has made available an acreage of cropland greater than the total increase in cropland during the half century for the production, directly or indirectly, of meat, milk, eggs, and other food. The use of the tractor and related equipment for farm work, and the use of farm trucks for hauling and automobiles for traveling have increased the rate at which farm work is done and has increased the capacity of agricultural workers, enabling considerable numbers*

> *of farm workers to leave the farms or to engage in non-farm work, notwithstanding considerable increases in total farm production. Tractors and power-operated equipment have made an increase in the size of farms possible. The substitution of tractors for animal power has also made available additional power for farm use. With a tractor, the farmer of 1950 probably turned out twice the amount of farm products for market as his father did with a team of horses 50 years earlier. Moreover, less of the farmer's time was required to care for the tractor than to raise feed for and to produce and care for horses that were replaced by the tractor.*

There is high correlation worldwide between farm productivity and available tractor power [33] [73] [40] [39]. The Indian Agricultural Ministry [52] estimates that farm tractors' precision and timeliness increases farm yields by 5 to 20%, reduces waste seeds and fertilizer by 15 to 20%, and reduces the labor time required on a farm by 20 to 30%. Bullock owners are currently burdened with the high ownership costs of the animals, which outweigh initial costs over time. The total cost of buying and maintaining a pair of bullocks for 15 years is over two times higher than the equivalent costs for a tractor.

1.2 The conventional tractor design is not meant for small farms worldwide

The majority of farms in the world (84%) are less than 2 ha in size [58]. Small farms are particularly common in India, where the average farm size has steadily decreased from 2.28 ha in 1971 to 1.08 ha in 2016 [75]. Most small farmers use a pair of bullocks for all or most of their farming operations, supplementing the rest with pure manual labor or a hired tractor (particularly for primary and secondary tillage) [52][31]. Bullocks are compact, highly maneuverable, and have a low capital cost, making them well-suited to the technical and economic constraints of small farms. Conventional tractors, which are an icon of modern farming and typically associated with high farm yields [39], have not yet been able to reproduce these key bullock features [64][76]. As a result, farmers are constrained to the slow speed of bullocks and a lack of access to suitable modern, more effective made-for-tractor tools [31][30].

This misalignment between the tractor and needs of the small farmer is, in part, because conventional tractors were designed for a larger field size. The conventional small tractor was originally intended to operate in much larger farm holdings than what is typical around the world [44]. The conventional small tractor largely found its form in the USA between 1910 and 1940 [44] [107] [77] [61] [104], where the annual average farm size since 1900 has been at least 50 times greater than the present global average. Globally, at present, 72% of farms are <1 ha, while less than 2% of US farms have been <1 ha since 1900 [58] [33] [14] [99] [59]. As a result, for many small farmers, replacing their bullocks with a conventional tractor would require adjusting crop spacing (particularly for crops taller than a tractor's ground clearance), or sacrificing farmland as headland area to give the tractor space to maneuver at row ends. It might also require improving road access to their field due to the tractor's larger size and poorer off-roadability.

1.3 Bullocks can be preferable over tractors in small farms

As part of this study, the authors spoke about local agricultural practices and the suitability of existing tools with stakeholders of Indian small farming at 12 locations in India including the states of Maharashtra, Tamil Nadu, Gujarat, Rajasthan, Madhya Pradesh, West Bengal (Fig. 4-2).

Stakeholders included farmers, research organizations, governments, manufacturers, and dealers. A key observation from these visits was that farmers would use bullocks not only because of their low capital cost (about a third that of tractors) but because they have functional advantages over conventional small tractors. Some of these advantages are:

- Bullocks have a smaller width than tractors. This allows the bullocks to walk between rows of growing crops further into the season than a tractor could. In some cases even allowing the farmer to use a tighter row spacing than would be possible with tractors.
- Bullocks require less headland area. Headland area is space left at field ends to allow farm vehicle to maneuver between rows. Bullocks can make tight turns and are able to step over crops or rows to avoid damaging them when turning.
- Bullocks have better off-roadability. They only require narrow trails to advance, similar to human foot paths. They use legged locomotion which allows them to step over obstacles, including foot-high bunds of soil between farm fields. And they have a self-preservation instinct that can be reassuring to farmers when moving past cliffs or other

dangerous features. Tractors, in an effort to achieve high crop (i.e. ground) clearance have high centers of mass. This makes tractors more dangerous on sloped terrain than bullocks.

- Bullocks are easier to control at slow speeds and in tight spaces. This was particularly important to farmers operating in very wet fields where they are concerned with the tractor's straight tracking, ability to access field edges, and difficulty of salvaging if it gets stuck.

A tractor likely to be adopted by small Indian farmers should have the bullock's ability to access narrow inter-row spaces and the bullock's low capital cost while retaining the tractor's relatively low upkeep costs, efficient use of resources, better ability to interface with modern tools, and low user fatigue.

1.4 The Bullkey design

The research presented in this research manifested in the design of Bullkey, which has features and performance to address Indian farmer needs. *Bullkey* is a portmanteau of *bullock* and *key* - indicating its goal of being the key to unlocking the bullock market to mechanization.

Bullkey features a three-wheeled layout that supports nearly all of the vehicle's mass on inline drive wheels and shifts the tillage tool ahead of the rear axle (Fig. 1-1). This layout increases the load on all drive tires during plowing and allows the trailing drive tire to roll on already-compacted terrain - improving drawbar pull while also preventing the vehicle from rolling over backward. To stabilize itself in roll, Bullkey can utilize an outrigger arm or a custom-designed balance board system. The outrigger arm has high ground clearance and can straddle growing crop. The balance board utilizes some user effort for stability but keeps the Bullkey overall width comparable to bullocks; this allows Bullkey to fully operate between rows of growing crop without the need to straddle them.

Validation of the Bullkey design was two-fold: the design was field tested to validate the physics model that drove its design, and the design was discussed with 24 small farmers in India to receive their feedback on its viability as a replacement for bullocks. The field tests demonstrated that the Bullkey tractor layout can generate more drawbar pull per unit mass than a conventional tractor. The user interviews in India showed that farmers were able to

Figure 1-1: Images of the proposed Bullkey tractor. This design is discussed in detail in Chapters 3 and 4. It features inline drive wheels, an outrigger wheel, and an option for a centrally located tillage tool or conventional rear mounted tools.

identify Bullkey's ability to replace bullocks on farms and would be willing to purchase it for a price equal to or higher than the predicted sales price for the Bullkey design.

1.5 Outline of Thesis

Chapter 2 discusses the origins of the conventional tractor. It elucidates the key features of the conventional tractor design and what motivated their development. This is done via a review of the tractor's history from an engineering perspective and the application of a tractor physics model to study key design parameters. Understanding the reasoning behind the conventional tractor design can empower the engineer to more confidently modify it to meet the needs of new users. This review provided inspiration and motivation for the design of Bullkey.

Chapter 3 explains the motivation and reasoning for the Bullkey design. It also describes a proof-of-physics prototype created to validate the performance advantages of Bullkey. It is shown that the Bullkey design can generate more drawbar pull per unit mass than conventional tractors and is a viable design for accessing narrow spaces on farm fields.

Chapter 4 describes the creation of a Bullkey prototype capable of performing farming operations key to small Indian farmers, the field tests of that prototype, and the feedback from one-on-one interviews with Indian farmers about their perception on the Bullkey's viability for performing those operations. It is shown that Bullkey can succesfully perform the farming operations it would be expected to and that farmers perceive as a vehicle that integrates the key advantages of both tractors and bullocks.

Chapter 5 summarizes the results from this thesis and discusses its impact, along with high value directions for future work. Bullkey has been shown to have high potential for replacing bullocks in small Indian farms. Future work could interview Indian farmers who have tested the tractor on their own farm fields and refine the design to get it ready for production. Additionally, the physics model used to create Bullkey could be refined further to increase its accuracy at low tire slips.

Chapter 2

An Engineering Review of the Farm Tractor's Evolution to a Dominant Design

2.1 Introduction

Tractors are an icon of industrialized, modern farming and their presence has been noted as a differentiator between farming in developed versus developing countries [39] [32]. There is high correlation worldwide between farm productivity and available tractor power [39][33] [73] [40]. In 1950, the USA Census Bureau summarized the benefits of mechanizing American agriculture during the past 50 years [98]: mechanical power on farms influenced agriculture more than any other factor; mobile, powered farm equipment increased the rate at which farm work was done and has increased the capacity of agricultural workers, enabling considerable numbers of farm workers to leave the farms or to engage in non-farm work; and tractors and power-operated equipment made an increase in the size of farms possible.

This chapter provides historical and physics context for why the modern tractor evolved to its dominant design. This understanding and the analysis framework used to explain it are valuable tools for evaluating new tractor designs. The work presented herein is of contemporary relevance. Farm mechanization is growing in emerging markets and common pitfalls of engineers designing for those markets include poor assumptions about the needs of end users and a lack of knowledge about the specific problem space, cultural norms, and technical area[109]. This chapter can help these engineers by supplying them with the context in which tractors were originally developed (and thus a reference point to compare to their target market) and by accelerating their development of expertise on farm tractors by understanding the underlying physics. A historical background on tractor design can also help gain insights on new innovation opportunities; for example, relatively new autonomous driving and precision farming technologies encourage the development of novel tractor-like vehicle platforms [110]. Engineers may more confidently break away from the dominant tractor design if they understand its origins.

2.2 History of farm tractor evolution to a dominant design

2.2.1 Design features of the conventional farm tractor

The conventional small tractor produced today found its form mostly in the USA between 1910 and 1940 [107] [77] [61] [104]. The most salient features of the "conventional tractor" or "dominant tractor design" are:

- Four wheels laid out in a rectangular pattern, attached to front and rear axles.
- Pneumatic tires on all wheels, with the rear tires having larger diameter and width than the front tires.
- Front wheel steering.
- Rear-wheel-drive with the wheels joined by a differential axle (front wheel assist sometimes present).
- Independently controlled braking force at each rear wheel (two brake pedals are provided).
- Engine rests over the front axle.
- Operator sits between both axles, usually only slightly ahead of rear axle.
- Trailing implement behind the rear axle, option to attach implement rigidly (via "Three-Point Hitch").
- Rear-pointing, engine-powered exposed shaft behind the rear axle for powering implements ("Power Take-Off").

- Engine crankcase and transmission case used as structural components.

Similar to many products, these characteristics did not evolve solely to improve farm field performance; they were also determined by pressure to lower manufacturing and distribution costs, improve marketability, increase versatility and ease-of-use, and comply with government regulations. Some of these pressures and their impacts are discussed in Sections 2.2.2 and 2.2.3. They are also summarized in Fig. 2-1.

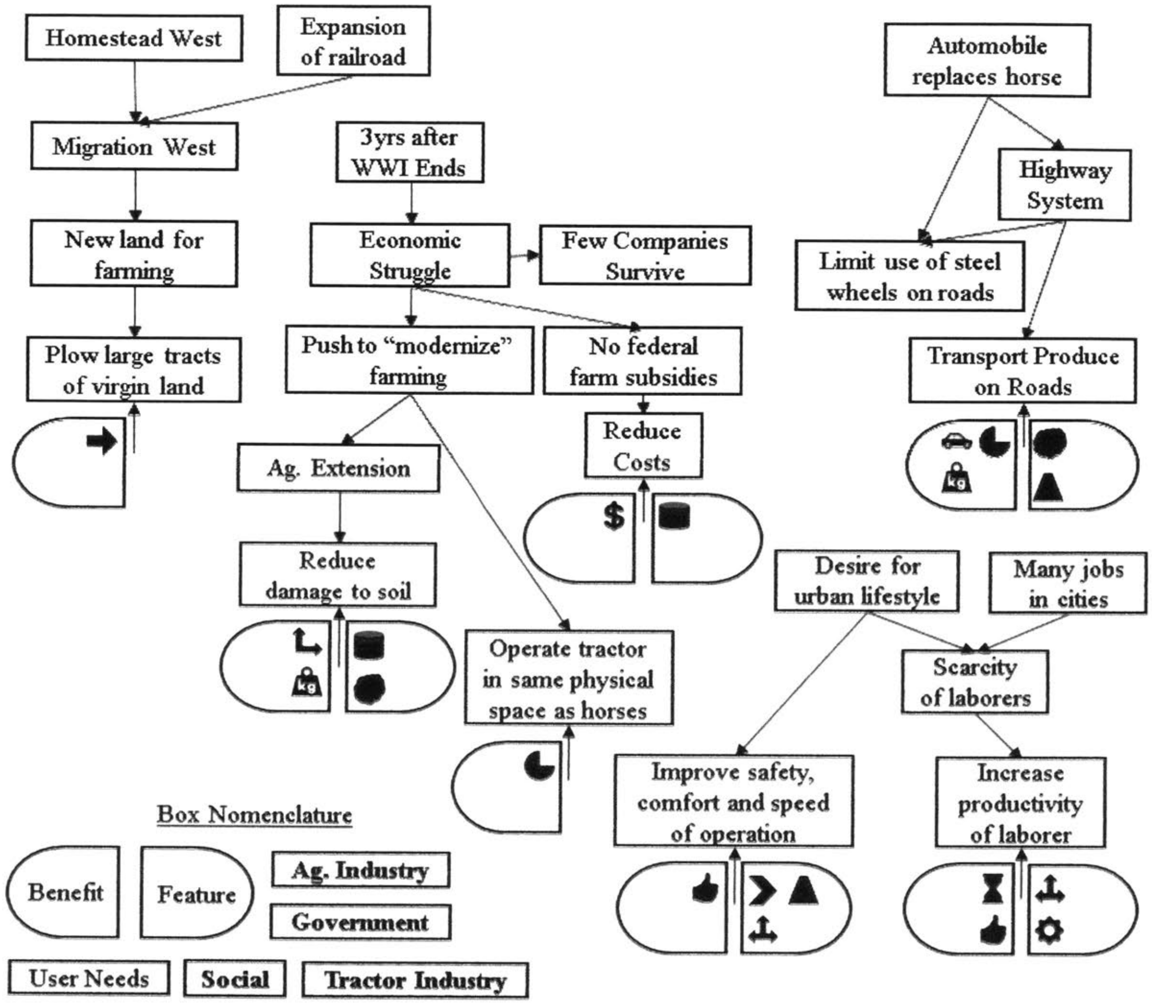
To emphasize the other design directions the nascent tractor industry could have taken, Fig. 2-2 shows 24 production tractor layouts from between 1910 and 1920. Layouts varied widely in traction gear (mostly combinations of tracks, wheels, and drums), number of axles, driver position, tool position, and overall dimensions.

Few of these designs would have a significant and lasting impact on the industry, however. Figure 2-3 highlights a selection of production tractors whose most salient features would influence future models and later become enduring characteristics of the dominant tractor design.

2.2.2 1900 to 1920: early history of the modern farm tractor

In 1903 the term "tractor" was first coined in advertisements by the Hart Parr Gasoline Engine company of Charles City, Iowa. At the time, horses and mules were the primary source of draft power in the burgeoning American farming industry. In the USA the Homestead Act of 1862 was still ongoing with minor revisions and motivated farmers to extend westward from the northeastern cities. Earnest farmers tilled the wild soil and rapidly expanded the total amount of available arable land [107]. The large tractors (often steam powered) of the time were more capable than animals at tilling the expansive tracts of land in the Midwest prairies but were also unwieldy and expensive. These tractors were specialized tools aimed at heavy tillage of large areas and as mobile motors to power crop processing machines.

During the late 1910s the agricultural industry in the USA became highly profitable as food exports increased dramatically to feed resource depleted Europe and Russia during and after WWI. Between 1915 and 1920 the agricultural output of Eastern Europe and Northwestern Europe dropped by half and a third, respectively [36]. During those five years USA farms sold at almost continually rising prices that drove their net income to almost triple, and farmland prices to more than double, as farming became a more attractive investment [21][37]. American farms grew in number and size, yet farm labor was more



Symbol	Benefits vs. predecessors and contemporaries
↳	High drawbar pull per unit weight
➡	High drawbar pull
$	Reduced cost
🚗	Better performance/access on roads
⧗	Better reliability
kg	Lower weight
◕	Smaller size
👍	Easier to use and/or more versatile

Symbol	Dominant Design Feature
▮	Structural crankcase and transmission
⊥	Three-point hitch
●	Pneumatic Tires
❯	Automatic draft control
▲	Four wheel layout
⚙	Power Take Off

Figure 2-1: Graphic chronology of tractor evolution as influenced by historical context and stakeholder expectations.

scarce as the rural youth went to fight in WWI and later returned preferring an urban lifestyle. Farm tractors became an attractive way to multiply the capacity of each laborer

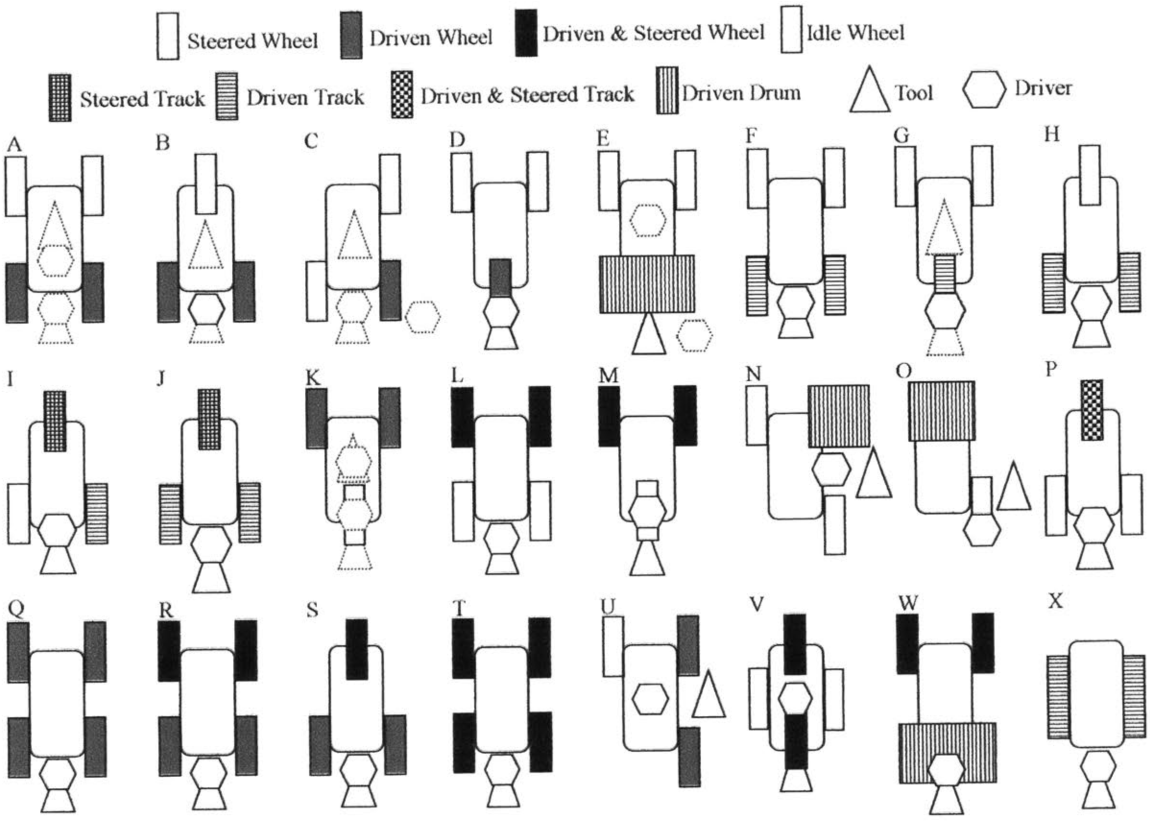
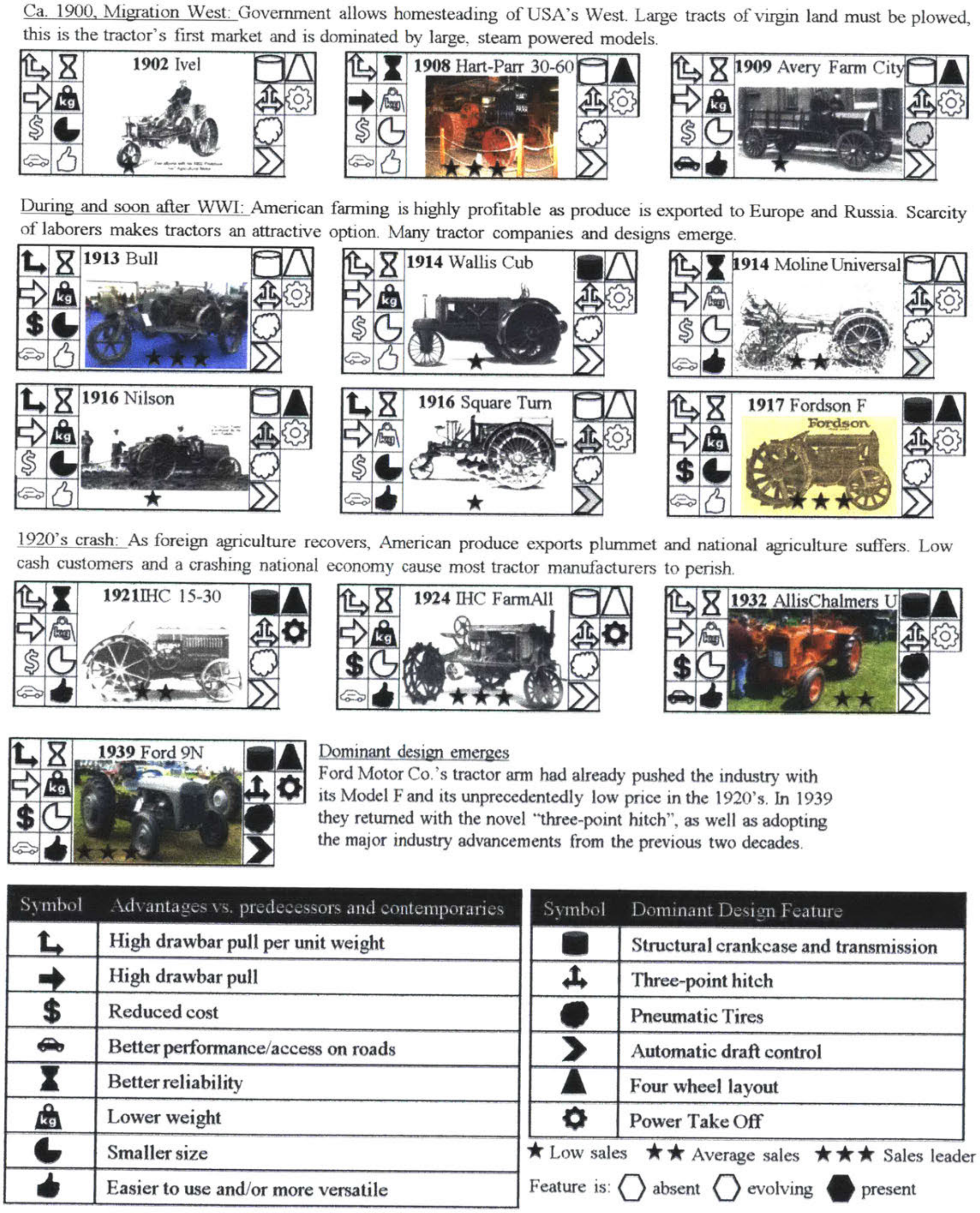


Figure 2-2: Components with a dotted outline represent multiple possible locations in otherwise identical layouts. Designs A through J are rear axle driven, K through P are front axle driven, and Q through X are driven by both front and rear axles. A list of some production tractors using each layout can be found in Appendix A1.

[98].

The blooming tractor industry innovated quickly as it received feedback from a rapidly expanding customer base and adopted engineering knowledge from its younger but more refined cousin, the automobile [20]. It was often the case that the farmer who owned a tractor still had to own horses, which were more maneuverable and smaller, for cultivation operations [20][78]. Very large tractors that had been used to open large fields in the expanding West were too specialized and would lay rusting with little or no use after that initial heavy ploughing operation [107] [113]. The demand for a less expensive, smaller, and lighter tractor was growing, and manufacturers new and old rushed to fill the void [28] [112].

The first tractor to meet the demands of the common farmer in size and price was offered by the Bull Tractor Company in 1913 (Fig. 2-3). This lightweight tractor had three wheels with a single drive-wheel and had an initial price comparable to a team of horses.



Ca. 1900, Migration West: Government allows homesteading of USA's West. Large tracts of virgin land must be plowed, this is the tractor's first market and is dominated by large, steam powered models.

During and soon after WWI: American farming is highly profitable as produce is exported to Europe and Russia. Scarcity of laborers makes tractors an attractive option. Many tractor companies and designs emerge.

1920's crash: As foreign agriculture recovers, American produce exports plummet and national agriculture suffers. Low cash customers and a crashing national economy cause most tractor manufacturers to perish.

Dominant design emerges

Ford Motor Co.'s tractor arm had already pushed the industry with its Model F and its unprecedentedly low price in the 1920's. In 1939 they returned with the novel "three-point hitch", as well as adopting the major industry advancements from the previous two decades.

Symbol	Advantages vs. predecessors and contemporaries
↳	High drawbar pull per unit weight
➡	High drawbar pull
$	Reduced cost
🚗	Better performance/access on roads
⧗	Better reliability
kg	Lower weight
◕	Smaller size
👍	Easier to use and/or more versatile

Symbol	Dominant Design Feature
■	Structural crankcase and transmission
⊥	Three-point hitch
●	Pneumatic Tires
❯	Automatic draft control
▲	Four wheel layout
⚙	Power Take Off

★ Low sales ★★ Average sales ★★★ Sales leader

Feature is: ⬡ absent ⬡ evolving ⬢ present

Figure 2-3: Graphic chronology of tractor evolution into conventional small tractor design. More vehicle data and larger images are found in Appendix A2. Photo Credits: 1902 Ivel [70], 1908 Hart-Parr 15-30 [114], 1909 Avery Farm City [29], 1913 Bull [101], 1914 Wallis Cub [94], 1914 Moline Universal [66], 1916 Nilson [91], 1916 Square Turn [92], 1917 Fordson F [105], 1921 IHC 15-30 [62], 1924 IHC FarmAll [35], 1924 Allis Chalmers U [100], 1939 Ford 9N [18]

By 1914 it was the best-selling tractor in the country [107]. The tractor industry still had reliability issues and production volume challenges that it would learn to solve partially from automobile experts becoming more involved. In 1917 Henry and Edsel Ford launched Fordson tractors. Their Model F quickly became the best-selling tractor in the world and would eventually be produced at a price and volume that would raise the entry barrier to tractor manufacturing beyond what most smaller competitors could muster[107]. The Model F was already highly reminiscent of today's modern small tractor and also of the traditional automobile layout. It had four wheels, front wheel steering, rear wheel drive, and a trailing tool. Not yet incorporated were pneumatic tires, a rigid tool attachment system (Three-Point Hitch), and an exposed engine-powered shaft for powering implements (Power Take Off).

2.2.3 1920 to 1950: farm tractors converge on a common design to power American farms

In 1920, 166 companies in the USA manufactured farm tractors and had a combined annual production of 203,207 tractors. These were dramatic increases from 1910, when only 15 farm tractor companies were in business and had a combined production of 4,000 tractors [43]. These 166 companies were competing to define the shape of the "farm tractor" and to distinguish themselves through innovative designs (a sample of tractor layouts is shown in Fig. 2-2) [20] [78].

During 1921, a dramatic shift occurred in USA production. Agricultural output in Eastern and Northwestern Europe had quickly recovered to pre-WWI levels to suddenly make them largely independent of imported food [36]. Farmers in the USA had misjudged international demand and food overproduction caused the prices of agricultural produce to plummet. Farmers abruptly found themselves unprofitable and with outstanding bank loans used to purchase farmland that had since collapsed in value[37]. Farm tractor production plunged by two-thirds from 203,277 units in 1920 to 68,029 units in 1921 [43].

The Great Depression and Stock Market Crash of 1929 would keep American farmers in a difficult position through the 1920s and 1930s. It forced tractor manufacturers to adapt to a low cash flow style of farming. In February 1922, the "Tractor Price Wars" started when Fordson (a Ford Motor Co. brand) slashed the price of its popular Model F from $625 to $395 [107]. Over the next 20 years a fiercely price-competitive tractor market would see manufacturers converge on similar designs. Many manufacturers would disappear in this "war", from 166 manufacturers in 1920 to only 38 in 1930. However, the industry's annual tractor production had rebounded to 196,297 units in 1930, very similar to the output of 1920 [43]. Yearly total production of American tractors would keep rising until reaching a peak in 1951, when 564,000 tractors were manufactured. By 1950 there were over 3.6 million tractors operating in American farms (about 1 tractor for every 6 people living on a farm) and the internal combustion engine had become the primary source of draft power for farmers [98].

Farm tractor production between 1910 and 1950 was significantly higher in the USA than elsewhere in the world. In any given year, production in the USA was at least ten times higher than any other single country, and at least five times greater than the net global production excluding the USA. American tractors were in high demand domestically and also exported extensively[56][49].

2.2.4 Emergence of the dominant tractor design features between 1910 and 1940

Major innovations that shaped the dominant tractor design and products that exemplified them are discussed below.

1914 - The Wallis Cub (Fig. 2-3) was the first tractor to use the engine crankcase and transmission case as structural components. Launched in 1917, the Fordson F (Fig. 2-3) would leverage this construction style to reduce production costs by using less materials and more streamlined manufacturing than its competitors. The Fordson F's runaway success in domestic and international markets would help cement the structural crankcase and transmission as features of the dominant tractor design.

1916 - The Square Turn (Fig. 2-3) featured innovations that signaled trends to come. The Square Turn's name boasts its ability to control both of its drive wheels independently for tight turning (even reversing one wheel while the other drives forward). The dominant tractor design that would emerge later features a differential axle and allows independent braking of either rear drive wheel for tight turning (a skilled driver may also use independent braking as a differential axle quasi lock). The Square turn also used engine power for lowering and raising farming implements even while the tractor is stationary.

1921 - All tractors sold in Nebraska must henceforth go through the standarized Nebraska

Tractor Test, the results of which are public [69]. This test would go on to become the mandatory national, and later international, standard for tractor testing. For the manufacturers, outstanding performance in the test can provide a major marketing tool. Some of the more marketable results from the test involve towing a braked vehicle behind the tractor, an operation generally better suited to tractors designed to pull heavy tillage tools behind them.

1921 - International Harvester introduces the Power Take Off (PTO) as an option in the 15-30 tractor (Fig. 2-3), allowing the tractor's engine to power actuators in farming implements through a rigid speed-controlled shaft instead of using a flat belt. Implement manufacturers rush to take advantage of this innovation.

1925 - International Harvester introduces its Farmall "General Purpose" (GP) tractor (Fig. 2-3). The Farmall series would become the best-selling tractor series ever in the USA. Compared to most other tractors on the market it: was lighter, had higher ground clearance, utilized smaller front wheels (enabling tighter turns), had adjustable track width, and it was as advertised for cultivating, plowing, and cutting.

1932 - Firestone pneumatic tires are offered as standard equipment on the Allis Chalmers U (Fig. 2-3). Pneumatic tires allowed tractors on the growing network of paved roads (where steel, lugged wheel were not permitted) and enabled farmers to increase fuel efficiency and operate at higher speeds.

Circa 1935 - Diesel engines are advanced enough to become standard in farm tractors [104]. This improves reliability (especially after storage periods), and gives the tractor a wider high-power RPM operating band.

1939 - Ford and Ferguson introduced the three-point hitch tool mounting system in the Ford 9N (Fig. 2-3). The system efficiently leverages draft forces from heavy tillage tools to improve the tractor's drawbar pull performance; a better implementation of the idea pioneered by the 1916 Nilson Tractor (Fig. 2-3). The 9N featured hydraulic-powered coarse and fine control over implement vertical position, reducing the drudgery of tractor driving and tool attachment while also increasing the tractor's field capacity (actual acres worked per hour). The three point hitch is the standard today for mounting trailing farming implements.

2.3 Analytical modeling of the conventional tractor's design

Insights into success of the conventional tractor design are elucidated by modeling its performance and then exploring the effects of altering the design. The modeling of a tractor on soil can be separated into two inter-related parts: calculating the distribution of forces among all tires (the tires hold the tractor afloat and propel it forward) and, given that load distribution, calculating the power consumption and other performance metrics at each individual tire. A detailed description of modelling off-road vehicles in uneven terrain can be found in [97].

2.3.1 Conventional tractor dimensions and relevant forces

Calculation of the tractor-applied forces at the tire-soil interface requires a force balance of the tractor and farm implement system. Under the assumption of the tractor being a laterally symmetric rigid body, being in steady-state equilibrium, and all the wheels having their rotation axes orthogonal to gravity and parallel to each other, the tractor free-body diagram (Fig. 2-4) can be simplified to include only:

- overall center of mass location and magnitude
- draft tool force direction, magnitude, and origin (center of pressure)
- location of ground reaction force points and associated vectors
- tractor orientation with respect to gravity (uphill or downhill slope)

Overall, the sum of the vertical force V_f on the front wheels is

$$\begin{aligned} V_f = \frac{1}{x_f + x_r} & (W_T(x_r cos(\theta) - y_g sin(\theta)) \\ & + D(y_D + cos(\alpha) - x_D sin(\alpha)) \\ & + W_I(-x_I cos(\theta) - y_I sin(\theta))), \end{aligned} \tag{2.1}$$

and the sum of the vertical force V_r on the rear wheels is

$$\begin{aligned} V_r = \frac{1}{x_f + x_r} & (W_T(x_r cos(\theta) + y_g sin(\theta)) \\ & + D(-y_D + cos(\alpha) + x_D sin(\alpha)) \\ & + W_I((x_I + x_r + x_f) cos(\theta) + y_I sin(\theta))), \end{aligned} \tag{2.2}$$

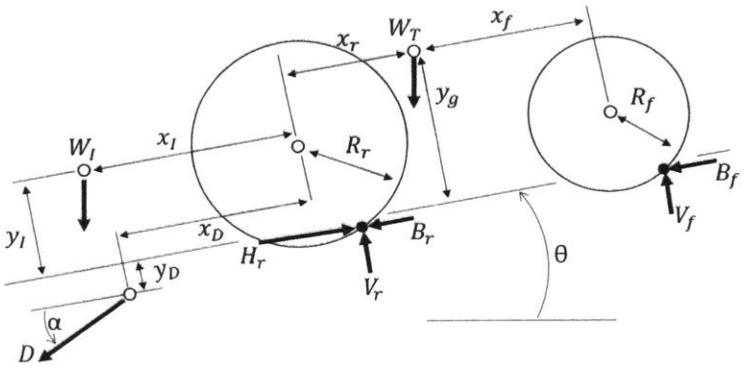


Figure 2-4: Free body diagram for farm tractor in 2D.

where x_f is the distance from the tractor center of gravity (CG) to the front axle, x_r is the longitudinal distance from the tractor CG to the rear axle, W_T is the weight of the tractor, θ is the ground slope angle, y_g is the distance from the CG to the ground, D is the tillage force, y_D is the depth of the tillage tool center of pressure (COP), x_D is the longitudinal distance from the tillage tool COP to the rear axle, α is the angle of the drawbar force vector relative to the ground slope, W_I is the weight of the implement, x_I is the longitudinal distance from the rear axle to the tillage tool CG, and y_I is the distance from the ground to the tillage tool CG.

It is assumed in the conventional tractor configuration that only the rear wheels are driven. To move the tractor forward at a constant speed, the rear tires must provide the net horizontal force

$$H_r = B_f + B_r + Dcos(\alpha) + (W_T + W_I)sin(\theta), \tag{2.3}$$

where B_f is the force from the soil on the front wheel opposing vehicle forward motion, B_r is the force from the soil on the rear wheel opposing vehicle forward motion, D is the tillage force, W_T is the weight of the tractor, and W_I is the weight of the implement.

The calculation of the actual wheel torque necessary to achieve H_r and the calculation of resistance forces B_f and B_r requires further analysis described in Section 2.3.3.

2.3.2 Qualitative description of importance of soil-tire interaction in tractor design

A refined terramechanic design can reduce the power lost at the soil-tire interfaces, something especially critical for farm tractors which seek to minimize fuel consumption and damage to soil. While drivetrain mechanical losses in a small tractor can be under 5%, power conversion at the tire-soil interface usually involves losses of 30 to 60% [16].

The two major causes of power loss are soil deformation and slippage at the tire-soil interface [108]. The effects of soil deformation from wheeled vehicles are observed in the ruts they leave behind. As the wheel rolls forward it deforms soil ahead of it (known as "bulldozing"). This deformation requires energy but achieves no useful work. Slippage occurs when the tangential speed of the tire contact is faster than the forward speed of the vehicle. Presence of at least minimal slippage is unavoidable as for a thrust force to occur the tire must exert a shear force on the soil (therefore causing soil deformation). When the shear strength of the soil is low relative to the traction being generated, the shear stress may result in large shear deformation and thus higher slippage.

An efficient terramechanic design must strike a balance between sinkage and slippage. The amount of power lost to slippage and bulldozing are both correlated to ground pressure, but with usually with opposite effects [108][90]. As ground pressure increases, the shear strength of soils with a frictional component (most natural soils) increases, and thus less shear deformation is provoked by a given shear stress. This reduces slippage and energy losses provoked by it. On the other hand, as the ground pressure increases so does the sinkage of the tire into the soil, which results in more energy lost to bulldozing.

2.3.3 Model for interaction of a single drive tire with soil

The tire-soil model summarized here is an implementation of that described by Wong [108], which is commonly accepted in terramechanics.

For analytically studying the tire-soil interface, it is helpful to investigate it as a 2D system and separate the net stress into normal stress (normal to the wheel perimeter) and shear stress (tangent to wheel perimeter). All weight-bearing wheels generate a normal stress on the soil. Only braked or powered wheels generate significant shear stress on the soil. In Fig. 2-5 stress distributions at the soil-tire interface are shown for a rigid, smooth wheel in a homogeneous soil. Note that the soil is deformed plastically, as the wheel moves through it and thus the soil surface is lower behind the wheel than ahead of it.

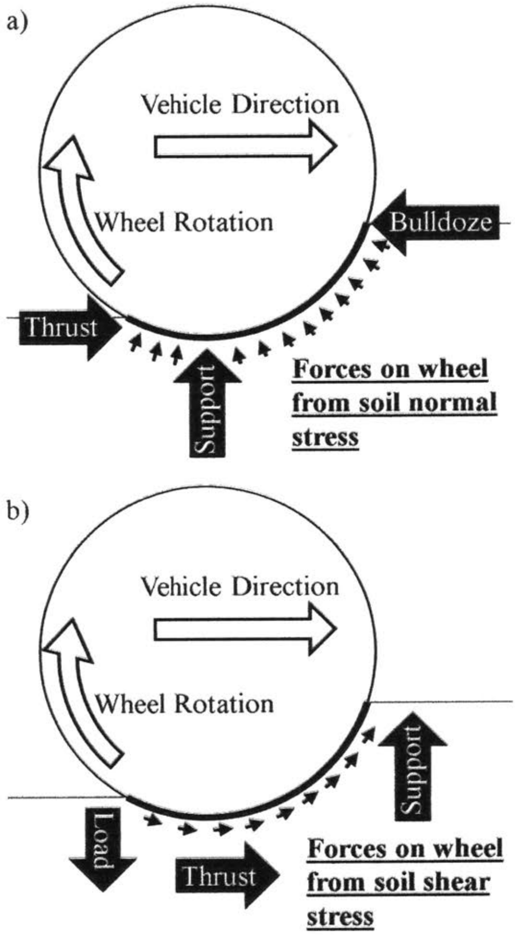


Figure 2-5: Stress under rigid driven wheels rolling on deformable soil. Stress at the tire-soil interface is separated for clarity into normal (a) and shear (b). Wheels are moving to the right and rolling clockwise. Nomenclature according to reaction force direction (as felt by wheel) are shown in soil.

In agricultural soils, the pressure required to penetrate into the ground increases with depth. Soil pressure as a function of depth is commonly expressed in terramechanics using Bekker's [10] or Reece's equations [54]. Reece's equation is used in this analysis because its soil constants are not a function of tire contact patch size. The resulting equation for soil pressure is

$$p = (ck'_c + w\gamma_s k'_\phi)(z/w)^n, \tag{2.4}$$

where p is soil normal stress, c is soil cohesion, k_c' is the cohesion constant, w is tire width, γ_s is the soil bulk density, k_ϕ' is the friction constant, z is the depth below the soil surface, and n is the depth exponent (an experimental value relating penetration depth to penetration resistance).

The shear strength of frictional soil increases with pressure, and the pressure exerted by soil increases with depth. This means that a wheel operating while sunk in soil may be interacting with different soil shear strengths along its perimeter. The soil strength can be reasonably predicted by the Mohr-Coulomb shear strength equation as a function of normal pressure,

$$s = (c + ptan(\phi))(1 - e^{-j(i)/k}), \tag{2.5}$$

where s is soil shear stress, p is soil normal stress, c is soil cohesion, ϕ is soil friction angle, k is shear modulus, j is shear deformation, and i is slip at interface.

To calculate the total reaction forces experienced by the tire when contacting soil, the shear and normal stresses can be integrated along the tire's casing. If the deformed tire is assumed to take the shape in Fig. 2-6, it can be separated into three sections: front circular arc of the tire, flat horizontal section at the bottom of the tire (the depth at which the tire total pressure matches the soil pressure), and rear circular arc of the tire. Tire sinkage and deformation are therefore defined by the angles θ_c, θ_f, and θ_r.

The net vertical force may then be mathematically expressed as

$$\begin{aligned} V =& wR \int_{\theta_c}^{\theta_f} [p(\theta)cos(\theta) + s(\theta, i)sin(\theta)]d\theta \\ &+ w2RP_t sin(\theta) \\ &+ wR \int_{\theta_c}^{\theta_r} [p(\theta)cos(\theta) - s(\theta, i)sin(\theta)]d\theta]. \end{aligned} \tag{2.6}$$

The horizontal force is expressed as

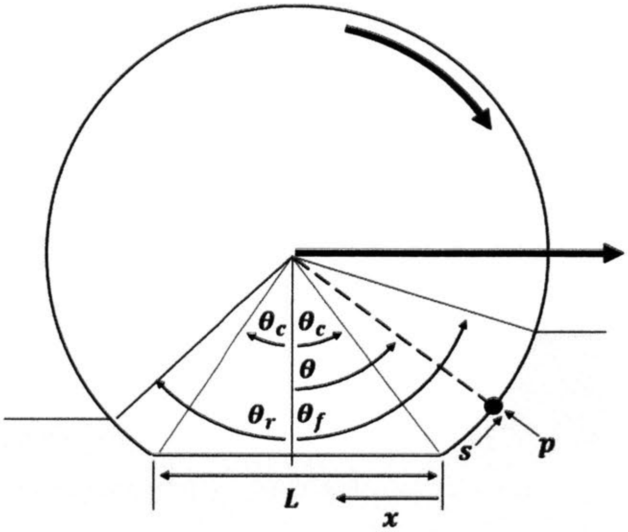


Figure 2-6: Parameters of tire perimeter for calculation of forces at soil interface.

$$
\begin{aligned}
H = & wR \int_{\theta_c}^{\theta_f} [-p(z)sin(\theta) + s(\theta, i)cos(\theta)]d\theta \\
& + w \int_{0}^{L(\theta_c, R)} s(\theta)dx \\
& + wR \int_{\theta_c}^{\theta_r} [p(\theta)sin(\theta) + s(\theta, i)cos(\theta)]d\theta].
\end{aligned}
\tag{2.7}
$$

For both equations, H is drawbar pull, V is vertical ground reaction, w is tire width, R is tire radius, p is soil normal stress, s is soil shear stress, z is the maximum depth of the tire into soil, and L is the length of the tire's deformed flat section. The angles θ_c, θ_f, and θ_r define the tire shape and sinkage into the soil (Fig. 2-6).

All tires are assumed to be rigid (θ_c is zero) if the maximum soil normal pressure p exerted on them is less than the sum of the tire carcass stiffness and the tire inflation pressure. Once the tire has sunk into the soil (depth z) to the point where the soil normal pressure p exceeds the tire inflation pressure and carcass stiffness, it is assumed the tire starts deforming and soil depth z remains constant (i.e. θ_c grows to support the extant vertical load, see Fig. 2-6).

It is often the case that nominal reaction forces at the tires are known but not the tire sinkage, deformation, and slippage - these are needed to solve for power consumption and maximum drawbar pull. These values must first be solved for idle wheels to find the their horizontal force H, which will oppose vehicle motion and must be overcome by driven wheels.

Slippage i is assumed to be zero for tires that are idle (are not driven) and thus the soil shear strength $s(i)$ terms in Eq. 2.6 and Eq. 2.7 are zero. In this case only the angles θ_c, θ_f, and θ_r must be solved for. These are found by allowing the tire to sink into the soil until the vertical load on that tire matches the soil reaction V from Eq. 2.6. All values are now known to calculate from Eq. 2.7 the horizontal force H on the tire (which will be negative and opposing vehicle motion in this case).

For the driven wheels, an optimization routine must be implemented to simultaneously solve for slippage i as well as the tire deformation and sinkage parameters θ_c, θ_f, and θ_r. This is achieved by finding the solution that minimizes the power consumed at the wheel while maintaining force equilibrium (vertical load at the tire is equal to V from Eq. 2.6 and horizontal load is equal to H from Eq. 2.7).

2.3.4 Validation of Tractor Model with Published Data

To verify the model's accuracy as implemented, in this section its outputs are compared to published data on production tractors. Experimental data were obtained from Battiato, Diserens, and Sartori [7][8], where four different sized production tractors were tested in various soil conditions. To test a tractor's drawbar pull performance, it towed a braking tractor behind it via an instrumented cable. The braking tractor was set to generate only the desired horizontal drawbar pull force on the tractor being evaluated. The pulling cable attachment height matched the CG height of the tractor being evaluated. The model shows good agreement with the experimental data (Fig. 2-7).

2.4 Results and discussion: analytical model insights into tractor dominant design

This section summarizes, based on governing physics, why the dominant tractor design is a viable engineering product.

2.4.1 Advantages of conventional tractor weight distribution

Modeling (Fig. 2-8) and historical data (Fig. 2-9) show that drawbar performance is maximized by placing 70 to 80% of the tractor's weight on the rear wheels. Shifting the center

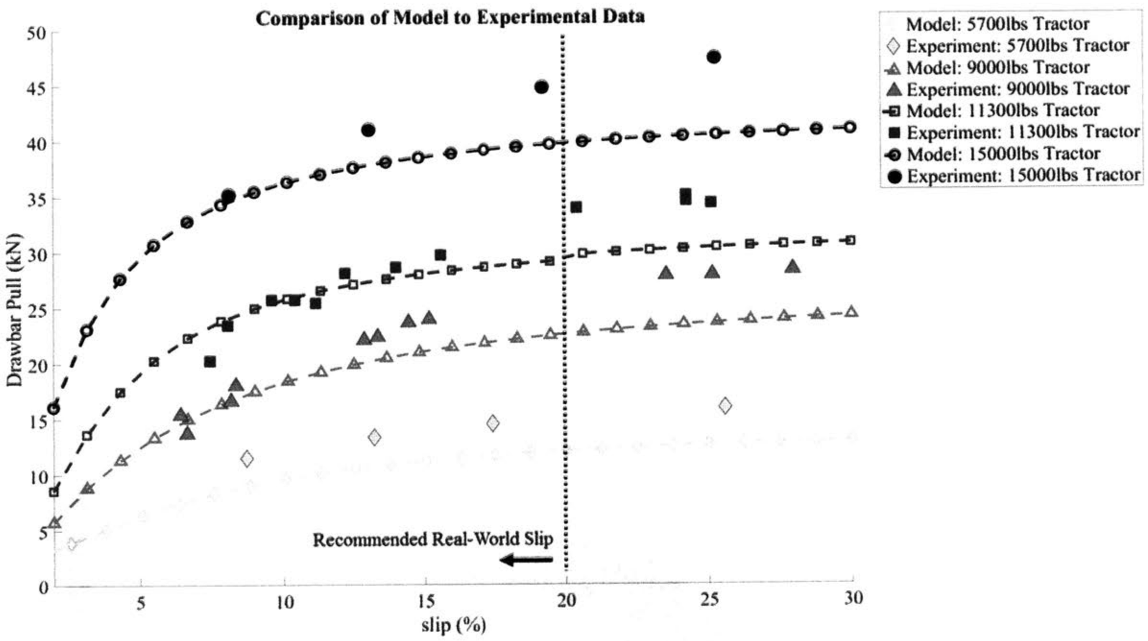


Figure 2-7: Comparison of tractor model as described in section 2.3 to published experiments. Experimental data from work of Battiato, Diserens, and Sartori [7][8]. Model has its best accuracy between 5% AND 20% slip, Which is the range recommended for farm tractor operation [16][108][90][31].

of mass forward reduces pulling capacity while shifting it backward produces a negligible increase in pulling capacity but dangerously increases the risk of upending the tractor.

Figure 2-8 shows modeling results for the effect on tractor pulling performance from weight, weight distribution, and draft magnitude. In Fig. 2-8, weight distribution is defined as the value when the vehicle is static at zero drawbar pull. The effective weight distribution during operation is accounted for during simulation calculations. Note that when moving along the "Weight distribution on rear axle (%)" axis, power required to move (color bar value) is reduced by shifting weight backwards until it asymptotes at around 70% of the tractor weight on back wheels.

The historical data in Fig. 2-9 were obtained from the Nebraska Tractor Test archives [69]. These tests are a standardized method to evaluate the performance of farm tractors. Test results are public and often used by manufacturers when promoting their tractors. For the manufacturers, one of the more marketable parts of the test involves the maximum generated drawbar pull force when towing a braked vehicle behind the tractor. Before 1950 the tests were performed on soil instead of the concrete track now used. Farm tractors below

25 hp tested between 1941 and 1950 (Fig. 2-9) were selected for comparison to the trends established in Fig. 2-8.

For the Nebraska Tractors Tests, engineers employed by the manufacturer whose tractor was being tested were allowed to ballast their vehicles as they preferred before testing began. The preferred setups provide valuable insight into what adjustments the company's engineers believed would maximize their tractor's performance. In Fig. 2-9, it can be observed that the engineers would generally set up their tractors to maximize drawbar performance by increasing vehicle mass and placing 70 to 80% of the tractor's total weight on the rear wheels. These adjustments are supported by the findings in the Section 2.3 model.

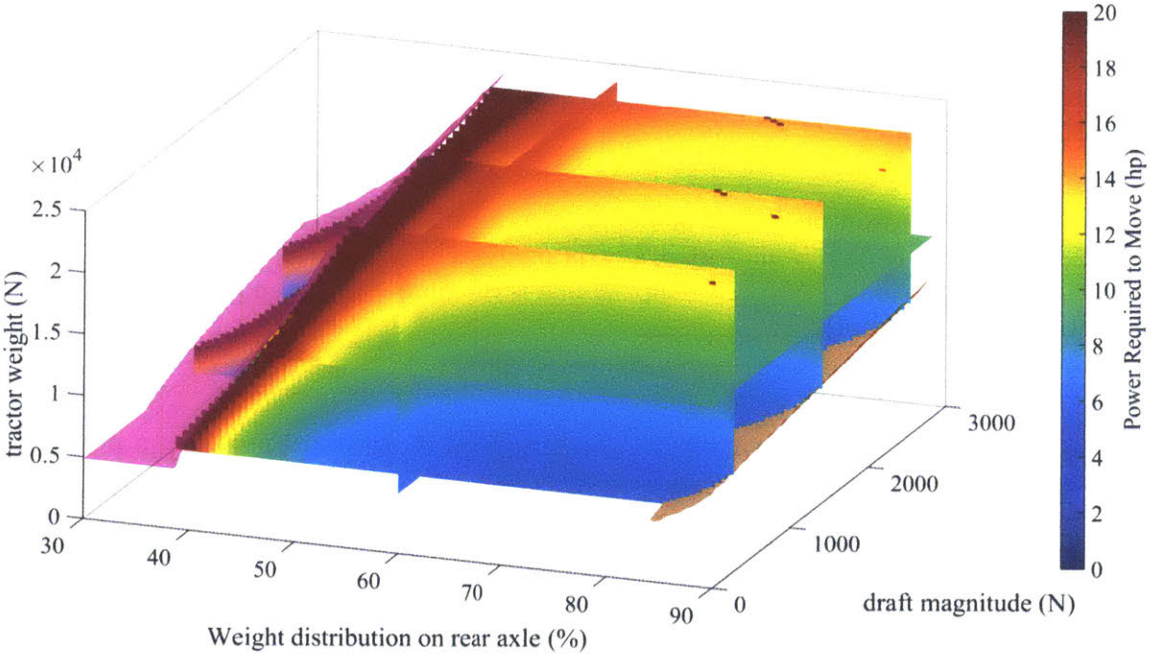


Figure 2-8: Simulation data for tractor configurations with varying weight, weight distribution, and draft load. Demonstrates that optimal weight distribution for drawbar pull is 70% to 80% of vehicle mass on the rear wheels. The semi-transparent purple frontier on the left represents where tractor wheels slip fully without generating progress or where any wheel sinks past its radius. The semi-transparent brown frontier on the right represents when the tractor upends and flips backwards.

2.4.2 Advantages of tillage tool rigid mounting behind the rear axle

Rigidly mounting heavy tillage tools behind the rear axle is a major characteristic of the dominant tractor design. The utilization of draft forces to increase the vertical load on the

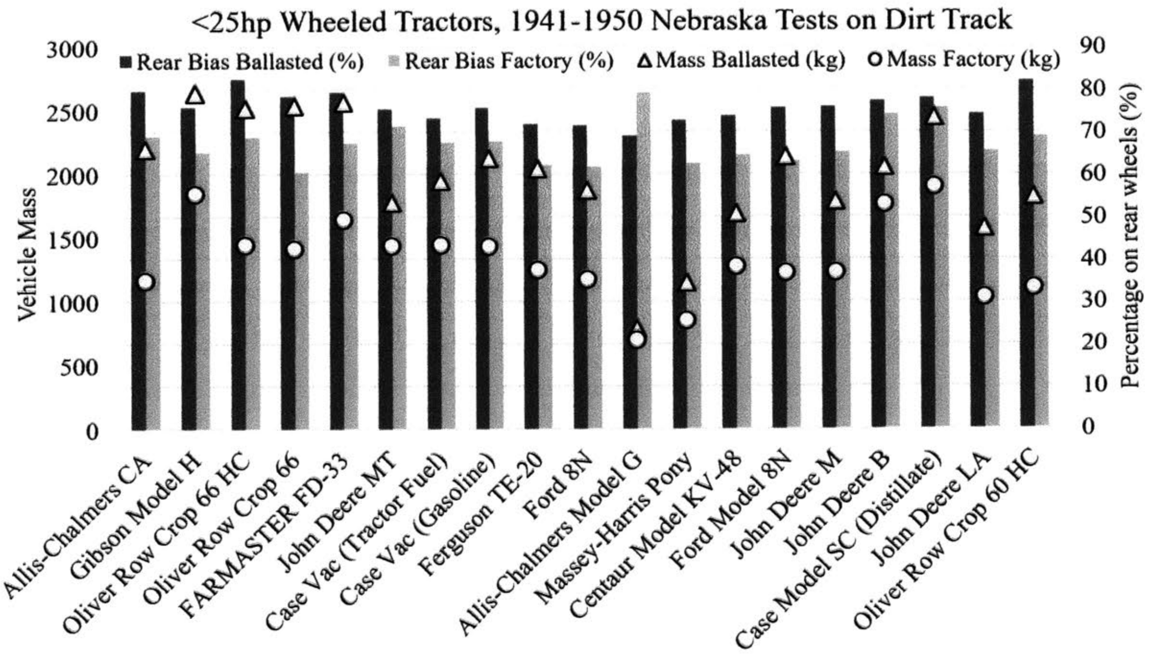


Figure 2-9: Drawbar pull data compiled from Nebraska Tractor Test Archives [69]. A highly publicized part of the Nebraska Test measures maximum drawbar pull, this table shows how engineers would set up their vehicles for the test. Notice that, in an effort to maximize performance, company engineers would ballast their tractors to have about 70 to 80% of the total vehicle mass on the rear wheels.

rear wheels (and thus the maximum drawbar pull) was a critical enabler to reducing the size and cost of tractors to the point where they could be a general purpose tool for the common farmer. From the free body diagram (Fig. 2-4) and the terramechanics theory in Section 2.3, the following observations are made about rear tool mounting: it is efficient for tillage, it is convenient for the user, and it facilitates manufacturing. A background on the introduction of this "Three Point Hitch" mounting style is given in Section 2.2.4.

The maximum pulling force the tractor can produce increases approximately constantly with the tillage tool draft force D. As seen in Fig. 2-4, tillage tool draft force D generates a net moment on the tractor - the backward component of D acts on the relatively short lever arm Y_D, while the downward component acts on the longer lever arm X_D. The net moment wants to lift the front end wheels off the ground. This increases the vertical load on the rear wheels V_r, which augments the soil's shear strength and thus the traction force H_r generated at a given soil-tire slip. It also reduces the vertical load on the front wheels V_f, reducing soil bulldozing force B_f due to tire sinkage.

Mounting the farming implement on a hydraulically actuated rear hitch is practical and safe for the operator. The driver need only reverse the implement-less tractor towards an implement, lock the implement attachment points, and drive away. Placing the implement behind the rear axle does not directly constrain the length or width of the implement since the tractor tires will not physically interfere with the implement or immediately drive over soil that the implement has already worked on. This in an important advantage for more powerful tractors that can pull several ground engaging "bottoms" at once. Finally, the driver is physically safe from the implement behind them while driving the tractor. This can be especially important for implements that have moving parts powered by the engine or that launch significant amounts of debris.

Placing the implement (tillage tool) behind the rear axle can facilitate manufacturing via beneficial component packaging and a short load path between the traction gear and tool. The drive axle, hydraulics, and power take-off (PTO) shaft are all around the same location where engine power is being delivered (thus creating a short load path between heavy drawbar pull tools and the tractor's driven tires). Additionally, the space behind the rear axle can be fully dedicated to the implement, its attachment linkages, and its power sources (hydraulics and PTO). This setup also allows placing the engine over the front wheels and using the drivetrain's transmission case and crank case as the structural "frame" of the tractor which minimizes the amount of components, facilitates fabrication, and reduces mass. This method of construction was critical to helping Henry Ford create farm tractor assembly lines [107].

2.4.3 Advantages of conventional rear wheel drive

Driven side-by-side rear wheels connected via a differential axle are well suited for farm tractors - some of their advantages are tight turning, simple construction, and being able to leverage trailing tool forces for improved performance.

Tight turning is a feature of the conventional layout for two main reasons: a large steering angle enabled by small radii front wheels and the ability to independently brake each rear wheel.

Tractor construction was simplified by side-by-side rear drive wheels since it allowed use of a standard differential axle (as also engineered for emerging automobiles) and required less structural reinforcements. If front (steered) wheels are driven, additional linkages must be added to the driveline to enable steering. Since most heavy draft implements are attached closely behind the rear axle, the tractor load path from the rear wheels' traction force to the implement attachment points is short and most of the tractor's structure need not be reinforced to support the tool's loads.

A tillage tool attached behind the tractor will cause the effective weight distribution of the tractor to shift rearward. This added vertical load on the rear wheels can increase their maximum tractive force as supported by production vehicle data [4] and modeling.

2.4.4 Advantages of four wheel rectangular layout

A four wheel rectangular layout is sound from a manufacturing, stability, and terramechanics perspective. By rectangular, it is meant that the front and rear axle dimensions allow the rear wheels to run over the "ruts" or "tracks" formed by the front wheels. In other words, both right wheels are longitudinally inline with each other, as are the left wheels. More than four wheels would increase manufacturing and maintenance complexity (and cost). Fewer than four wheels decreases the stability of the tractor [26][89].

There are two key advantages of a rectangular wheel layout from a terramechanics perspective: improved crop yields and better tractive efficiency. It is less detrimental to crop yields to drive over the same patch of soil in the field multiple times (as is the case with inline front and rear wheels) than it is to drive over more areas of soil on the field only once. Applying this when planning routes for field operations is called "Controlled Traffic" and has been proven beneficial in farm fields across the world [102] [3] [24] [79] [17] [25]. Each tire pass strengthens (compacts) the patch of soil it runs on, making it a better rolling surface for trailing tires. This means the idle front wheels can partially "pre-compact" the soil for the driven rear wheels, thus improving the vehicle's maximum drawbar pull and tractive efficiency [108][41][51].

2.5 Conclusions

This research chapter describes how the dominant farm tractor design evolved mostly in the USA between 1910 and 1940. It provides a historical reflection on the priorities that drove the creation of the tractor. It also uses engineering analysis to justify why the conventional tractor design is well suited to farming and has endured the test of time.

The conventional farm tractor evolved not only to maximize farming performance but also to satisfy intense pressures from the social and political context it developed in. In particular, an unpredictable economic backdrop and sharing engineering with the new automotive industry rapidly pushed the tractor industry towards standardization and competitively priced mass manufactured vehicles by a few large corporations.

The conventional farm tractor has a sensible design that is easy to use, easy to manufacture, and offers efficient performance. In particular, at least within the constraints of its standard overall layout, it has nearly optimal weight distribution and tillage tool attachment.

Contemporary engineers may wish to use this chapter to explore which features of the existing dominant tractor design are applicable to their own novel tractor layout implementations. Consider that the dominant tractor design evolved mostly in the USA between 1910 and 1940 and is sold worldwide today; however, during that period, and since, American farms have been about 100 times larger than at least 80% of today's farms globally [58][14][99][59]. As mechanization increases in developing and emerging markets, engineers may question if the dominant tractor design is the ideal one to sell to these small farms. At possibly a different end of the price spectrum, new technologies like autonomous driving may enable design freedoms for modern tractors that were not available in the 1940s. This Chapter provides insights on tractor features that enhance user comfort and farming productivity, as well as the physics behind tractor performance, which may be of value to engineers designing new farming equipment for developing and developed markets around the globe.

Chapter 3

Design of a specialized tractor to replace draft animals in small farms

3.1 Introduction

A tractor designed specifically to meet the needs of small farmers in India, who would otherwise use draft animals, has the potential to create significant impact by improving farmers' economic health and India's overall food production capacity [50, 111, 63]. Small farms ($<$ 2 ha) are common; in India the average farm size has steadily decreased from 2.28 ha in 1971 to 1.08 ha in 2016 [75], and globally (84%) of farms are less than 2 ha in size [58]. Most small farmers use a pair of bovine draft animals known as bullocks (sometimes called oxen in other countries) for all or most of their farming operations, supplemented by manual labor or a hired tractor [52, 31]. Bullocks are compact, highly maneuverable, and have a low capital cost, making them well-suited to the technical and economic constraints of small farms.

Conventional tractors, which are an icon of modern farming, are able to produce much higher farm yields than bullocks [39, 33, 73, 40]. Farm tractors increase the capacity of each agricultural worker and enable larger, more profitable farms [98]. The Indian Agricultural Ministry estimates that farm tractors increase farm yields by 5 to 20%, reduce wasted seeds and fertilizer by 15 to 20%, and reduce farm labor by 20 to 30% [52]. However, tractors have not yet been able to replace key bullock features of maneuverability and compactness that are essential to work on a small Indian farm [57]. Tractors also have a high upfront cost that puts them out of reach of many small farmers in low income regions[87]. As a result, small-scale farmers are constrained to the slow speed of bullocks and a lack of access to suitable modern, more effective made-for-tractor tools [31, 30].

Although tractors are more expensive upfront, they are less expensive than bullocks in the long term. Fig. 3-1 shows the initial cost and 15 year operating costs for a bullock pair, a financed tractor, and a tractor bought upfront. A bullock pair is approximately twice as expensive as using tractors over 15 years. There are alternatives to acquiring tractors at full price up front, like financing and renting, but they are inaccessible to many farmers [27, 38, 87] and have financial drawbacks. For example, those who rent tractors forgo using the tractor for supplemental income work and risk not having access a tractor when they need one if demand is high. An ideal vehicle would retain the low upfront cost of the bullocks and the low overall cost of the tractor (e.g. the proposed vehicle in Fig. 3-1). Such a vehicle would have an higher value proposition than both bullocks and tractors.

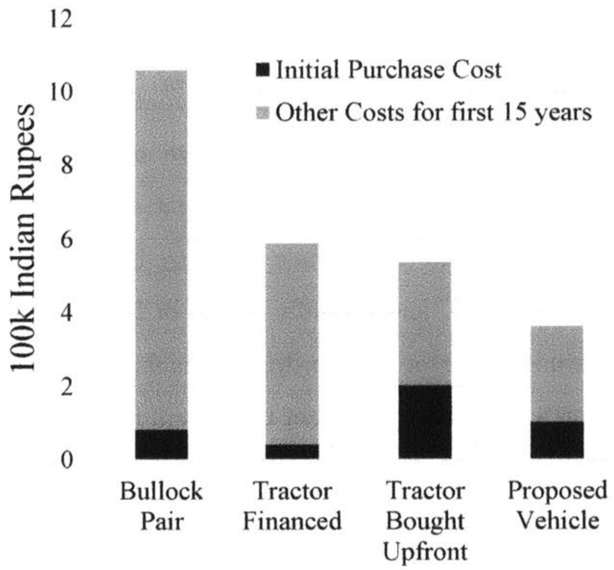


Figure 3-1: Cumulative costs of farming 1 ha with bullocks or small farm tractors. The ownership costs of bullocks outweigh their low initial purchase cost. Ownership costs are recurring costs like maintenance, loan payments, animal feed, and fuel. The purchase cost shown for Bullkey is a target as mentioned by farmers during interviews - the final price is not yet determined. A breakdown of the costs shown here is provided in Appendix B1. Values are from [81, 80, 22, 31, 30, 47]. .

To elucidate both the financial and functional requirements of a tractor specialized for small farmers, the author interviewed stakeholders of small farming in India regarding local agricultural practices and the suitability of existing alternatives. The author spoke with stakeholders at 12 locations in the Indian states of Maharashtra, Tamil Nadu, Gujarat, Rajasthan, Madhya Pradesh, and West Bengal. Stakeholders included farmers, research organizations, governments, and tractor manufacturers and dealers. A key observation from these visits was that small farmers used bullocks both because of their low capital cost and because of bullocks' suitability to the narrow inter-row spaces in a farm field. Bullocks have a smaller width than tractors and are more maneuverable. These characteristics allow bullocks to walk between rows of growing crops later into the season when crops are taller and wider, leaving less space between crop rows. Compared to tractors, bullocks require less space to turn at row ends, and can better traverse unfinished dirt paths leading to farm fields. These critical features of low upfront cost and ability to access narrow spaces are generally not present in commercially available small tractors. The few tractors that approach the purchase price of bullocks cannot match the bullock's maximum pulling force, a key requirement for seamlessly replacing them.

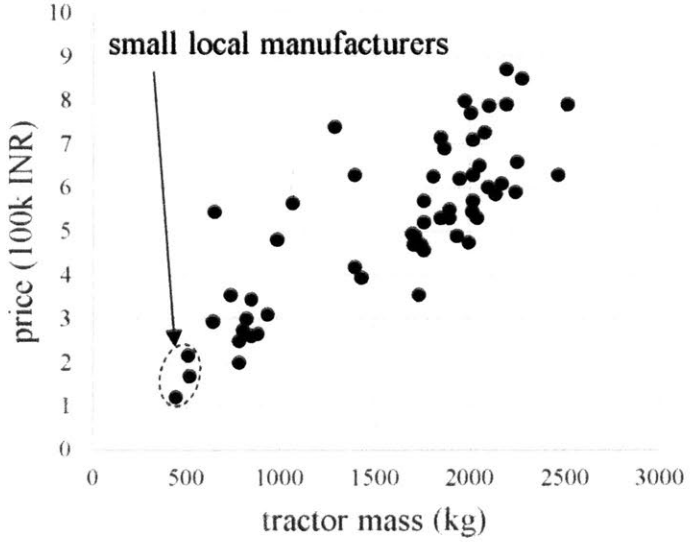


Figure 3-2: Relationship of tractor sales price to tractor mass for common Indian tractors, as compiled by the author. The full dataset is provided in Appendix B3. To be competitive with bullocks' sale price, a tractor would have to cost ~100k INR.

In conventional tractors, lower cost often comes at the expense of pulling force. Pulling force is related to a tractor's mass, which is correlated to purchase price. To be sold for a price comparable to bullocks (~100k INR, as shown in Fig. 3-1), a tractor would likely have a mass between 350 and 500 kg given the current trends of the Indian tractor market

(Fig. 3-2) [31, 4]. The layout of a conventional, rear-wheel-drive tractor with a mass of 350-500 kg would only produce a maximum pulling force of ~60% of its weight (2060 N to 2940 N) in near ideal tilling conditions, and closer to ~35% of its weight in soft soils (1200 N to 1720 N) [13, 115, 4]. This could not, under most conditions, match the maximum pulling force of a bullock pair (~2800 N [42, 106]).

A lightweight tractor capable of replacing bullocks in small farms, and thereby improving farmers' livelihoods, must match bullocks' pulling force, their purchase price, and their ability to enter narrow spaces. No major manufacturers currently make tractors in the bullock price range of <100k INR or with dimensions comparable to bullocks. The lightest tractors (Fig. 3-2) have limited pulling force (approximately 1720 N to 2940 N depending on soil conditions and actual mass) and are unable to access narrow inter-row spaces. These vehicles are made by small-volume local manufacturers near smallholder farms [82] and are not widely distributed. A manufacturer capable of making and widely distributing a low-cost tractor with the characteristics to near seamlessly supplant bullocks could likely access ~80 million farmers currently underserved by mechanization [82, 76].

The goal of the research presented herein was to codify the parametric behavior of tractor performance, and combine this understanding with market insights to generate a tractor architecture well suited to the needs of Indian small farmers. We present our modeling approach, proposed design, and evaluation of a novel tractor.

3.2 Physics behind maximizing traction performance

A terramechanics-based physics model of tractors' performance derived in our prior work [44] (fully described in Ch. 2) was used to gain parametric insights on how the design of a small tractor could be manipulated to maximize drawbar force per vehicle mass. Figure 3-3 shows a free body diagram of the main forces acting on a farm tractor overlaid on a conventional tractor layout. For a tractor to perform an operation successfully, two main conditions based on the free body diagram must be met: (I) the vehicle must not tip over, which necessitates positive vertical ground reaction forces V_f and V_r; and (II) the tractor must achieve forward motion, which occurs when the drawbar pull force F (the sum of traction forces H and bulldozing forces B in Fig. 3-3) is greater than the tool draft force parallel to vehicle motion, $Dcos(\alpha)$. Additionally, when building a low-cost tractor, it is of interest to include one more condition: (III) maximize the drawbar pull to mass ratio of the tractor.

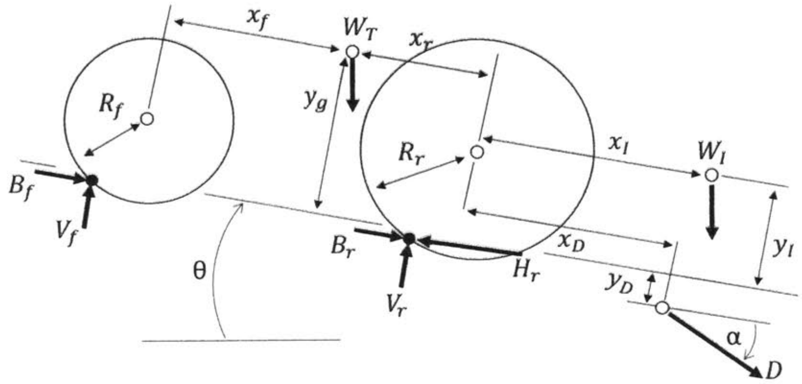


Figure 3-3: Force free body diagram for a conventional small tractor. Shown are the tractor ground reaction forces (V_f,V_r,B_f,B_r, and H_r), which support the tractor weight (W_T) and tool draft (D). Key dimensions are shown, including ground slope (θ), tractor CG location (x_f, x_r, and y_g), tool CG location (x_I and y_I), tool draft center of pressure (x_D and y_D), and tool draft angle (α).

Condition (I) was evaluated by assuming the vehicle would rotate at points directly below the wheel axles and solving for the reaction forces at V_f and V_r, giving respectively:

$$\begin{aligned} V_f = \frac{1}{x_f + x_r}&(W_T(x_r cos(\theta) - y_g sin(\theta)) \\ &+ D(y_D + cos(\alpha) - x_D sin(\alpha)) \\ &+ W_I(-x_I cos(\theta) - y_I sin(\theta))), \end{aligned} \tag{3.1}$$

and

$$\begin{aligned} V_r = \frac{1}{x_f + x_r}&(W_T(x_r cos(\theta) + y_g sin(\theta)) \\ &+ D(-y_D + cos(\alpha) + x_D sin(\alpha)) \\ &+ W_I((x_I + x_r + x_f) cos(\theta) + y_I sin(\theta))). \end{aligned} \tag{3.2}$$

Where x_f is the distance from the tractor center of gravity (CG) to the front axle, x_r is the longitudinal distance from the CG to the rear axle, W_T is the weight of the tractor. θ is the ground slope angle, y_g is the distance from the CG to the ground, D is the tillage force,

y_D is the depth of the tillage tool center of pressure (COP), x_D is the longitudinal distance from the tillage tool COP to the rear axle, α is the angle of the draft force vector relative to the ground slope, W_I is the weight of the implement, x_I is the longitudinal distance from the rear axle to the tillage tool CG, and y_I is the distance from the ground to the tillage tool CG.

Checking condition (II) and designing for condition (III) required an analysis that considered the physics of tire-soil interactions to calculate traction force H and tire bulldozing force B. The soil exerts a pressure on the tire (normal to the wheel perimeter) and a shear stress (tangent to wheel perimeter). All weight-bearing wheels generate a normal stress on the soil (i.e. flotation). Only braked or powered wheels generate significant shear stress on the soil (i.e. traction). The normal and shear stresses at the tire-soil interfaces were calculated from the soil's mechanical behavior.

To calculate the soil pressure p along the tire's perimeter, a common equation used in terramechanics was applied [54]:

$$p = (ck'_c + w\gamma_s k'_\phi)(z/w)^n, \tag{3.3}$$

where c is soil cohesion, k'_c is the cohesion constant, w is tire width, γ_s is the soil bulk density, k'_ϕ is the friction constant, z is the depth below the soil surface, and n is the depth exponent (an experimental value relating penetration depth to penetration resistance).

The soil shear stress s is a function of tire-soil pressure and soil properties, and is scaled by deformation at the tire soil interface represented by term $1 - e^{-j(i)/k}$ [10]:

$$s = (c + ptan(\phi))(1 - e^{-j(i)/k}), \tag{3.4}$$

where ϕ is soil friction angle, k is shear modulus, and $j(i)$ is the shear displacement at the tire-soil interface, which is a function of tire slip i. Tire slip i is defined as $1 - \frac{S}{R\omega}$, where S is the forward speed of the vehicle, while R and ω respectively are the effective radius and the angular velocity of the wheel being evaluated for slip.

To calculate the total reaction forces on the tire when contacting soil, the shear and normal stresses were integrated along the tire's casing. If the deformed tire is assumed to take the shape in Fig. 3-4, it can be separated into three sections: a circular arc at the front of the tire, a flat horizontal section at the bottom of the tire (the depth at which the tire total pressure matches the soil pressure), and a circular arc of the rear of the tire. Tire sinkage and deformation can therefore defined by the angles θ_c, θ_f, and θ_r in Fig. 3-4.

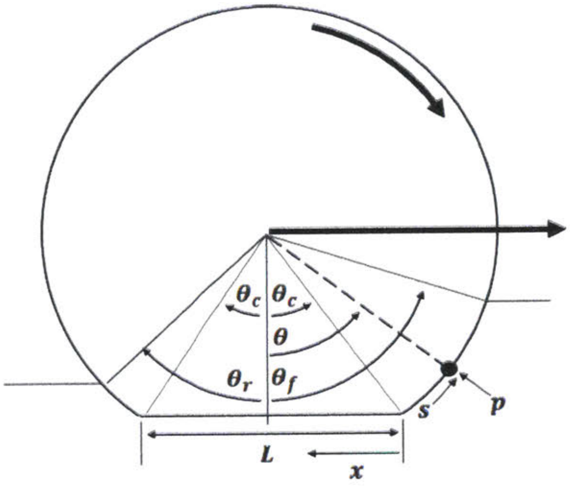


Figure 3-4: Parameters of tire perimeter for the calculation of forces at the tire soil interface.

Each tire's vertical (flotation) force must satisfy Eq. 3.5. From this, the tire shape angles θ_c, θ_f, and θ_r can be solved for via a control strategy as shown in [85].

$$\begin{aligned} V =& wR\int_{\theta_c}^{\theta_f}[p(\theta)cos(\theta)+s(\theta,i)sin(\theta)]d\theta \\ &+ w2RP_tsin(\theta) \\ &+ wR\int_{\theta_c}^{\theta_r}[p(\theta)cos(\theta)-s(\theta,i)sin(\theta)]d\theta] \end{aligned} \tag{3.5}$$

The traction force H and bulldozing force B can now be calculated using Eqs. 3.6 and 3.7, respectively.

$$\begin{aligned} H =& wR\int_{\theta_c}^{\theta_f}[s(\theta,i)cos(\theta)]d\theta \\ &+ w\int_{0}^{L(\theta_c,R)} s(\theta)dx \\ &+ wR\int_{\theta_c}^{\theta_r}[p(\theta)sin(\theta)+s(\theta,i)cos(\theta)]d\theta] \end{aligned} \tag{3.6}$$

$$B = wR \int_{\theta_c}^{\theta_f} [-p(z) sin(\theta)] d\theta \tag{3.7}$$

In these expressions, w is tire width, R is tire radius, and L is the length of the tire's deformed flat section.

The drawbar pull from a single tire is the difference between its traction force H and its bulldozing force B (Fig. 3-3). The drawbar pull of the tractor is the sum of the drawbar pull from all of its tires. For a tractor with n number of tires, this is

$$F = \sum_{v=1}^{n} (H_v - B_v). \tag{3.8}$$

The forces exerted on agricultural soil by tires affect the soil's mechanical properties (apparent in the plastic deformation in the soil in Fig. 3-4). Each tire pass compacts and strengthens the patch of soil it rolls over, improving the surface for trailing tires [51, 41]. Compaction is accounted for as an increase in the soil's cohesion c and bulk density γ [108]. Figure 3-5 is an idealized diagram demonstrating the interactions of inline drive tires on soil during loading, unloading and reloading.

Figure 3-6 presents a sensitivity study of drawbar pull and tractive efficiency for a conventional tractor in a common soil, loamy sand, to highlight the influence of key design parameters on small tractor performance. Tractive efficiency is the efficiency in converting power at the drive axle(s) into useful work. It is defined as $\eta = (F * S)/P$ where, η is tractive efficiency and P is power delivered to the wheel. The terramechanics model described here is highly non-linear and depends on a large number of inputted tractor parameters. Figure 3-6 demonstrates that the maximum drawbar pull (net horizontal force) is approximately linearly related to the tractor mass for a large range of values.

In conventional tractors this leads to two usage trends: tractors are ballasted to increase their mass for work when a high drawbar pull is required, and high drawbar pull tools are typically mounted to the tractor behind the rear drive axle. This results in the rear axle supporting both the vertical draft forces and the tool weight, and in weight transfer from the front axle to the rear axle due to the moment generated by these forces. However,

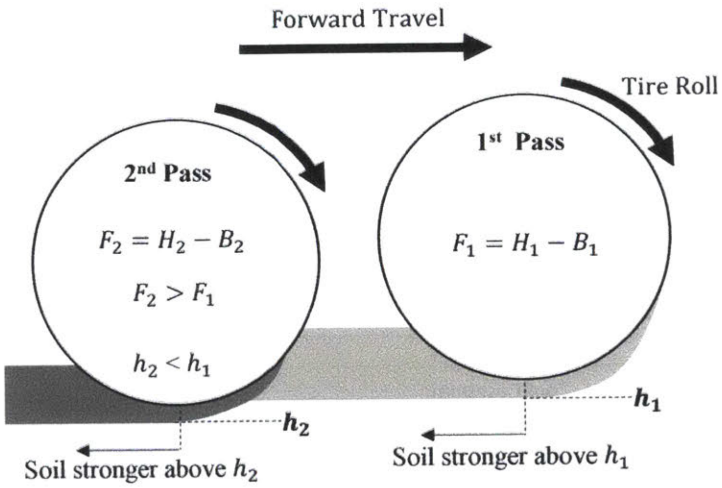
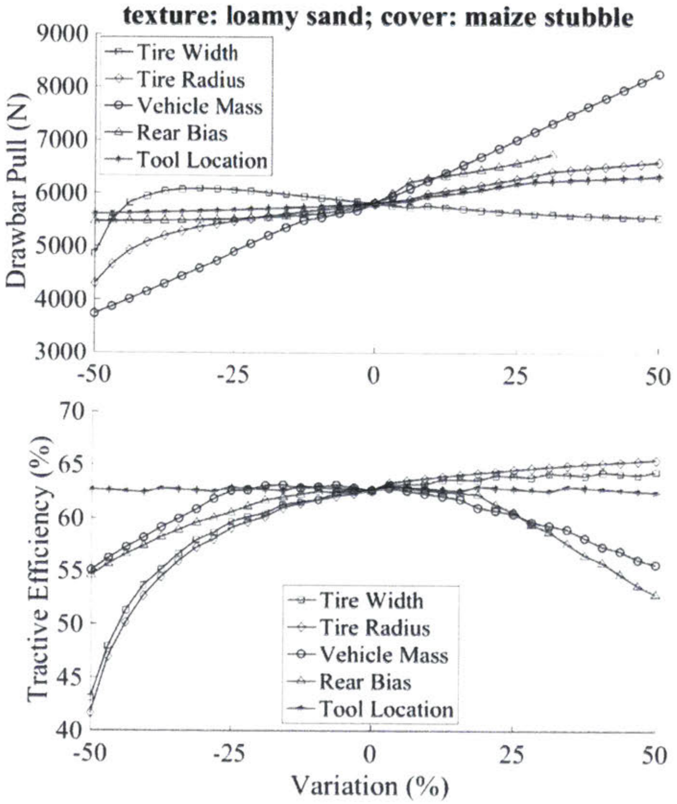


Figure 3-5: Illustration of tire-soil interaction and multi-pass effect used in analysis. h is the depth of the compaction effect on the soil. The 2nd pass tire, which is rolling on compacted soil, can generate more drawbar pull F than it would on fresh soil since it sinks less into the soil (reducing bulldozing force B) and the soil can provide a higher shear force (increasing traction force H).

while maximum drawbar pull may increase, tractive efficiency may decrease - showing the importance of correctly matching tractor mass to tire size (and thus ground contact shape and pressure distribution). Too little weight on the tires or tires that are too wide may apply insufficient pressure to the soil, resulting in a soil that requires excessive deformation j to produce sufficient drawbar pull and therefore in power losses. Excessive weight on tires, or tires that are too thin for the required weight, will increase pressure on the soil to a detrimental degree, causing the tires to sink into the soil and exacerbating power losses to bulldozing force B.

3.3 Design exploration

The tractor performance model from Sec. 3.2 was used to identify beneficial design features to incorporate in tractors that are well suited to small Indian farmers. These features were combined to create the Bullkey tractor layout (Fig. 3-7). The Bullkey name is a portmanteau of *bullock* and *key* - indicating its goal of being the key to unlocking the bullock market to mechanization.



<u>Nominal Values</u>

Tire Width Fr.: 132mm
Tire Width R.: 203.2mm
Tire Radius: 272mm
Vehicle Mass: 850kg
Mass Rear Bias: 0.55
Tool Loc.: 0.6m after rear axle
Tool Mass: 100kg
Tool soil depth: 200mm

Figure 3-6: Sensitivity analysis of drawbar pull and tractive efficiency at 15% tire slip (a typical heavy tillage operating point [90]) for a conventional small tractor. Data were generated using the terramechanics model described in Sec. 3.2. Soil conditions for typical loamy sand are from [8]. In the sensitivity analysis, variables were varied ±50% from their nominal value.

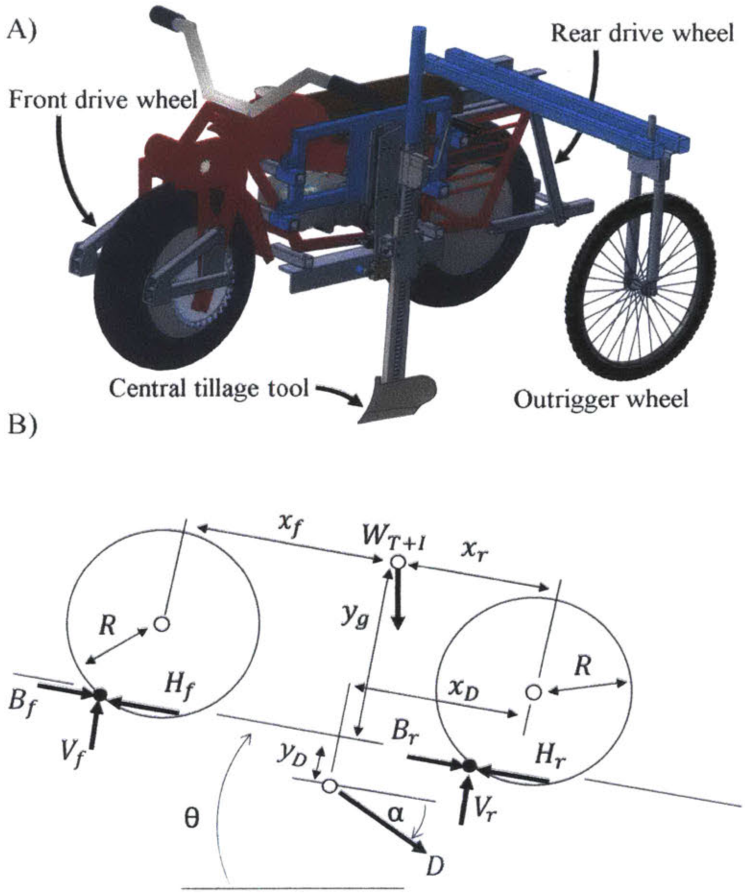


Figure 3-7: (A) Isometric view with labeled soil engaging components and (B) force free body diagram for Bullkey tractor.

3.3.1 Physics-based design insights

The physics-based theory of Sec. 3.2 led to insights about the behavior of lightweight tractors that can improve their design and functionality for smallholder Indian farmers currently relying on bullocks as a source of draft power. The following design strategies incorporated into the Bullkey tractor (Fig. 3-7) maximize traction performance while incorporating or improving on many of the bullock maneuverability advantages described in Section 3.1.

Support the tractor mass almost exclusively on driven wheels: Only driven wheels apply a positive (drawbar pull generating) shear stress, s, on the soil. The maximum drawbar pull, F, that a tire can generate (Eqs. 3.6–3.8) is limited by soil shear strength, which depends on tire-soil pressure, p, and soil cohesion, c (term $c + ptan(\phi)$ in Eq. 3.4). The soil's shear strength can be improved by increasing pressure or by increasing soil cohesion. such as via soil compaction induced by inline drive wheels (as in Fig. 3-5). Increasing tire-soil pressure for drive wheels is best achieved by placing more vertical load on the tires, because reducing tire width, w, or radius, R, to lower their contact area would also scale down the magnitude of traction force H in Eq. 3.6. It is also beneficial to limit pressure on non-driven wheels to only what is needed for stability. Idle wheels detract from the tractor's drawbar pull F since they generate no measurable traction force H (given that $s = 0$) and can still generate a significant bulldozing force B which increases with applied tire-soil pressure p (Eq. 3.7).

Shifting weight towards the driven tires is fundamental to achieving a high drawbar pull to mass ratio. A pneumatic agricultural tire can generally generate as drawbar pull no more than 80% of the vertical load it supports[115, 13], and a conventional tractor design has 50 to 80% of its total mass on its driven rear wheels [44]. Shifting more weight to the rear wheels in this layout would increase the risk of upending the tractor and reduce vehicle safety. A conventional tractor is therefore nominally able to pull up to 64% of its operating weight (even less if considering the detrimental bulldozing forces from idle wheels) in near ideal conditions, and much less in non-ideal conditions. Changing the layout to support all of the mass on the drive wheels should increase the maximum pull capacity to 80% of the vehicle's operating weight. If a tractor layout must use additional idle wheels for stability, they should be designed so that stability can be achieved while only lightly loading the idle wheels – therefore limiting the detracting opposing force they can generate and maximizing the mass supported by drive wheels.

Match tire ground pressure to required soil shear stress by operating between 10% and 25% tire slip: A tire slip of 10 to 25% has been found to be an efficient compromise between energy losses to soil shear deformation j (which is a function of tire slip i) and to soil bulldozing B [10, 108, 115]. A well designed tractor should have its mass and tires sized appropriately to reach its desired drawbar pull F in that tire slip range. To increase the drawbar pull generating traction force H, one must increase the applied soil shear stress s, which increases with i (Eq. 3.4), or increase the tire contact area (term wR in Eq. 3.6). Some soil shear deformation must always exist at the tire-soil interface to generate a traction force H. Reducing tire-soil slip while maintaining constant applied shear stress requires increasing the soil pressure, p, which is typically done by adding ballast to the tractor. However, increasing pressure also results in a larger tire bulldozing force B (Eq. 3.7), which is detrimental to drawbar pull F (Eq. 3.8). If instead, ground pressure is adjusted by changing tire size (i.e. contact area), the wR term will be affected in both H (Eq. 3.6) and B (Eq. 3.7), causing them both to either increase or decrease simultaneously. Therefore, an all encompassing design rule cannot be given but it is recommended to use the model from Sec. 3.2 to select tire sizes and a weight distribution that generate sufficient drawbar pull while staying in the desirable tire slip range.

Use inline drive wheels with similar vertical loads: Compared to side-by-side wheels, inline drive wheels increase tractor drawbar pull and efficiency because the rear drive wheel operates on soil that has become stronger (higher cohesion, c, and bulk density, γ_s) after being compacted by the front drive wheel [108, 9]. In conventional tractors the front drive wheels are much smaller and lightly loaded compared to their rear side-by-side drive wheels – so the front wheels do not strengthen the soil significantly for the rear drive wheels. In agriculture, soil compaction is often considered undesirable because it hinders crop growth. However, inline drive wheels leverage a technique known as "controlled traffic", in which one patch of soil is driven over multiple times rather than driving over more areas of soil only once. This method takes advantage of the fact that if all tire passes are equivalent, compaction will be highest after the first pass and much lower for subsequent passes [51, 86]. This method is less detrimental to crop yields and has been proven in farm fields across the world [102, 3, 24, 79, 17, 25].

Add a mount for high drawbar tools between both driven axles: Adding a mount for high drawbar tillage tools between the front and rear axles uses the downward forces from tillage ($D * sin(\alpha)$) to increase the vertical loading on both the front and rear wheels, respectively V_f and V_R (Fig. 3-7). This results in higher soil-tire pressure, p, and thus higher soil shear strength (represented by $c + ptan(\phi)$ in Eq. 3.4). If both axles are driven, this produces a higher maximum traction force H at both drive tires and increases the tractor's maximum drawbar pull F (Eqs. 3.6) and 3.8.

Additionally, the central mount improves steering authority and stability by firmly planting both wheels on the ground, which allows the operator to safely operate the proposed tractor design near its performance limits. In contrast, the draft force, D, in the conventional tractor design (Fig. 3-3) causes the front wheels to become unweighted; even though the horizontal draft component, $Dcos(\alpha)$, is typically larger than the vertical component, $Dsin(\alpha)$, it exerts a torque over a much shorter moment arm (y_D vs. x_D). This unweighting of the front wheels can cause the vehicle to upend (i.e. tip over backwards) and severely

		Layout			
Beneficial Design Features	**User Need Met**	A	B	C	D
Weight transfer during tillage improves drawbar pull	drawbar pull	✓	✓		✓
Weight transfer during tillage improves steering authority	safety, comfort			✓	✓
Safe to operate near tillage force limits (will not upend)	safety, drawbar pull			✓	✓
Tillage tool is near farmer's driving line of sight	comfort, ease-of-use			✓	✓
All drive tires are in a single lane with farmer and tool	narrow, low compaction				✓

Table 3.1: Occurrence of desirable design characteristics in evaluated tractor layouts of Fig. 3-8

injure the operator [44, 74, 34], and limits the operator's confidence when operating the tractor near its performance limits. In India, tractors account for over 25% of farming accidents and the upending of tractors is a common cause of serious injury [68]. This risk is mitigated by the added stability of mounting the drawbar tool between the front and rear axles.

3.3.2 Comparison of tractor layouts

Bullkey was designed by combining the strategies discussed in Sec. 3.3.1 resulting from physics modeling with insights gathered from farmer interviews, while utilizing advantageous characteristics of existing small tractor designs. Major needs of Indian small farmers are unmet by existing designs, including the ability to enter narrow (<70 cm) inter-row spaces like bullocks can, and achieving a purchase price comparable to bullocks (~100k INR) while generating sufficient drawbar pull. A successful design should meet these needs and also account for other important considerations farmers use when evaluating tractors, like soil compaction and ease of operation. Additionally, the design must maintain desirable features of existing tractors relative to bullocks, such as reduced ownership costs, reduced drudgery, and improved farming productivity [52, 31, 76]. The analysis in this section shows that Indian small farmer needs could be better met by a novel tractor layout – particularly with respect to the location of drive wheels and the location of tillage tools.

Possible tractor layouts (Fig. 3-8) were selected for evaluation with respect to user needs because they are either currently popular in India (layouts A and B), have been well adopted in other countries by farms smaller than their national average (layout C) [44], or include the features identified as desirable for the Bullkey design (layout D). These layouts have distinct configurations: (A) is a conventional small farm tractor with side-by-side steering idle wheels on the front axle, side-by-side drive wheels on the rear axle, and tools behind the rear axle, (B) is a tricycle tractor similar to the conventional tractor layout but with a single front idle wheel, and (C) has a design similar to a conventional tractor but with tools ahead of the rear axle. The proposed Bullkey layout, (D), has inline drive wheels and tillage tools between the front and rear drive wheels.

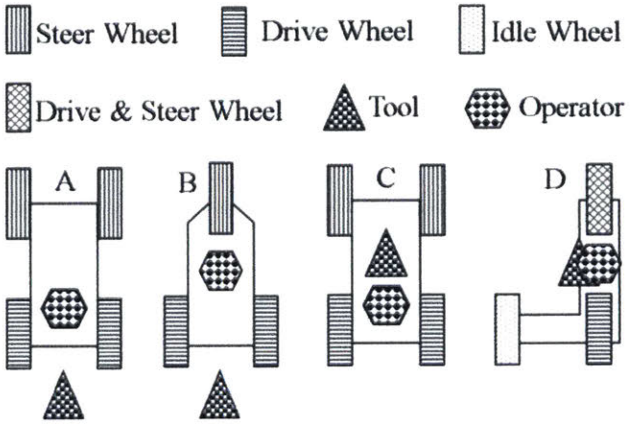


Figure 3-8: Tractor layouts considered for Bullkey. A and B are typical small tractor layouts in India. C is an alternative vintage design that was considered. D is the chosen Bullkey layout.

Tool location impacts user comfort and safety, along with the tractor's drawbar pull capability. Placing the tool behind the rear axle, as in layouts (A) and (B), improves comfort by keeping soil detritus away from the driver during tillage and, more importantly, improves drawbar pull by transferring weight to the driven rear axle during tillage. However, this weight transfer is also detrimental to comfort and safety, as it unweights the front wheels, resulting in loss of steering authority or, ultimately, in upending the tractor. Placing the tool between the front and rear axles, as in layouts (C) and (D), improves comfort and safety by placing the tool's action near the farmer's driving line of sight and eliminating the risk of upending the tractor.

Layout (D) is singular in its ability to enter narrow spaces. Layouts (A), (B), and (C) are limited by their side-by-side drive wheels, which prevent them from straddling crop rows taller than their low ground clearance. In the case of (B), the situation is worsened by the front wheel requiring a third travel lane – meaning the rows must be widened to accommodate the full vehicle in a single inter-row space or the vehicle must straddle two rows of crop. In these layouts, the major mass components – engine, transmission, and operator – are between, not in line, with the drive wheels. As such, for a vehicle of this configuration to straddle crops, a large amount of mass would have to be elevated above the crop height. In the case of tall crops, this is deleterious to the vehicle's stability and would limit its ability to use ground engaging tools. The inline drive wheels configuration of Bullkey, layout (D), places all the major mass components in line with the drive wheels. This naturally places the components in a narrow package, allowing access to inter-row lanes and maintaining a low center of mass. Since the outrigger wheel does not need to generate traction or provide steering, it does not need to bear much weight and can be attached via a simple high ground clearance extension arm from the main tractor frame (Fig.3-7A). This allows the outrigger arm to straddle tall crops and the tractor to generate a single compaction lane (that of its drive wheels).

The side-by-side drive wheel configuration in layouts (A), (B) and (C) allows for differential steering, which can be an advantage in some situations. Differential steering is the simultaneous application of different torques on each of two side-by-side drive wheels, which generates a moment on the tractor body and causes it to rotate in yaw. Differential steering can reduce the tractor's turning radius and enables the driver to maintain some control even when the steering authority of the front wheel is low (e.g., when the front wheels are unweighted). This could be replicated in (D) by a differential drive-line and steering system that allows the rear tire to be completely braked (i.e. stopped) while the front wheel is turned 90° and driven, therefore pivoting the whole vehicle around the rear tire's contact patch.

The novel layout, (D), was selected for Bullkey because it combines the drawbar pull advantages of weight transfer of (A) and (B) with the improved safety and comfort of (C). Additionally, Bullkey has a unique ability to operate in narrow spaces. The advantages of Bullkey, both in terms of drawbar pull and usability, are significant (Table 3.1) and allow it to meet the needs of small farmers in India elucidated in Sec. 3.1. The inline drive wheels allow Bullkey to enter narrow spaces currently only accessible to bullocks. The combination of the wheel placement and a central tool location improves the vehicle's drawbar pull per unit mass. Thus, the Bullkey design meets the required drawbar pull with a lower overall mass, lowering the purchase price for the user relative to a conventional tractor that can produce equivalent drawbar pull. Bullkey also meets the farmers' needs for improved comfort and safety by providing improved visibility of the tillage tool and eliminating the risk of upending the tractor during tillage. Additionally, soil compaction, which is detrimental to crop growth, is reduced by limiting the vehicle to a single compaction lane. Bullkey (Fig. 3-7) is thus uniquely capable of providing the benefits of both a pair of bullocks and a tractor.

3.3.3 Predicted performance

To demonstrate the relative performance advantages of Bullkey, its predicted drawbar force (using the Sec. 3.2 model) was compared to that of an equal mass tractor and a pair of bullocks. The mass of the modeled Bullkey and conventional tractor was set to 500 kg because market trends of cost-to-mass ratio suggest that a tractor with a cost comparable to a pair of bullocks would have a mass 500 kg or less (Fig. 3-2). Dimensions of the conventional tractor, except for mass, are the same as on the Mahindra Yuvraj (Yuvraj NXT 215 by Mahindra Tractors, India [60]), a popular small tractor in India. The Bullkey dimensions are those of the prototype vehicle described in detail in Sec. 3.4. Dimensions for both vehicles are shown in Table 3.2.

Tractor Layout	Conventional	Bullkey
Vehicle Mass (kg)	500	500
Rider Mass (kg)	60	60
Weight Front/Rear (%)	45/55	50/50
Wheelbase (m)	1.5	1.3
Tool Horz. from CG (m)	-1.5	0
Plow depth (m)	0.13	0.13
Tire sidewall height (m)	0.085	0.165
Tire diameter (m)	0.72	0.64
Tire width (m)	0.2	0.2
Tire Pressure (psi)	8.7	8.7

Table 3.2: Parameters for a conventional tractor and the Bullkey compared in Figure 3-9.

The pulling force of a pair of bullocks was calculated for comparison with these tractors. The bullocks' pulling force has two values, a steady pull and a maximum pull. The steady, sustained pull is about 15% of the animals' combined weight (each bullock has a mass of ~300 kg[5]), while the maximum pull can be as much as 50% of the animals' combined weight [83, 106]. The maximum pull plays a critical role – it allows the animals to briefly pull a tillage tool through a harder patch of soil. A tractor that cannot reach an equivalent maximum pull would become stuck in similar situations and require a decrease in drawbar pull (by reducing tool depth) to proceed. Minimizing the unplanned depth adjustments during operations improves the quality of the work and reduces drudgery. Therefore, it is valuable to have Bullkey match the maximum pulling force of bullocks to negate the need for depth adjustments in any tillage situations where the bullocks could pull through.

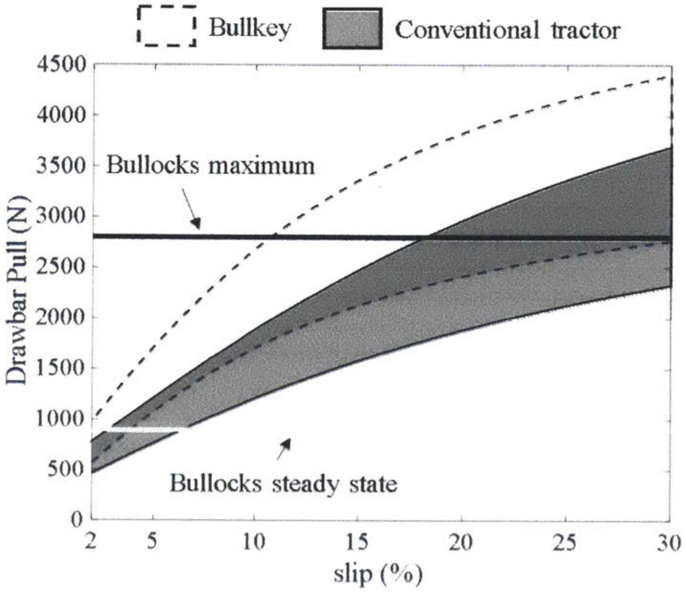


Figure 3-9: A comparison of the drawbar pull versus slip performance in weak to strong agricultural soil for a 500 kg hypothetical implementation of a conventional tractor and Bullkey (more details Table 3.2). The drawbar pull of a bullock pair has been added for reference. Soil data in Appendix B1.

The model predicted that Bullkey can exceed the maximum pull of bullocks over a significantly wider range of soil conditions than conventional tractors can (Fig. 3-9). This translates to improved usability of Bullkey over other light tractors by reducing the likelihood of the vehicle being bogged down during tillage.

3.4 Proof-of-concept vehicle design

A prototype vehicle was built to validate the Bullkey concept and evaluate the model of tractor traction performance that was used to design it (Fig. 3-10). The prototype incorporates key Bullkey design features, including: supporting nearly all the vehicle's mass on its two inline drive wheels, incorporating a centrally mounted tillage tool, and incorporating a lightly loaded outrigger wheel that can straddle rows of growing crop. The prototype was built on a Rokon Scout motorcycle (Scout by Rokon International Inc., New Hampshire [84]), which is an all-wheel-drive, two-wheeled motorcycle meant for heavy off-road duty. A

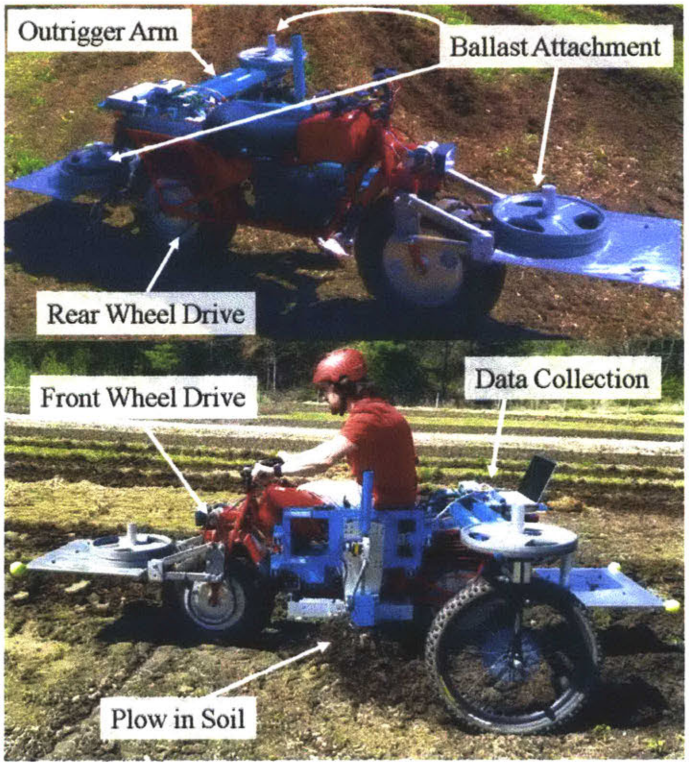


Figure 3-10: Bullkey prototype vehicle highlighting the implementation of desirable design features for a small tractor intended to replace a pair of bullock. These features include two inline drive wheels supporting almost the full vehicle weight, a manually controlled and centrally mounted heavy tillage tool, and motorcycle-type controls. Gym weights were used for ballast at the front, rear, and over the outrigger wheel.

removable frame (next to the driver in Fig. 3-10) was attached to the left side of the motorcycle to control the tillage tool position and record the forces it experienced. An outrigger arm extended parallel to the rear axle of the motorcycle, also on the left side (behind the driver's left in Fig. 3-10). The outrigger wheel's axle was in the same vertical plane as the rear drive wheel axle, making side-slip during slow speed turning negligible for the outrigger wheel. The parameters of the test vehicle are given in Table 3.3.

The prototype mass could be varied between 192 kg and 305 kg during testing. This mass range allowed testing of the tractor physics model at drawbar pull loads comparable to bullocks but without overloading the stock frame and transmission of the Rokon. The transmission began slipping at drawbar forces produced by the 305 kg tested configuration, and so the prototype could not be tested at the maximum expected production mass of 500 kg. The Rokon, which weighs only 98 kg, had crucial benefits not present in other heavier vehicles, including a unique inline drive wheel system and a frame designed for 20 cm wide tires. Building the Bullkey prototype with a commercially-available base vehicle allowed its most critical features to be evaluated without the time and financial burden of manufacturing an entirely new operator-safe vehicle. The prototype design incorporated the full proposed novel layout and was thus suitable for evaluating the drawbar pull force and overall functionality of the Bullkey concept. In combination with our prior work validating the traction model with published data for heavier commercial tractors [44], the prototype can be used to validate the physics model presented here, and so its predictions for other mass configurations should be accurate.

The prototype was designed to evaluate if the lightweight Bullkey tractor could achieve the predicted high drawbar pull force at tire slips recommended for plowing (15 to 25% [90]) and also have the ability to enter narrow inter-row spaces. Sensors were mounted to record tillage tool forces (equal and opposite to the tractor's generated drawbar pull when parallel to the tractor's pull), tillage tool force location, acceleration, and tire slip (Fig. 3-11). Tillage tool forces and their location were isolated for measurement by the attachment structure described in Fig. 3-12 and shown in Fig. 3-11A. The desired operating tillage tool depth was controlled by a Haacon 1524 rack and pinion jack (1524 SS by Haacon, Germany [48]) and recorded by a string potentiometer (CWP-S by CALT, China [15]) that attached to the pinion housing and the rack. The horizontal and vertical components of the tool force could be resolved from the three axial load cells (104-500 by DYLY, China [19]) that exactly

Bullkey proof-of-physics prototype	
Base Vehicle	ROKON Scout [84]
Mass unballasted	192 kg
Mass supported by front wheel	82.5 kg
Mass supported by rear wheel	94 kg
Mass supported by outrigger	15 kg
Wheelbase	1.3 m
Rear ballast to rear axle	0.56 m
Front ballast to front axle	0.48 m
Turn radius (no lean)	1.4 m
Tire pressure	7 psi
Tire model	TITAN 489XT [95]
Tire size	12" rim, 8" x 25"
Tool used	0.3 m wide furrower

Table 3.3: Basic parameters for Bullkey prototype.

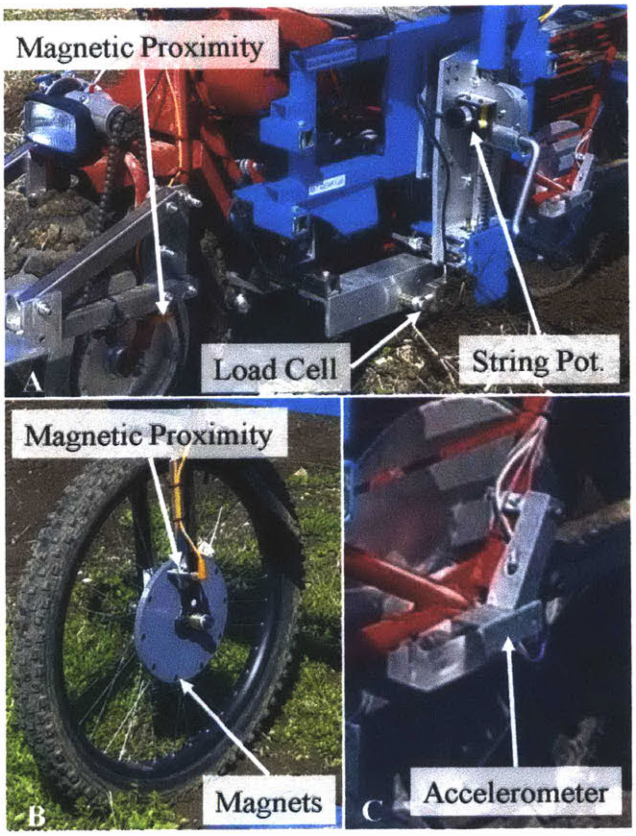


Figure 3-11: Close-up views of sensor installation examples. Views of prototype shown are (A) left-side, (B) outrigger wheel right side, and (C) rear axle left side

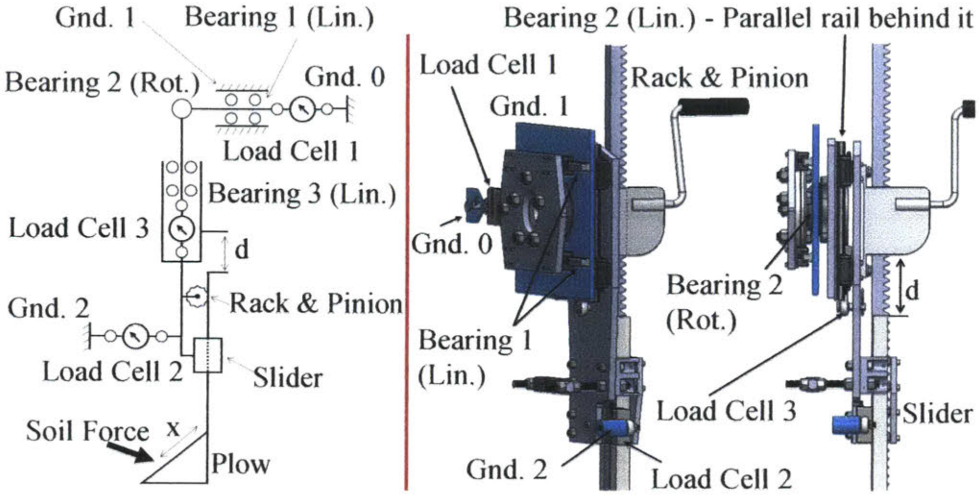


Figure 3-12: Mechanical diagram and CAD of the structure used to measure tillage forces on the Bullkey proof-of-physics prototype. Gnd. stands for ground (i.e. fixed to Bullkey's frame), Lin. for linear, and Rot. for rotary.

constrained the motion of the tillage tool (Fig. 3-12). To exactly constrain each load cell, they were mounted in conjunction with a single degree-of-freedom linear (HSR15-600-A by Joomen, China [53]) or rotary (513267 Wheel Bearing and Hub by MOOG, USA [67]) bearing and placed to be the only load bearing elements in the force path of the loads they measured. These three load cells also allowed spatial resolution of the center of pressure for forces exerted on the tillage tool (along the x dimension in Fig. 3-12).

All three wheels were fitted with magnetic proximity sensors, with 10 evenly spaced magnets placed on each wheel (Fig. 3-11B). Tire slip can be calculated using the rotation of these senors, assuming that the idle outrigger wheel has near zero slip and can be used as the reference point for distance travelled. An accelerometer (ADXL335 by Adafruit, USA [2]) was placed at the rear axle to provide higher time resolution on vehicle speed and to assist in confirming short-term measurements from the outrigger wheel rotations (Fig. 3-11C). Appendix B4 lists the sensors used for measurement and their characteristics.

3.5 Field testing and performance results

3.5.1 Field testing methods

Field tests were performed on a working farm in Massachusetts to validate the terramechanics model, investigate the traction performance of the Bullkey prototype, and obtain user feedback after operating the vehicle among actual growing crops. Traction performance tests were conducted at different tillage depths and different ballasting levels to alter the vehicle mass distribution from the base distribution specified in Sec. 3.4. Ballast on the front and rear ballast trays varied between 0 and 56 kg ±0.5 kg, operator mass (of the author) during recorded tests was 79 kg ±1 kg, and tire pressure was set to 41 kPa (6 PSI) ±4 kPa. For each configuration, the tractor was driven in a straight line at about 1 m/s for 30 to 50 m with a 30 cm wide furrowing tool at a constant depth between 12 and 19 cm. Tool depth was set for each configuration to force tire slip to be near 20% – approximately the upper limit of what would be useful on a farm field and thus close to the vehicle's maximum practical drawbar pull [115][13].

In addition to sensor data, field tests with the prototype vehicle provided an opportunity to gain valuable feedback on the usability of the proposed tractor design. Six local Massachusetts farmers observed the field tests and provided their feedback in a spoken survey. The survey was approved by MIT's Committe on Use of Humans as Experimental Subjects (COUHES). In addition to the drawbar pull tests on open farm fields, qualitative tests were performed by driving Bullkey between growing crop using a 15 cm wide sweep tillage point at 3 to 6 cm depth. A sweep is a thin "V" shaped tillage tool used cut weeds at their root between rows of growing crop during intercultivation.

The sensor data collected was processed to have a similar format as the initial simulations (Fig. 3-9). First, the collected time-force signals were passed through a 1 Hz low pass filter. This filtering frequency was selected because the 30 cm long tool travels at least three characteristic lengths every second. Then, the distance traveled by all wheels was calculated by summing the new distance traveled each time a wheel magnet (Fig. 3-11B) was detected, using linear interpolation to fill in the distance travelled for intervals between detections. The distance travelled between magnet detections is $2\pi/10 * R$, where $2\pi/10$ is the angular spacing between neighboring magnets in radians (there are 10 magnets per wheel) and R is the effective radius of the wheel (estimated by counting the number of wheel rotations to travel 30 m under the test conditions). The three (one per wheel) distance-travelled vectors were then processed through a 1 Hz low pass filter as well.

The drawbar pull versus tire slip binned data shown in Fig. 3-13 were generated by the following procedure: (1) The highest drive tire slip was selected at each timestamp and stored along with the drawbar pull measured at that timestamp to generate a slip vs.

drawbar matrix. (2) This matrix was then rearranged so that all drawbar pull instances were assigned to the closest integer slip (i.e. all slip instances ≥13.5% and <14.5% were assigned to the 14% slip bin). (3) Finally, in each slip bin the average, minimum, and maximum drawbar pull were obtained and stored. As presented in Fig. 3-13, squares represent the average drawbar pull at that tire slip bin while the error bars represent that maximum and minimum drawbar pull recorded at that tire slip bin. Further details are presented in Appendix B5.

3.5.2 Field performance results

Figure 3-13 compares the drawbar pull performance for each of the Bullkey mass configurations tested against the steady state and the maximum pulling force of a bullock pair [83, 106, 42], as well as to the model-predicted performance for the soil conditions during the test and for the range of common farm soil conditions. The results validated that the physics model from Sec. 3.2 made predictions for the maximum drawbar pull that are sufficiently accurate to inform tractor design. The model average absolute error compared to experimental data was 7% at 15% slip, 9% at 20% slip, and 12% at 25% slip. The standard deviation for the absolute error was 4% at 15% slip, 5% at 20% slip, and 8% at 25% slip. The drawbar versus slip results are presented in more detail in Appendix B2. All tested configurations comfortably surpassed the steady-state pulling of bullocks. The maximum drawbar pull for the 305 kg Bullkey configuration, despite being limited by the test soil not being at the upper limit of strength for agricultural soils, was near to the maximum pulling force for a pair bullocks. More importantly, given the demonstrated accuracy of the model, it is expected that a heavier Bullkey (up to 500 kg) would be able to match or exceed the maximum pulling force of a bullock pair for any common agricultural soil condition, as was predicted in Fig. 3-9. This cannot be matched by a conventional tractor layout of the same mass. The properties for the soils used for the model are provided in Appendix B4.

3.5.3 User feedback

On-site farmers who observed the Bullkey prototype during field tests said that the vehicle had valuable and unique benefits for small farmers. Farmers appreciated the ease with which the tool could be observed during tillage and the tall height of the outrigger arm, which allowed the vehicle to easily straddle crop rows. They also commented positively on

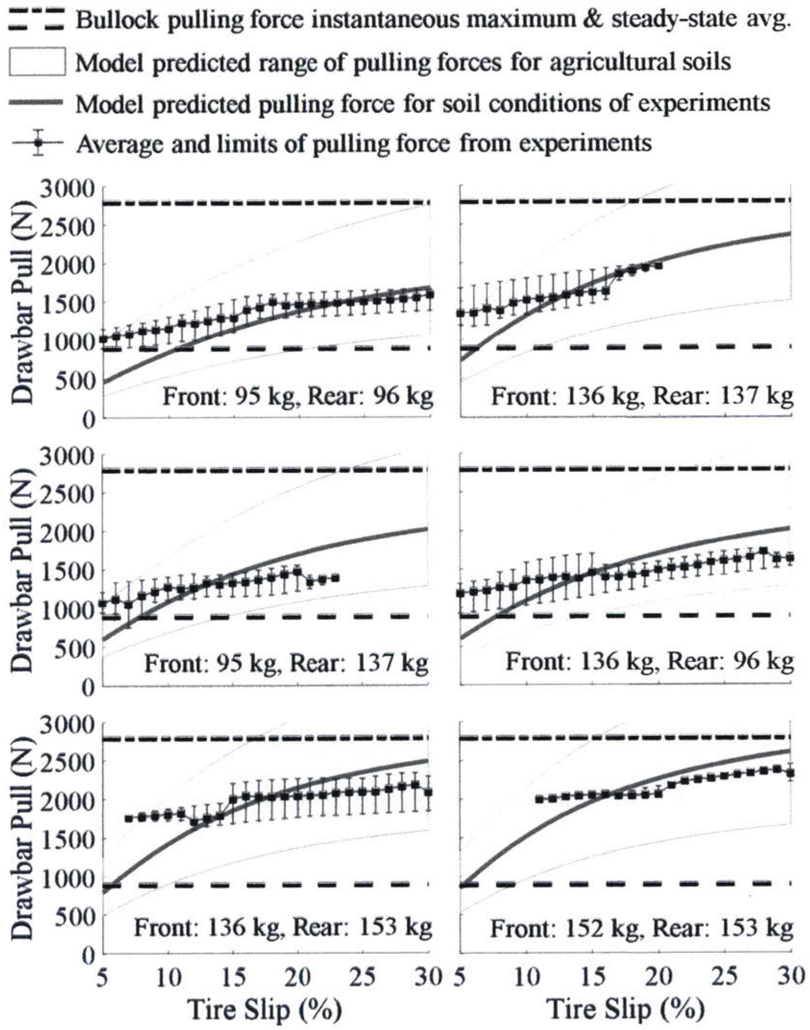


Figure 3-13: Examples of measured forces for prototype configurations tested. Indicated in each plot are the masses supported by the Bullkey prototype's front and rear wheels when static and with no driver on board. The masses were adjusted by adding and removing ballast.

the Bullkey prototype's ability to plough deeper than they would have expected from such a small vehicle. Farmers were initially concerned that the tillage tool's lateral offset from the drive tires might cause Bullkey to veer off-track – this concern was allayed when they watched Bullkey maneuver and saw that it was easy to drive the vehicle in a straight line under all conditions. The farmers also had some suggestions for improving the vehicle. They suggested having a mount for low drawbar force tools, like those used during intercultivation, set up behind the rear axle and in line with the drive wheels in order to provide better access to narrow rows while crops are growing.

3.6 Discussion

The Bullkey prototype's measured maximum drawbar pull matched well to model predictions in both trends and absolute values. This showed that the model is a useful tool to evaluate potential tractor designs for traction performance and identify promising design directions. The average absolute error of the model at high slips (when maximum drawbar pull occurs) was generally less than 10%. The model's performance and its parametric, physics-based foundation make it useful for exploring a large design space of previously unrealized tractor designs. These capabilities of the model made it a powerful tool for identifying and establishing the Bullkey design.

The prototype's field performance showed that the Bullkey design satisfied the outlined user needs for an easy to use, highly maneuverable lightweight vehicle with high drawbar pull capability for a low mass device. Bullkey was able to straddle rows of growing crops on the field because of its configuration of inline drive wheels with an outrigger arm. This enabled Bullkey to operate in narrow inter-row spaces like bullocks do – something that is not possible with conventional tractors. Bullkey generated more drawbar pull per unit mass than conventional tractors with rear drive wheels and rear mounted tools – this is significant because mass is correlated approximately linearly with cost (Fig. 3-2). Bullkey's performance on the field therefore suggests that a production-version of the tractor could be sold at a lower cost for a given drawbar pull capacity than available tractors, enabling the distribution of a tractor that can compete with the maximum pulling force and the purchase price of bullocks.

Bullkey was comfortable to operate after some adjustments were made. A 20 kg ballast was added to the outrigger wheel after early field tests and mitigated the risk of the tractor rolling over sideways. During instrumented testing the operator would sit side saddle - a remnant habit from an earlier, taller version of the tillage tool attachment mechanism shown in Fig 3-12 - which shifted the overall center of mass away from the outrigger wheel and decreased stability. During later driving the operator sat as is conventional, straddling the motorcycle frame and the tillage tool mounting frame, which was an improvement in comfort. The front drive wheel never became unweighted during tests with heavy drawbar loads (a common occurrence with conventional tractors [1, 26, 89]), which enables Bullkey to operate near its traction limits more safely than conventional tractors.

The proof-of-physics Bullkey prototype allowed testing to find its drawbar pull at slips relevant to tillage and near its traction limits (15 to 25% tire slip). A limitation of the presented work is that the accuracy of the modeled drawbar pull drops for slips under 10% (Fig. 3-13). It is possible that at lower slip the assumed soil deformation mechanics are less applicable, or that the vehicle was at least partially relying on other methods of forward propulsion during low slips (like its inertia when slowing down). These errors could have been accentuated by the experimental methods, which focused on finding the tractor's maximum drawbar pull at high tire slips and not on generating steady drawbar pull at low tire slips. Future work could include experiments at constant low tire slips, to better capture the performance of the model in those conditions and identify strategies for model improvements. The model is usable for its design purposes in this Chapter, which is to estimate the maximum drawbar pull of multiple designs, which occurs at high tire slips.

The Bullkey prototype was usable for farming operations that could be performed with tillage tools mounted centrally on the vehicle (like plowing and furrowing). To add flexibility, a future prototype could allow low drawbar force farming tools via conventional mounting points behind the tractor, like a three point hitch and a pin or ball hitch. Future work could also allow for ballast to be added without extending the overall length of the vehicle. A key next step is to discuss the Bullkey vehicle with small Indian farmers – the target users – to solicit feedback on the vehicle design and usability. In these discussions, farmers could also be asked if they might use Bullkey (with some attachments removed) as a conventional two-wheel motorcycle for personal transportation. If Bullkey is viable as a two-wheeler, it could replace both a pair of bullocks and a motorcycle for farmers, further increasing its value proposition.

3.7 Conclusions

The presented tractor design, Bullkey, is novel in its high potential to concurrently match bullocks' sales price, pulling strength, and unique ability to access a field with growing crop, while also offering farmers major conventional tractor benefits like increased productivity, lower maintenance costs, and improved comfort. This allows Bullkey to fulfill the unique needs of small farmers in India, which are not currently being met by commercially available tractors.

Bullkey has inline drive-wheels that support the majority of the its mass, a crop clearance similar to a bullock team yoke, and a centrally located tillage tool attachment. Inline drive enabled improved traction, reduced soil compaction, and operating in narrow inter-row spaces between growing crop. Central tool attachment increased traction and improved safety while also facilitating the operator maintaining control over the direction they are driving as well as the tillage operation being performed. These beneficial design features were identified by combining insights from a physics-based traction model and farmer interviews. The traction performance predicted by the model was validated by building an instrumented prototype of Bullkey and field testing it.

Replacing bullocks with a suitable farm tractor, such as the Bullkey design proposed here, could increase farmer income by 20% and reduce their recurring expenses by 60%. Farmer income could increase because of higher crop yields from more precise and timely farm operations. Recurring expenses would be reduced because tractor maintenance is much lower over the course of a year than the daily feed and care costs of bullocks. The findings presented in this Chapter will be useful to engineers developing lightweight, high drawbar pull vehicles and/or vehicles that are well suited to in-field use by small farmers in emerging markets.

Chapter 4

Investigation of viability to replace draft animals with all-wheel-drive motorcycles on small Indian farms

4.1 Introduction

This Chapter describes the motivation, design, and validation for a farm tractor prototype specialized to small farmers in low resource settings, particularly in India. In these settings, farmers' prosperity is currently stymied by the limitations of draft animals. Draft animals are inefficient and expensive to maintain compared to tractors (Fig. 4-1) [52, 39], but conventional tractors cannot replace animal's small dimensions and low capital cost [64, 76]. This misalignment between conventional tractors and the needs of small farmers is, in part, because conventional tractors were designed for larger fields than what is typical around the world [44]. The majority of farms in the world (84%), and particularly in India (86%), are less than 2 ha in size [58, 75], whereas the conventional tractor largely evolved for farms in the US that are at least 30 times larger [14, 99, 59].

A tractor layout specialized to the contemporary needs of small farms, called **Bullkey**, has been previously introduced by the author [45] (fully described in Ch. 3). *Bullkey* is a portmanteau of *bullock* and *key* - indicating its goal of being the key to unlocking the bullock market to mechanization. In prior work work [45], Bullkey was shown to generate more drawbar pull per unit mass than conventional tractors. This is important because mass

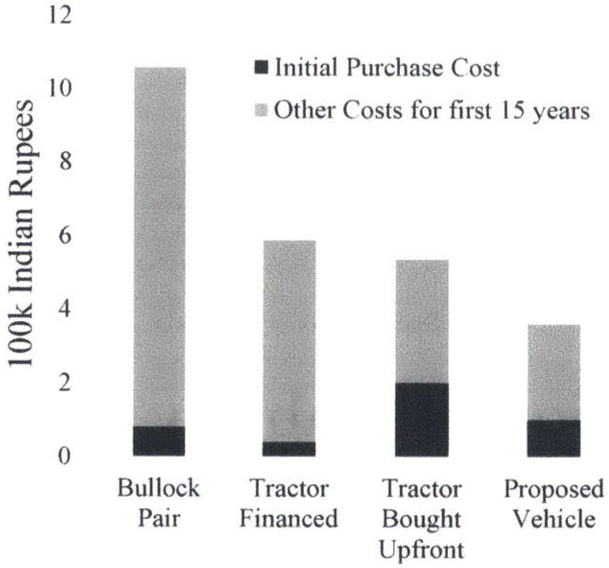


Figure 4-1: Ownership costs over 15 years for a bullock pair, a small tractor, and the Bullkey tractor. In addition to purchase price, other costs include fuel/food, and maintenance. An ideal solution would have the low purchase price of bullocks and the low upkeep cost of tractors - shown as Bullkey tractor. Financing or renting may be inaccessible to many farmers. Renters forgo using the tractor for supplemental income work and potentially timeliness of completing operations. [81, 80, 22, 31, 30, 47]. A breakdown of the costs shown here is provided in Appendix C5 Tables 6.10 and 6.11.

is correlated to both tractor price [45] and drawbar pull [115, 13, 4]. A conventional tractor that is light enough to be sold at a price competitive to bullocks would be too light to match the maximum pulling force of the bullocks. Bullkey overcomes that with a three-wheeled layout that supports nearly all of the vehicle's mass on inline drive wheels and shifts the tillage tool ahead of the rear axle. This layout increases the load on all drive tires during plowing and allows the trailing drive tire to roll on already-compacted terrain - improving drawbar pull while also preventing the vehicle from rolling over backward.

In Chapter 2, Bullkey was field tested to validate its traction performance and to preliminary assess its usability with farmers' feedback. This Chapter expands on that work by demonstrating the design's viability for performing specific and comprehensive agricultural operations key to Indian farmers. Section 4.2 presents the needs of small Indian farmers elucidated during field interviews and from background research that drove the design of Bullkey. Section 4.3 describes Bullkey's overall design and how it was engineered to achieve the operations required by Indian small farmers. Section 4.4 describes field tests in Massachusetts conducted to validate Bullkey's performance on these operations. This section also presents feedback collected with small and marginal farmers in India on their views on the tested tractor regarding its viability, the likelihood they would use Bullkey for various farming operations, the overall design, and the price point at which they would purchase the vehicle. The collected feedback suggests that Bullkey is useful and attractive to the targeted user population.

4.2 Description of Farmer Needs

Figure 4-2: Locations visited during the development of the Bullkey tractor prototype. The final interviews assessing the developed concept were performed at locations with white background, and were not conducted with the same farmers as the initial user needs assessment.

Bullkey was conceptualized based on interviews on local agricultural practices and the suitability of existing tools with stakeholders of Indian small farming at 12 locations in India, including the states of Maharashtra, Tamil Nadu, Gujarat, Rajasthan, Madhya Pradesh, West Bengal (Fig. 4-2). Farmer interviews were approved by MIT's Committee on the Use of Humans as Experimental Subjects (COUHES). Stakeholders interviewed included farmers, research organizations, governments, manufacturers, and farm tractor dealers. A key insight from these visits was that farmers used bullocks not only because of their low capital cost (about a third that of tractors) but because they have functional advantages over conventional small tractors. Bullocks have a smaller width than tractors and are more maneuverable. This allows the bullocks to walk between rows of growing crops further into the season, require less space to turn at row ends, and better traverse unfinished dirt paths

Major design requirements from user needs		**Reference Alternative (in gray)**	
Aspect	**Bullkey**	**Bullock Pair**	**Small Tractor**
Purchase cost (INR)	~100000	80000	265000
Ownership cost (INR/year)	<12500/Ha	93000[22]	12500/Ha[47]
Overall Width (m)	1.7	2.1	1.7
Required Path Width (m)	<0.7	0.6 to 0.9	1.7
Headland needed (m)	<1.5	1.5	2.6
Max. Drawbar Pull (N)	>2800	2800 [42]	4600
Daily work hours	unlimited	5	unlimited
Top road speed (km/h)	26	4	26

Table 4.1: Major user needs identified via interviews with stakeholders in India and background research. Unless otherwise noted, bullock values are from the author's farmer interviews and tractor values are from the Mahindra Yuvraj NXT 215 (Mahindra Tractors, India [60]) - a market leader in the small tractor segment. Actual Bullkey price will be affected by distribution possibilities.

leading to farm fields.

Also elucidated during the visits were key farmer-required field operations that are typically completed by a small tractor or bullocks. Early in the season and prior to planting, seed bed preparation is completed via plowing, disc harrows, and/or use of a rotavator. Next, planting is executed by precision seed drills that can position seeds at consistent depths and spacings both laterally and longitudinally. While the crop is growing, intercultivation is performend by mechanically removing weeds between rows of crops, often done with "S" or "C" shaped cultivator tines. This tillage-based deweeding is typically supplemented by manual laborers who pick weeds between crops within a row. Concurrently, spraying of fertilizer, herbicide, and other liquid-based inputs may be performed. When crops are tall (above 30 cm), this is often done by manual laborers carrying backpack-based sprayers since bullocks are not compatible with most sprayers and tractors are much wider than crop row spacing but do not have sufficient ground clearance to straddle the crop. Throughout the season, moving inputs and outputs between farms and towns by haulage trailers is an important usage case for both bullocks and tractors. The identified operations of interest are in agreement with prior work [76] [38][31].

From the aforementioned key targeted agricultural operations, and using information from our project partner's field research, design specifications for Bullkey were established and are provided in Table 4.1. Bullkey should be comparable to bullocks in purchase cost (Fig. 4-1), width, drawbar pull, headland required, and have ability to traverse unfinished dirt paths. Bullkey should be comparable to conventional small tractors in ownership cost (Fig. 4-1), user comfort, daily work hours, and road speed. Finally, it is desirable that Bullkey have a familiar interface to users, since a current barrier to tractor adoption is the training required to operate them [76][38]. Critically, farmers must also be willing to purchase Bullkey at a price that allows those in its supply chain to earn a profit.

A design that can succeed in the Indian small farmer markets should be able to demonstrate in field testing - and intuitively convince holder farmers of - its ability to perform plowing, disc harrowing, rotavator tillage, seed drill planting, deweeding with a cultivator, and pulling a trailer. In the next sections, we present the design of a Bullkey prototype and demonstrate its ability to complete these operations.

4.3 Prototype Vehicle Design

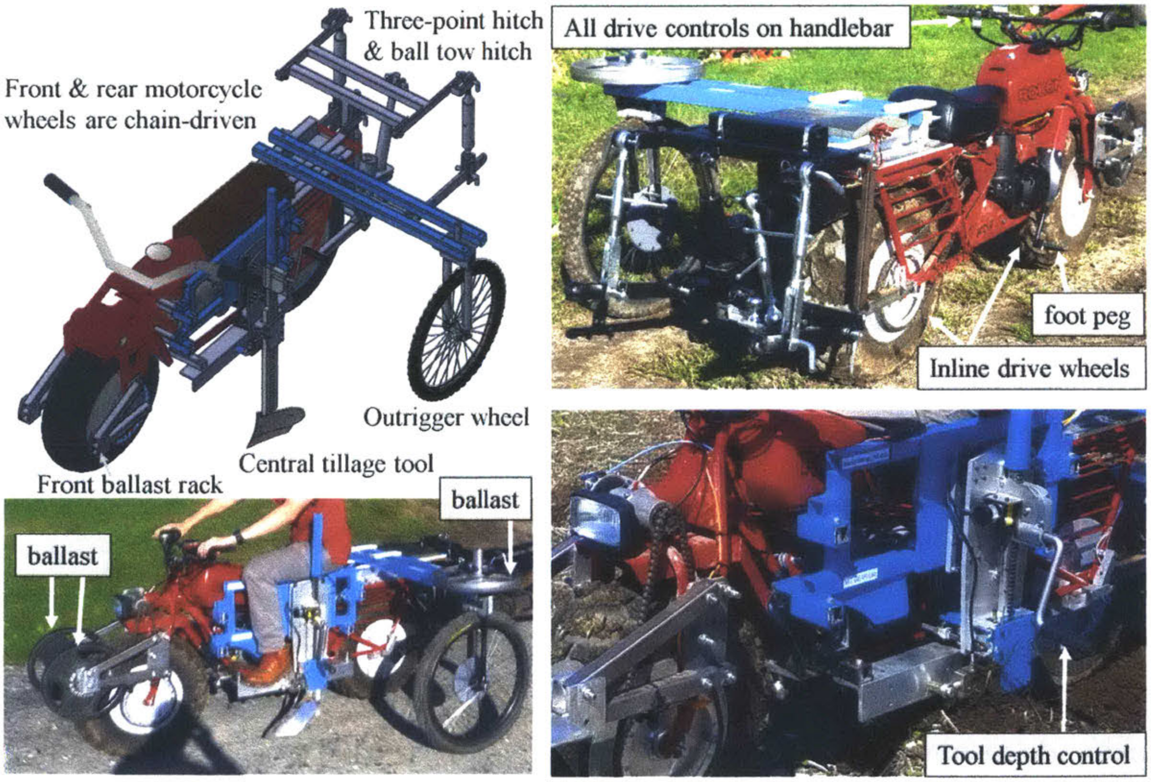


Figure 4-3: Overview of the Bullkey design. The CAD drawing on top left highlights key features of proposed tractor design. This is supplemented by three pictures of the physical prototype where those features are clearly visible.

Bullkey dimensions with outrigger arm	
Base Vehicle	ROKON Scout
Mass	125 kg
Mass supported by front wheel	60 kg
Mass supported by rear wheel	65 kg
Wheelbase	1.3 m
Turn radius (no lean)	1.4 m
Overall width	1.2 m
Path Width	0.6 m
Outrigger arm height	1 m
Drive Tire pressure	6 psi
Drive tire size	12" rim, 8" x 25"
Outrigger Tire pressure	20 psi
Outrigger tire size	3" wide, 26" diam.

Table 4.2: Key Bullkey dimensions.

To validate the performance of the Bullkey concept tractor on field operations that are important to Indian farmers, a prototype vehicle capable of the aforementioned functions was built.

4.3.1 Prototype vehicle

The Bullkey prototype was built by modifying a ROKON Scout utility motorcycle (ROKON, New Hampshire [84]) with factory installed all-wheel-drive. Major modifications included the addition of a centrally-located tillage tool attachment, an outrigger arm, a rear mounted three-point hitch compatible with conventional small tractor tools, a ball hitch for towing, and interfaces for ballasting. The prototype's key features are highlighted in Fig. 4-3 and its main dimensions are listed in Table 4.2.

This design can generate a high tillage drawbar pull for two main reasons: a high proportion of its total mass is supported by the front and rear drive tires, and tillage forces from the centrally mounted tool increase the vertical load on both drive tires [45]. The latter not only further improves traction but also allows safe operation near the vehicle's traction limits. By contrast, conventional tractors with a rear mounted tool can rollover backward during heavy tillage due to the tillage forces unweighting the front tires - a dangerous and common situation [1][26][89].

Two tested options for stabilizing the motorcycle are presented: Bullkey's default rigid outrigger arm with a third wheel to the operator's left and aligned with the rear drive wheel

(Fig. 4-3), and a specially-created, human-powered stabilization design. The outrigger arm has high ground clearance and adjustable width, allowing it to straddle rows of crop. Its alignment with the rear wheel keeps it from side-slipping during turns. The human powered stabilization design allows Bullkey to retain an overall width comparable to a single bullock, therefore avoiding the need to straddle crop. It is described in Section 4.3.2.

The Bullkey prototype described here meets the farmer needs outlined in the previous section. Its overall dimensions allow it to operate in a spaces similar to bullocks - something not possible with conventional tractors due to their large width and low axle height that prohibits straddling crops over 0.3 m tall. Bullkey's inline drive wheels and central tillage tool location allow it to generate more drawbar pull per unit mass - enabling it to theoretically be sold at a lower price than a conventional tractor of comparable traction since mass and sales price are correlated [45]. Finally, its tool attachment points make it safe to operate and compatible with the tools needed to complete key tasks mandated by small Indian farmers.

4.3.2 Balance Board

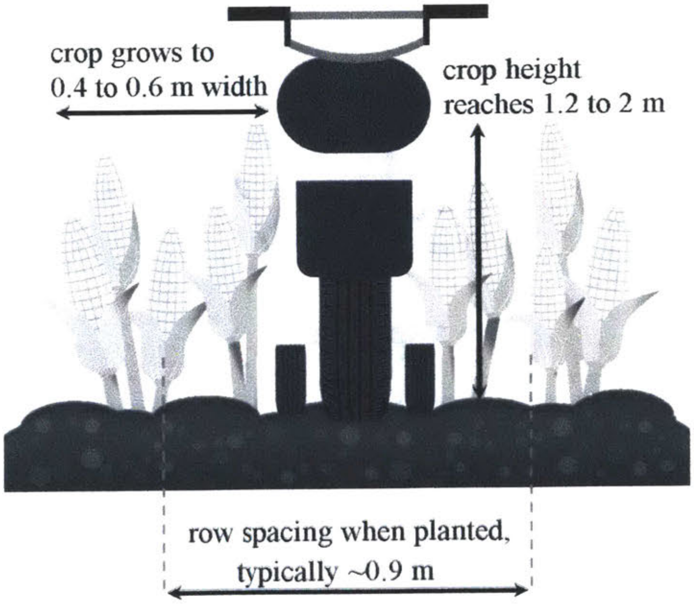


Figure 4-4: Bullkey with balance board between crop rows. The balance board allows Bullkey to operate between rows of tall growing crop by keeping all of its ground contact points in a single lane narrower than the distance between adjacent crops.

To enable Bullkey to operate in the same overall space as a single bullock, a human-powered roll stabilization attachment for utilitarian two-wheeled vehicles was created [57]. This device is called a balance board and is narrower than the motorcycle's handlebars - keeping all ground contact points within a single lane under 0.52 m wide and maintaining the stock motorcycle overall width (Fig. 4-4)). The balance board allows the motorcycle to operate late into the season between tall rows of growing crop. It also allows the motorcycle to lean relative to the ground, which is beneficial for comfortable operation in side slopes or when turning at higher speeds (Fig. 4-5).

Figure 4-5: The balance is a rigid, wheeled platform connected to the motorcycle frame by a ball hitch. The user steps on the balance board to stabilize themselves but can still comfortably stay upright on side slopes or lean in turns.

The balance board provides a rolling platform under the motorcycle for the operator to place their feet on. It is attached via a ball hitch underneath the motorcycle frame and directly behind the front wheel. Nominally, the rotation of the balance board is independent of the motorcycle rotation for a large range of motion. When driving at slow speeds the motorcycle is unstable in the roll direction and may start to tip sideways. When side roll initiates, the user can press down on the balance board (which remains parallel to the ground) with the leg on the side towards which the motorcycle is tipping. This, in practice, has a very similar stabilization effect as pressing against the ground (as one would do without the balance board) but has two major advantages: (1) the reach to the balance board is much shorter than to the ground, allowing the driver to maintain a natural riding position; and (2) since the balance board is moving forward with the motorcycle, the rider is pressing down on a surface that is largely static relative to them (as opposed to dragging a foot on the ground or tip-toeing on the ground).

The basic operation principle of the balance board is converting an internal force (the user's feet on the motorcycle foot pegs) to an external force (user's feet on the not fully constrained balance board). This stabilizes the motorcycle in roll. By contrast, with normal foot pegs, the leg forces would be redistributed internally between the foot pegs and motorcycle frame. The balance board is also enabled by having all of the Bullkey controls be hand actuated, thereby fully liberating the legs and feet for other tasks.

Figure 4-6 demonstrates the basic operating principle of the balance board. In the top row the user leg force flow paths are shown going through the balance board and to the ground. This stabilizes the motorcycle in roll since the balance board can rotate relative to the motorcycle body and its contact points are laterally offset from the vehicle centerline. By contrast, with normal foot pegs (bottom image) the force goes through the rigid motorcycle frame and to the vehicle centerline - thereby applying no roll stabilization.

Compared to the outrigger arm, the balance board has the advantage of being agnostic to crop height since it keeps the overall vehicle identical to the stock motorcycle and all ground contact points in a single lane narrower than the motorcycle handlebar - allowing it to roll freely between rows of growing crop. However, the balance board also increases the width of the contact footprint of the vehicle within a row, since its wheels are not inline with the drive wheels. By contrast, the outrigger wheel rolls in the center of the row neighboring the motorcycle's path, but its outrigger arm must be tall and wide enough to straddle the growing crop between the drive wheels and the outrigger wheel.

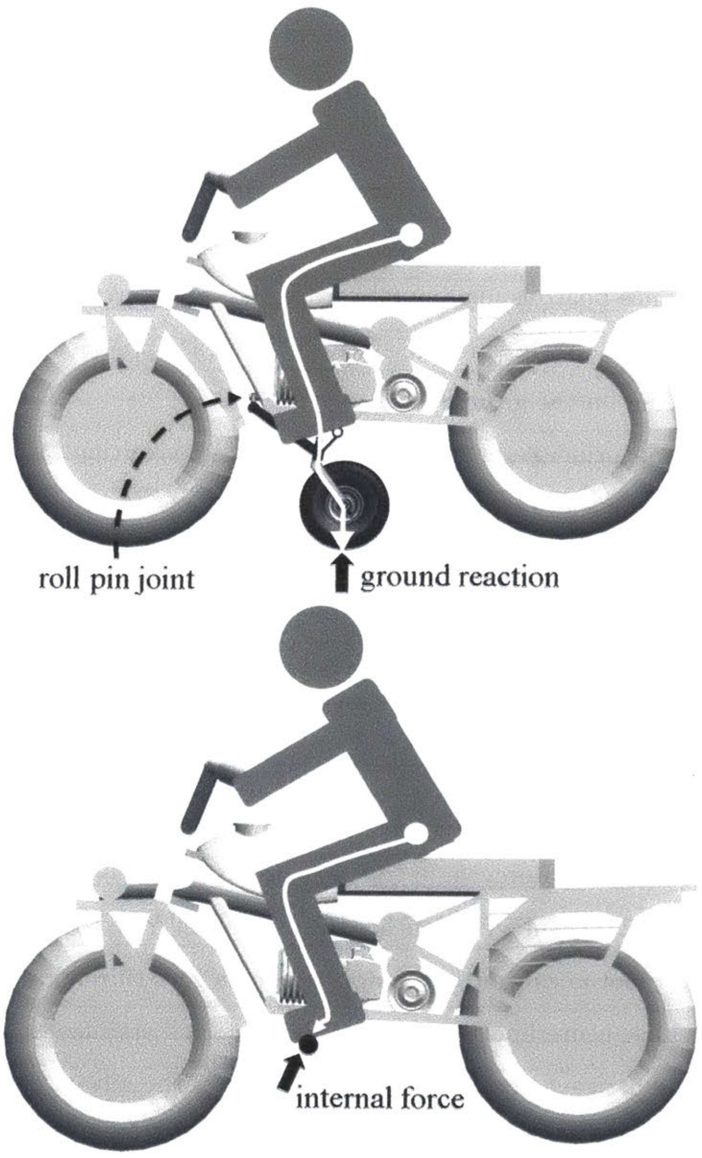


Figure 4-6: FORCE FLOW PATHS WHEN USING BALANCE BOARD (TOP IMAGE) AND IN CONVENTIONAL MOTORCYCLE (BOTTOM IMAGE). White arrows represent the force applied by the user legs on and opposed by the black arrow reaction forces.

4.3.3 Implement Utilization

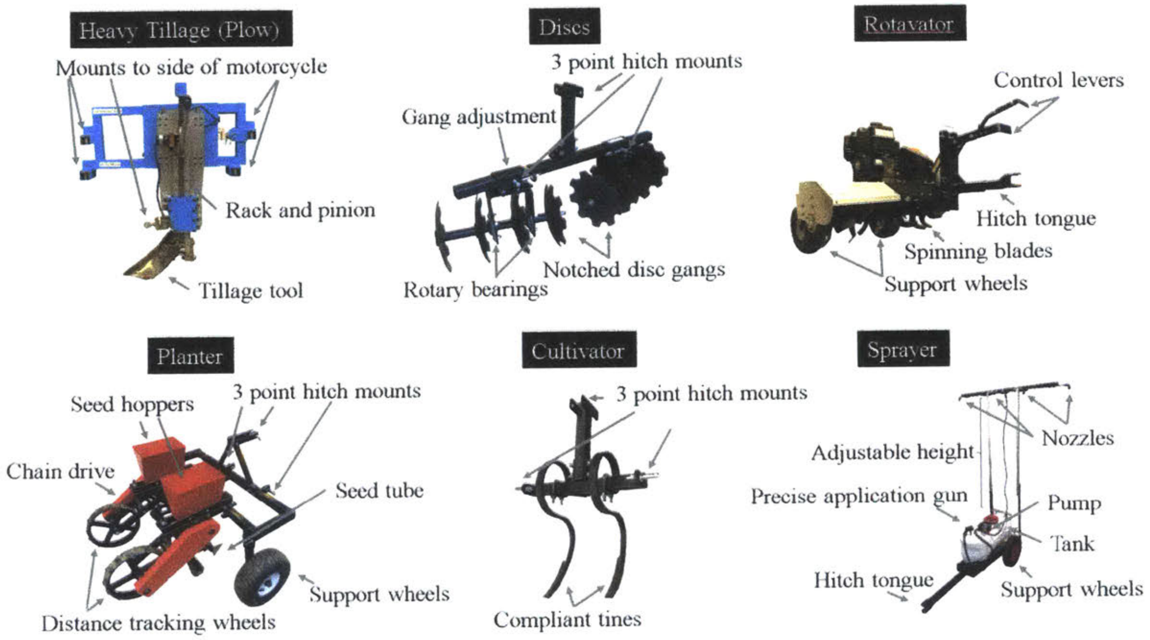


Figure 4-7: Close up views and key components of the farming implements used during field testing.

The following is a list of implements that were tested with the Bullkey prototype. These implements were selected because they perform the operations needed by Indian small farmers from, as outlined in Section 4.2. These tools perform seed bed preparation, planting, intercultivation, and spraying to a degree equal or better than bullocks. Close-ups of the implements are shown in Fig. 4-7 and tool dimensions are provided in Appendix C1.

Plow: unearths soil from 10 to 20 cm depth to loosen and dry it. In the prototype, this tool is mounted between the front and rear axles. The plow used was 20 cm wide with depth controlled manually via a Haacon 1540 jack (Haacon, Germany [48]) located adjacent to the driver. This tool is expected to be used exclusively with the prototype in the outrigger arm configuration.

Rotavator: breaks up large soil clumps near the surface. In the prototype, the rotary tiller is attached behind the rear axle with a single vertical pin hitch connection. Via control levers extending forward from the tiller, the transmission engagement and tillage depth can be adjusted. The rotary tiller is a model Field Tuff (Field Tuff, Illinois [72]), with 0.92 m tillage width, 0.3 m diameter blades, and powered by a 208cc Briggs & Stratton (Briggs &

Stratton, Wisconsin [12]) 9.5 hp engine. This tool can be used with the prototype stabilized by either the outrigger arm or the balance board.

Disc harrows: improve top soil texture for planting. In the prototype, the disc harrow (Kolpin Outdoors, Minnesota [55]) consists of eight 0.3 m diameter discs with a total engagement width of 1.37 m. The disc harrow is mounted at the back of the vehicle to the three-point hitch. The hitch can fully raise the tool at row ends or for transportation, and then lower it for engagement during tillage. This tool is expected to be used exclusively with the prototype in the outrigger arm configuration.

Planter: lays down seed at controlled depth and spacing. In the prototype, the planter (Field Tuff, Illinois [71]) is mounted behind the rear axle to the three-point hitch. The planter was set up with two planting units spaced 0.9 m apart and planted black beans and soy beans at a 3cm depth. At row ends the planter can be fully raised (without its wheel touching the ground). During planting, engagement is controlled via the three-point hitch and the tool is partially carried by its wheels. When transporting the planter, it can be fully carried by Bullkey or partially supported by the tractor's wheels. When planting, it is recommended the planter be stabilized using the outrigger arm Bullkey configuration.

Cultivator: mechanically removes weeds between rows of growing crops. In the prototype, the cultivator (Black Boar, North Carolina [11]) is attached to the three-point hitch behind the rear axle. The cultivator has multiple S-shaped spring tines that engage the soil between rows of growing crop at a 2 to 5 cm depth - tearing up weeds. When cultivating, the motorcycle can be stabilized by the outrigger arm or the balance board. When crops are large, it is recommended to use the balance board with two S-tines to allow access to narrow spaces that would typically only be accessible by bullocks.

Sprayer: pulling or carrying a tank to supply liquids (often fertilizers or pesticides) to plants at their leaves or roots. The sprayer (VEVOR Machinery, China [103]) used has a 60 L tank, a 9 bar pump, and six nozzles evenly spaced on a boom spanning a 1.5 m width. The boom can be set to heights between 0.4 m and 2 m in increments of 0.1 m. When the sprayer tank is carried by the motorcycle, it is recommended the vehicle be stabilized by the outrigger arm. If the sprayer tank is towed on a trailer, the balance board may be used for stabilization - allowing access to narrow spaces between rows of tall crops and spraying them with a tall boom height.

Trailer: used to transport farm inputs and outputs as well as for supplemental income.

The trailer (locally made in workshop) used in testing had a mass of 225 kg and a track width of 1.4 m. The overall length of the tractor and trailer is 3.1 m. The trailer is mounted to the prototype at a ball hitch located 0.3 m above the ground behind the rear axle.

4.4 Methods - Field Validation of Operations and Assessment Interviews

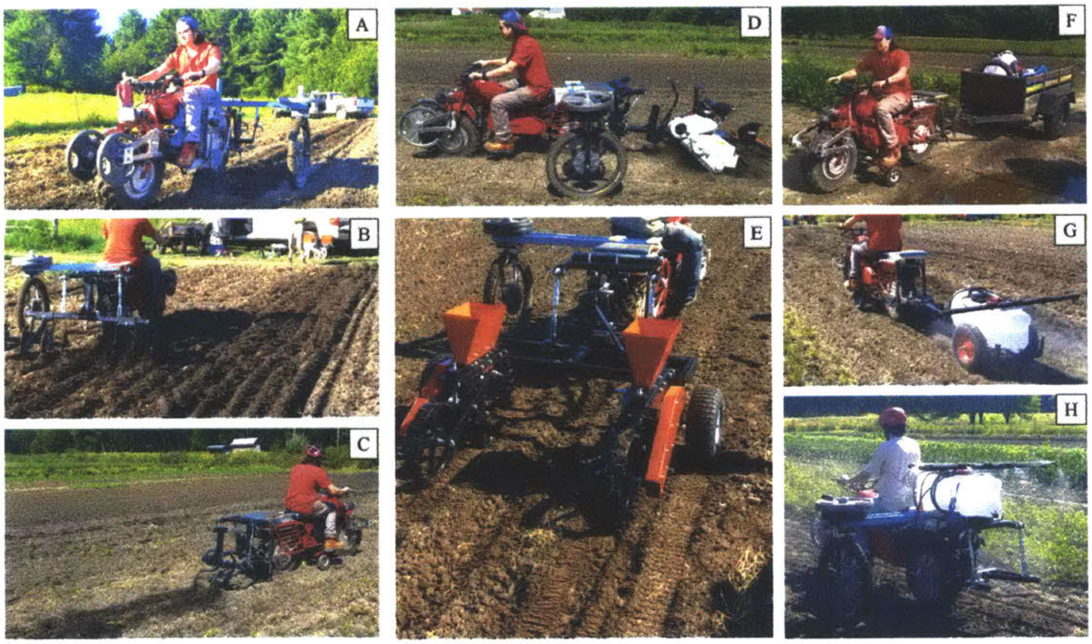


Figure 4-8: Images of the researchers performing key operations of interest to Indian farmers with Bullkey. A) Plow B) Disc harrows C) Cultivator D) Rotavator E) Planter F) Trailer G) Sprayer on its trailer H) Sprayer on motorcycle.

4.4.1 Methods - Field Validation in Massachusetts

Field tests of the Bullkey prototype were performed at a small farm in Carlisle, MA with silt loam and sand loam soil. The farm sells locally grown organic produce in the area, including berries, eggplant, leafy greens, vegetables, peppers, and cantaloupe. The goals of the field tests in Massachusetts were threefold: to validate the feasibility of the concept vehicle for farming, to capture media to show farmers in India during interviews, and to receive hands-on feedback from two Peruvian small farmers temporarily working at the farm. The prototype's tillage drawbar ability was earlier tested in detail as seen in [45].

Bullkey's ability to perform the previously described farming operations needed by small Indian farmers was assessed by using the vehicle for plowing, disc harrowing, rotavating, planting, intercultivation, spraying, and trailer pulling operations per the specifications of [88], a popular Indian handbook on farm machinery. The operations tested represent the key needs of small Indian farmers with best practice settings. The specifications were selected to ensure that the operations were representative of how Indian farmers would use Bullkey, so its success in performing the operations as specified would demonstrate its suitability for meeting the needs outlined by farmers. The test dimensions are summarized in Appendix C1 and are also described here.

Primary tillage consisted of plowing with 20 and 30 cm wide furrowing bottoms (one at a time) at depths between 10 and 20 cm. These operating dimensions were enough to generate drawbar forces in excess of 70% of the vehicle's weight (beyond what would be expected of a conventional tractor [115][13]) and generally operate the tires at 10 to 20% slip. These tests are discussed in detail in [45].

Secondary tillage included disc harrowing and rotavating to break up soil clumps and prepare seed beds. Disc harrowing was performed by two sets of four 30 cm diameter notched discs. The two sets were angled at 120 degrees relative to each other and covering a 1.37 cm width, forming a forward pointing "V" centered along the motorcycle's drive line. The discs were operated at 10 cm depth to till rows of approximately 50m length before being lifted by the three-point hitch at row ends to allow for no engagement during headland turning. The rotavator consisted of 24 blades 30 cm in length, organized in sets of four to form six rotating crosses (see Fig. 4-7). The machine was set to cut at 12 cm depth and was towed through 50 m long field rows. Motor-to-blade and blade-to-soil engagement were controlled by separate, manually actuated levers.

Post seed-bed preparation operations included planting, and simulated crop care (intercultivation) by an s-tine cultivator and a spraying unit. The planter utilized two seed drills spaced to plant rows 90 cm apart. One was filled with soy bean seeds and one with black beans. Seeds were in inserted into soil every 10 cm at 3 cm depth. Insertion depth was controlled by Bullkey's three-point hitch mechanism. The cultivator utilized two S-shaped tines at 2 to 6 cm depth for 50 m rows. The tines were 2.5 cm wide and set at 25 cm apart. Towing the 60 L sprayer tank was done with the outrigger arm and balance board. A 1.68 m wide sprayer boom with four nozzles was set at 40, 160, and 210 cm heights - representing heights valuable for vegetables crops as well as tall crops in the late stages of their growth.

Finally, a trailer was towed with the Bullkey prototype as a test, and to haul equipment to facilitate other tests. The trailer measures 1.4 m long and gave the vehicle an overall length of 5.4 m. Its base mass was 225 kg and it was loaded with at least 200 kg of equipment, then driven at up to 20 km/h. It was attached to the ball hitch at the rear of the motorcycle.

4.4.2 Massachusetts farmer interviews

Two Peruvian farmers who typically farm with animals in their home country attended the field tests in Massachusetts and provided feedback (Farmer interviews were approved by MIT's Committee on the Use of Humans as Experimental Subjects). One was a terrace farmer from the Andes who grows potatoes, corn, pumpkin, wheat, barley and quinoa. His crop rows are usually 10 to 15 m long. The second farmer was a jungle farmer who grows fruit trees, especially papaya. His crop rows are usually 15 to 20 m long. Both had been farming for about 25 years with heavy dependence on animal and manual labor.

After two field days of testing, the farmers were interviewed for 90 minutes at the end of the second day. They were asked the same questions as farmers in India (Appendix C3) with one exception - due to market differences, instead of being asked to estimate a price they would purchase Bullkey for, they were asked about the likelihood that they and their neighbors might purchase Bullkey if it were available. This questionnaire is discussed more in the next subsection.

4.4.3 Indian farmer interviews

Twenty-four Indian small farmers who use bullocks and/or small tractors were interviewed one-on-one in the states of Gujarat, Karnataka, and Tamil Nadu (Farmer interviews were approved by MIT's Committee on the Use of Humans as Experimental Subjects). Their median farm size was 2.4 ha and 63% of the farmers currently utilize bullocks. Twelve different crops are grown by the farmers interviewed, including: cotton (16 farmers), maize (10), wheat (9), peanut (8), onion (7), chilli (7), watermelon (5), and rice (3). These crops represent low vegetable crops, tall crops, and wide creeper crops - which account for the types of the nine major crops of India [27].

Indian farmers were interviewed individually for 45 to 90 minutes of conversation guided by prepared questions that can be separated into five categories: farm dimensions, demographic, farm tool perception, likelihood of adoption, and comments on prototype shown. Farm dimension and demographic questions were closed form but sometimes followed up by impromptu questions to inquire more about an unexpected response. Farm tool perception and comment on prototype questions were open ended with the intention of gaining insights into the user needs and if they were met by the proposed tractor. Finally, numerical questions were asked to the farmers to suggest an accessible purchase price as well, and to, using a Likert scale, rate their likelihood of using the tractor for different operations. Questions asked to farmers are provided in Appendix C3.

To better explain to the farmers the functionality of Bullkey, they were provided with a graphic booklet during the interview. The booklet contains four sections: a cover page showing the Bullkey prototype performing all operations, a graphics-based overview page summarizing the tractor's capabilities, more detailed pictures of the prototype performing each operation, and an overview of the balance board design with its usage scenarios. The booklet was described to farmers via a translator expert in farming. The description typically took about 20 minutes and included answering questions from the farmer. The booklet supplied to the farmers is provided in the Appendix C4 Figs. 6-2 to 6-7.

4.5 Results - Field Validation of Operations and Assessment Interviews

4.5.1 Field Validation in Massachusetts

Operations performed in field tests with the Bullkey prototype demonstrated its ability to satisfy the needs of small Indian farmers. Bullkey performed the required operations per the specifications of the guide, Prasad Singh's Indian Farm Machinery handbook [88], demonstrating that it can do the operations identified in Section 4.2.

The field tests suggested that Bullkey was comfortable and easy to set up to perform various farm operations. When plowing, the tool could be comfortably inserted into soil and extracted from the soil by the driving operator. The rotavator's 38 cm diameter pneumatic wheels always remained in contact with the ground and were used to adjust cut depth when the tool was engaged. The rotavator could also easily be towed by the Bullkey prototype at 15 to 20 km/h between fields. Rows of 50 m length were planted and the planter could be fully lifted (including wheels) by the Bullkey prototype at row ends to facilitate turning (with appropriate front wheel ballasting). The trailer was used to easily carry equipment from the farm parking area to field-side. The trailer could be comfortably towed using the outrigger arm or balance board, even when loaded.

Testing the Bullkey prototype highlighted some potential areas for improvement in future designs. With the prototype tractor, at least 55 kg of ballast on the front wheel was required to prevent front end lift when the planter was fully raised. In a more refined version of the prototype this could be reduced by placing the three-point hitch closer to the rear axle. During testing, drivers would naturally shift their weight forward on the motorcycle to prevent front end lift when possible. While the balance board worked comfortably for towing the trailer or sprayer, using it with the cultivator tines was viable but challenging due to the raised vehicle center of mass and the soil reaction forces generated by the engaged tines.

4.5.2 Results - Massachusetts farmer interviews

After observing the Bullkey field tests, two Peruvian farmers who have typically farmed with draft animals in their home country were interviewed. Overall, both farmers reported that they thought Bullkey was very usable for its intended operations and expressed their interest in looking to purchase it for their home farms if it were available. The farmers thought Bullkey would be easy to integrate into their work flow in Peru and thought there was a high likelihood (5/5) that the vehicle could be locally adopted in Peru (Fig. 4-9).

The mountain farmer thought that Bullkey was particularly valuable because of its predicted low price and its improved mobility compared to conventional tractors. He also appreciated Bullkey's light weight, which he said would make it easier to transport up rugged mountain trails, and that adequate temporary bridges could be constructed to move it across rivers, which is not possible with conventional tractors. The jungle farmer thought general driving training would be easier than on a typical tractor since most people he knows in Peru drive motorcycles, and thus would likely find the idea of using one on the farm attractive. He also valued that Bullkey could access spaces that a conventional tractor would not be able to and needed less space to turn. The farmers independently identified many of the original design requirements for Bullkey - road utility, turning radius, purchase cost, and vehicle size - as attractive features. They also suggested benefits of the design not previously identified, like that its light weight could enable it to reach geographically inaccessible regions. The

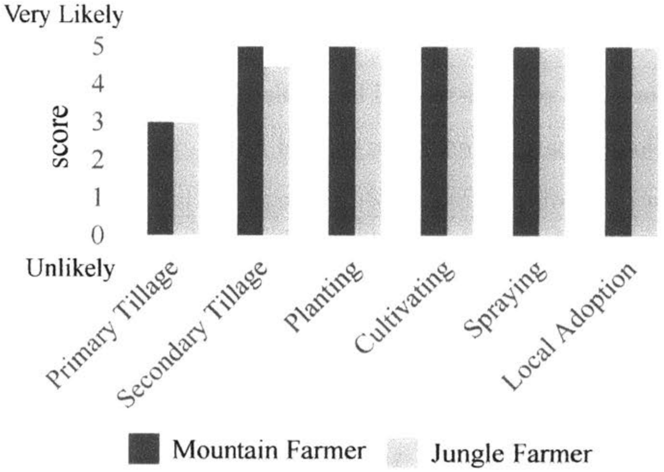


Figure 4-9: Self-described likelihood of two interviewed Peruvian farmers for doing an activity with Bullkey. These farmers were present to observe while Bullkey performed every operation described in this Chapter. "Local Adoption" refers to the likelihood that they and their neighbors would use the tractor for farming in Peru.

farmers' interest in these unique design aspects suggests that Bullkey has use for resource limited small farm settings globally, even though the initial interviews that drove the design requirements were conducted in India.

The two farmers were generally confident in Bullkey's ability to perform the outlined farm operations (Fig. 4-9) and rated the likelihood they would use Bullkey very highly for plowing (average 5/5), cultivating (5/5), spraying (5/5), and secondary tillage (4.5/5). Both farmers thought Bullkey was excellent for planting operations, and one noted that he was particularly happy with the consistent seed depth and spacing the tractor was able to achieve. Both farmers thought the tractor very convenient for de-weeding with a cultivator and would enable them to spray more conveniently than they have been able to before. The mountain-based farmer said that where it is hard to access crops over 1 m with a conventional tractor, he thinks Bullkey would be "perfect" in those conditions. He said that he valued that Bullkey could spray both tall crops and close to the ground. The jungle-based farmer liked the sprayer setup with its tallest arms and thought it was well suited to the trees he grows.

Informal discussions with American farmers attending the field tests suggested that Bullkey could also be valuable in certain situations in the United States. One American farmer said that since they grow many crops in a relatively small farm, conventional tractors available to them in the USA are often too large for their row lengths and spacing. This forces them to use more manual labor than the farm manager would like and they said that a design like Bullkey could be a valuable product for them for farming in Massachusetts.

4.5.3 Feedback from Indian farmers

Overall, Indian farmers were attracted to the possibility of a low cost alternative to tractors that could access narrow spaces and spaces between tall crops like bullocks but was less expensive to maintain and could work longer hours than animals. Sixty-seven percent of farmers said that a fault of conventional tractors designs is that they are too big for intercultivation. Ninety-two percent of farmers were satisfied with the Bullkey's width and 88% were satisfied with Bullkey's weight, two of the major design differentiators with conventional tractors.

Indian farmers saw a financial value in Bullkey. On average, they said they would be willing to pay 123,000 INR for Bullkey (standard deviation: 27,500 INR, min: 85,000 INR, max: 200,000 INR). One of the 24 interviewed farmers chose not to answer the question on price point. Based on the initial user needs interviews prior to its inception, Bullkey was targeted to have a price point of 100,000 INR. The assessment interviews suggested that the final design would be valuable to farmers at a higher price point, which makes a product-version of Bullkey more financially viable. The final price point of Bullkey can only be determined once more is known about its manufacturing and distribution costs.

All interviewed farmers saw Bullkey as a viable road vehicle as a two-wheeled motorcycle, which was an important design requirement. The average required minimum top speed reported was 33 km/hr (min: 17 km/hr, max.: 50 km/hr). The farmer who was willing to accept the slowest top speed said that he preferred a slow vehicle so he would not have to register it with the government. The preference for a petrol or a diesel engine was evenly split. A larger concern for farmers than fuel type was maintenance cost and fuel consumption.

The interviewed farmers thought Bullkey would be able to easily perform all tasks between planting and harvesting, including intercultivation and spraying (Fig. 4-10). Farmers rated tasks that would normally be done by bullocks as those they would be most likely to use Bullkey for - planting (4.7/5), inter-cultivation (4.8/5), and spraying (4.9/5). Farmers rated Bullkey well but not as highly for tasks that they would use rented medium size tractors for - primary tillage (plowing) (3.75/5), secondary tillage (3.8/5), and trailer operations (4.1/5). Farmers thought Bullkey would perform better at some tasks than any alternative, most commonly: intercultivation (80%), spraying (75%), ownership costs (66%), and small field seed drill (33%).

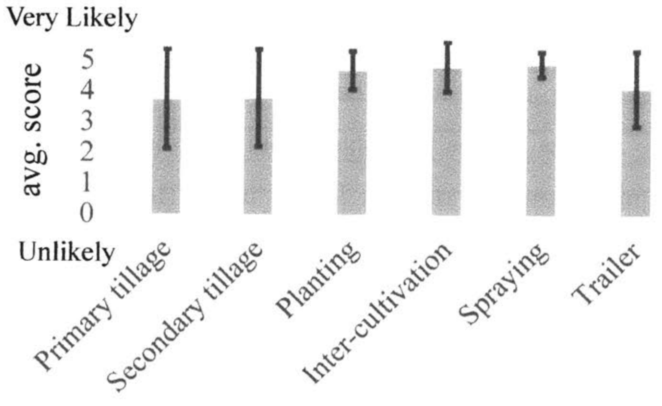


Figure 4-10: Self-described likelihood of interviewed Indian farmers for doing an activity with Bullkey tractor.

The farmer's feedback on the two stabilization configurations was solicited. Seventy percent of farmers preferred the outrigger arm and 30% preferred the balance board. With the balance board configuration, farmers were concerned about the total width of ground contact points for the vehicle. The balance board track width is larger than the width of one small tractor tire (which typically operates in single adjacent rows), forcing it to roll closer to the seed beds than the farmers are used to and would prefer. The balance board is too narrow and short to straddle a row of growing crop like the outrigger arm or even a tractor (if the crop is short) would. Ground contact width in a single row is important to farmers because it determines how close to the origin of the plant's roots soil compaction is occurring.

Ninety-six percent of farmers (all but one) felt confident in the viability of the outrigger arm for their operations. The unconvinced farmer was hesitant about the "too narrow" outrigger tire being able to roll on his soft soil - a concern that was also mentioned by another farmer. Forty-five percent of farmers said they would find the outrigger arm even more usable if it could have a higher ground clearance, allowing them to use it with even full grown crops. The desired height varied between 1.4 and 2.1 m. Two farmers also requested a greater range of lateral adjustment for the outrigger arm, from 0.7 to 1.4m instead of the current range of 0.9 to 1.2 m.

4.6 Discussion

4.6.1 Satisfying user needs

Originally, the major design requirements identified (Table 4.1) were related to drawbar pull, purchase and ownership cost, width, path width, turning radius, user comfort, daily work hours, and road speed. The conducted interviews showed that many of the design requirements - width, turning radius, user comfort, and road utility - have been well met. The drawbar pull requirement was validated during earlier technical assessments [45]. The interviewed farmers were delighted by Bullkey's small size, its ability to maneuver in tight spaces, and its clear road utility as a two-wheel drive motorcycle. The Bullkey prototype can travel at 45 km/hr, well above the average minimum top speed requested at 33 km/hr. While this is not the final vehicular configuration, this functionality shows that a vehicle can meet the road utility and other farming design requirements simultaneously. Farmers were generally willing to purchase Bullkey at a higher price point than anticipated, which provides added flexibility for future vehicle manufacturing considerations. Given this information and the low cost of the design, a product version of Bullkey should meet the identified purchase and ownership cost.

The three assessments presented here - field tests, and interviews with farmers in Massachusetts and India - show that Bullkey meets the intended design requirements. Feedback from interviewed farmers on how and why they would like to use Bullkey also confirmed the insights from the original user needs assessment. Some of the collected feedback suggested that Bullkey may have more general usability (e.g. in small farms in developed countries and mountainous regions) than originally expected.

4.6.2 Limitations and Future Work

From the functional tests themselves, the major identified areas for future improvement are moving the rear-mounted three-point hitch mechanism closer to the rear axle and lowering its center of mass. Placing the mechanism longitudinally closer to the rear axle will lower the upending moment exerted on the front wheels when lifting heavy implements like the planter. Lowering the mechanism's center of mass will facilitate using it with the balance board. These changes should be straightforward to implement in a motorcycle frame that is custom-built for Bullkey to feature three-point hitch arm pivots near the rear axle.

The farmers identified other areas for future improvement. Some of the feedback may be addressed technically and others may be addressed via clear operational instructions for the vehicle. In India, some interviewed farmers felt that Bullkey could be even narrower (for example, by allowing seating with knees together like in a scooter and/or by reducing handlebar width) or that Bullkey was too lightweight to adequately perform tillage operations. The latter group's concerns have been addressed in [45], where it is shown Bullkey can pull more per unit mass than conventional tractors. While 70% of farmers were content with Bullkey's towing capability of 600 kg, 30% wanted the ability to tow at least 1000 kg. The need to transport to centralized storage a day's worth of harvest in a single run was given as a major reason for large towing capacity. Current towing capacity is limited by the ability to quickly stop at road speeds and safely handle road speed turns with with a towed load. Towing capacity could be improved by having connectors to interface with trailers that feature an independent braking system and/or by limiting Bullkey's top speed when towing.

One farmer was concerned that the vehicle may not be stiff enough in roll to use a planter correctly, and that if the planter tracking wheels lost traction with the ground it might not seed at appropriate intervals. This did not show itself as an issue during field testing. One farmer expressed concern regarding misalignment between the implement wheels (like those of the planter) and Bullkey's wheels. They wanted alignment between the wheels to reduce the number of lanes of compacted soil on the field. One farmer mentioned that since the dirt paths around him have pronounced wheel ruts, he was unsure how the motorcycle would perform while driving on the hump between wheel ruts (potentially with the outrigger in one rut) and pulling a trailer which has its wheels in the ruts. Aligning the wheels of trailers differently relative to Bullkey could be readily achieved by laterally shifting the tow hitch mount towards the outrigger wheel or with custom implements that have a wheel layout to address this.

The Peruvian farmers suggested that users who have previously only driven draft animals may need training on which farming tools they should use, particularly for choosing a tillage tool appropriate for soil conditions. The jungle-based Peruvian farmer mentioned that he would like the option to add more than 55 kg of ballast over the front wheel in order to utilize an even larger planter with the tractor (raising the planter off the ground transfers weight away from the front wheel). Reinforcing the frame to allow for additional ballast should be straight forward in a final design.

4.7 Conclusions

This Chapter described why conventional tractors are not well suited to small farmers (<2 Ha) in India, and similar small farm markets globally. This is reflected in the majority of Indian small farmers relying on other sources of draft power, mainly bullocks and manual labor. A more suitable tractor design proposed by the author, called Bullkey, has dimensions akin to bullocks. This facilitates efficient use of scarce farmland, while retaining many advantages of conventional tractors including their lower ownership cost and longer operating hours. A Bullkey prototype was farm tested and demonstrated the ability to perform functions important to Indian farmers. At the test site, Peruvian farmers who have mostly farmed with draft animals observed field tests with Bullkey and were interviewed for feedback. They felt the design could satisfy their needs and those of their neighbors at their home farms.

Bullkey's design and its field performance, including images, were then discussed one-on-one with small farmers in three Indian states. These farmers felt Bullkey met their needs and suggested a purchase price above that which was identified as a target. The Bullkey design is well positioned to transition into a production vehicle. The design is based on well understood technologies, and the field tests and user studies presented here show that combining these technologies yields a functional farm vehicle able to operate in spaces not accessible with other options in the market.

The distribution of Bullkey could increase small farm mechanization. This would make farms more efficient in their use of resources (including labor time), increase crop production, and improve the quality of life for the farmers through reduced drudgery and increased income.

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Chapter 5

Conclusion

This thesis proposes a small tractor concept, called Bullkey, designed for small farms in low resource settings - particularly in rural India. The chapters provided a review of the evolution of the conventional tractor and why it is inadequate for small Indian farms (Chapter 2), a model of tractor physics and the user needs considered to create Bullkey (Chapters 3 and 4), the implementation and testing of a Bullkey proof-of-physics prototype demonstrating its high drawbar pull per unit mass capabilities (Chapter 3), and the creation of a Bullkey functional prototype that was tested performing key operations to Indian farmers and then evaluated by the farmers (Chapter 4).

5.1 Motivation of Research

The majority of farms in the world (84%) are less than 2 Ha in size [58]. Small farms are particularly common in India, where the average farm size has steadily decreased from 2.28 Ha in 1971 to 1.08 Ha in 2016 [75]. Most small farmers use a pair of bullocks (bovine draft animals) for all or most of their farming operations, supplementing the rest with manual labor or a hired tractor (particularly for primary and secondary tillage) [52][31]. Bullocks are compact, highly maneuverable, and have a low capital cost, making them well-suited to the technical and economic constraints of small farms. Conventional tractors, which are an icon of modern farming and typically associated with high farm yields [39], have not yet been able to reproduce these key bullock features [64][76]. As a result, farmers are constrained to the slow speed of bullocks and a lack of access to suitable modern, more effective made-for-tractor tools [31][30].

This misalignment between the tractor and needs of the small farmer is, in part, because conventional tractors were designed for a larger field size. The conventional small tractor was originally intended to operate in much larger farm holdings than what is typical around the world [44]. The conventional small tractor largely found its form in the US between 1910 and 1940 [44] [107] [77] [61] [104], where the annual average farm size since 1900 has been at least 50 times greater than the present global average. Globally, at present, 72% of farms are <1 Ha, while less than 2% of US farms have been <1 Ha since 1900 [58] [33] [14] [99] [59]. As a result, for many small farmers, replacing their bullocks with a conventional tractor would require adjusting crop spacing (particularly for crops taller than a tractor's ground clearance), or sacrificing farmland as headland area to give the tractor space to maneuver at row ends. It might also require improving road access to their field due to the tractor's larger size and poorer off-roadability.

5.2 Contributions from Research

5.2.1 Evolution of conventional tractor

Chapter 2 explains the origin and merits of the dominant farm tractor design, which has endured since the 1940s. Understanding the origins and rationale for this dominant design enables engineers to appreciate its merits, and understand its drawbacks, which could be addressed in future designs. Additionally, the methods used in this research to study tractor evolution are applicable to the study of other products with a longstanding dominant design. Two themes are covered in Chapter 2: first, the historical context that directed the farm tractor's design evolution is presented; and second, a terramechanics-based tractor model is used to analyze why the dominant design is conducive to good performance. The prominent characteristics of the dominant tractor design are its weight distribution, wheel layout, tool location, and construction. It's weight distribution maximizes drawbar pull by placing 70 to 80% of the total vehicle weight on the rear wheels. Shifting the weight forward reduces pulling force while shifting it backward produces a negligible increase in pulling capacity while dangerously increasing the risk of upending the tractor. The tractor has four wheels arranged in a rectangular pattern - the rear wheels are driven while the front ones are usually idle. Rear wheels are of large diameter to increase ground clearance and tractive efficiency. Front wheels are of small diameter to allow for a large steering angle despite a narrow track width. A narrow track width reduces the space required for making a U-turn at field ends and improves access to farm spaces. Inline front and rear wheels are desirable for ease of driving between rows and to best harness soil compaction. Attaching implements behind the rear axle leverages tillage forces to increase maximum drawbar pull and enables using large tools. The tractor's crankcase and transmission housing are structural components - this reduces mass and manufacturing complexity.

5.2.2 Design of Bullkey for small farms

Chapter 3 describes the motivation, design, and testing of a specialized farm tractor designed to replace draft animals in small farms, particularly in rural India. The vehicle is specially suitable for this use environment because it matches the low capital cost of animals and has their unique ability to operate in narrow inter-crop-row lanes while retaining the major advantages of tractors, such as low maintenance cost and reduced operator physical effort. The presented vehicle was designed based on user needs and our implementation of a detailed terramechanics model. The proposed tractor design improves drawbar pull per unit mass compared to conventional tractors by applying nearly the full vehicle's weight on the drive wheels, placing drive wheels inline, and locating the tillage tool between both axles. A proof-of-physics prototype of this design was built based on an all-wheel-drive motorcycle retrofitted with an outrigger wheel for stabilization, and a tillage tool attachment point between the front an rear axles. The prototype was instrumented to measure drawbar pull and tire slip to validate the terramechanics model and quantify traction performance. During field tests on a working farm, the vehicle successfully operated in the narrow spaces between growing crops that would typically not be accessible to a low cost ($<$ 15 hp) conventional small tractor. Traction experiment results showed that the proposed design is capable of pulling with more drawbar force per unit mass than conventional tractors and that this performance can be accurately predicted by the provided physics model. Initial farmer feedback on the design confirmed its high potential for performing tillage in small farms and other farming operations with further improvements.

5.2.3 Viability of Bullkey for replacing bullocks

Chapter 4 describes the design, functional testing, and user feedback for a tractor specialized for small farms in low resource settings, particularly India. The presented tractor is unique in its ability to compete with bullocks' physical dimensions, pulling performance, and sale price, while retaining key tractor advantages like compatibility with modern tools, low maintenance costs, and reduced drudgery. This tractor features motorcycle-like controls and seating, inline drive wheels, stabilization via an outrigger arm or a specially-developed balance board attachment, and the ability to attach implements ahead or behind the rear axle. A prototype of the tractor was built and its ability to complete key farming operations was demonstrated in a Massachusetts farm. The vehicle was able to complete plowing, disc harrowing, rotary tilling, planting, cultivating, spraying, and towing of a trailer per Indian industry specifications. Two Peruvian small farmers drove the vehicle and thought it could be a valuable replacement for draft animals in their domestic farms. A study was conducted to assess whether the vehicle would meet the needs of small and marginal farmers in India with 24 farmers in Karnataka, Gujarat, and Tamil Nadu. Farmers were shown photos and videos of the operating vehicle and performance data, and were asked numerical and open ended questions about the vehicle and their general farming experiences and needs during 45-90 minute one-on-one interviews. Indian farmers interviewed generally reported that the prototype tractor to be would meet their needs and suggested they would be willing to purchase the vehicle for around 123,000 Indian Rupees, about 22% higher than the price target with which the tractor was designed. The interviewed farmers' reported an average likelihood of 4.8/5 that they would use the vehicle for planting, inter-cultivation, and spraying and an average likelihood of 3.8/5 that they would use the tractor for primary or secondary tillage. Overall, in this work I found that the proposed vehicle is better suited than conventional small tractors to replacing draft animals in small Indian farms.

5.3 Future Work

Future work should demonstrate the Bullkey tractor on-site in small Indian farmers for the end users and other key stake holders to evaluate. This will give the stakeholders a clearer understanding of how Bullkey performs, allowing the researchers to collect more accurate data on Bullkey's likelihood of market success. Before demonstrating the tractor in India, the major opportunities for improvement are in the attachment interfaces for farming implements.

Improvements can be made to both rear and central tool attachment points. The rear tool attachment three point hitch (an industry standard) can be kept mostly as is but should be mounted closer to the rear axle - this will reduce the amount of front wheel ballast needed when lifting heavy implements. The central tillage tool attachment could be improved in its motion mechanics and the control input ergonomics.

It's motion mechanics should enable two things: the weight of the tractor to preload the tool during initial insertion into the soil and, once soil draft is pulling the tool down, for the tool to sink into the soil to user-set depth without constant user input. The former is already present in the current design and is important because of the light weight tools Bullkey is expected to use; the latter is not present in the current design and is important for presenting the user with a familiar and user-friendly work process. In a conventional tractor, tillage tools can be lifted out of the soil but not pushed into the soil - tools sinks into the soil to a user-set depth initially under their own weight and, once deep enough into the soil, due to soil draft forces. However, conventional tractors utilize hydraulic power that allows for heavier tools than a human operator can lift in manually powered mini tractor systems. Mini tractor operators in India hire an additional laborer to stand on the tool during insertion into the soil, effectively increasing the tool's weight, and then step off the relatively lightweight tool when it must be raised (Fig. 5-1). Hiring this extra laborer adds to operating costs.

5.3.1 Central tillage tool improved mechanism

The current Bullkey tillage tool control mechanism is non-backdriveable in both directions (upward and downward). This is behavior stems from it being powered by a hand cranked worm gear that drives the pinion gear in a rack and pinion system. It allows applying the tractor's weight to the soil-working tool in much the same way as a typical vehicle lifting jack pushes on the ground. However, it also prevents soil draft forces from moving the tool downward to a pre-set depth without constant user input. Instead, the user must manually crank the mechanism until it reaches the desired depth.

This could be improved by a ratchet-wrench-like direction switch on the crank handle, making the system non-backdriveable in only one user-selected direction. During insertion the user should set the switch to be able to push the tool down but not pull it up. In other words, during insertion turning the crank handle increases the minimum tool soil depth but does not interfere with soil draft forces pulling the tool further down. Then during lifting of

Figure 5-1: Images of people riding on tools to help them sink into the ground. These are tools mounted on conventional three point hitch linkages but that are manually operated.

the tool, the direction switch should be flipped to now allow the user to pull on the tool and raise it out of the soil. During active tillage, the user can flip the switch as needed to adjust tool depth. The tool should have an adjustable stop point to set maximum tool depth. This stop point could be achieved by a sliding collar on the tool rack or by a rack with holes for pin that limits motion.

If the current tool control mechanism is to be implemented, another improvement to explore is raising the crank handle by about 30 cm. This would improve the mechanism's user ergonomics by not requiring the operator to bend down when turning the crank handle. To explore this adjustment a simple fit test device able represent raising the crank handle by 3 to 60 cm was installed on the Bullkey prototype (Fig. 5-2A). Two researchers between 167 cm and 180 cm then tested raising and lowering the device's crank handle, agreeing on a most comfortable height 31.5 cm above the current height. This height allowed them to turn the crank handle in a comfortable riding position (Fig. 5-2B) instead of having to bend down as must be done on the current prototype (Fig. 5-2C).

Alternatively to incorporating a ratcheting feature on the current mechanism, a new mechanism with a motion path which intrinsically leverages the tractor weight for tool insertion could be investigated. In this design the tool would move backward and downward

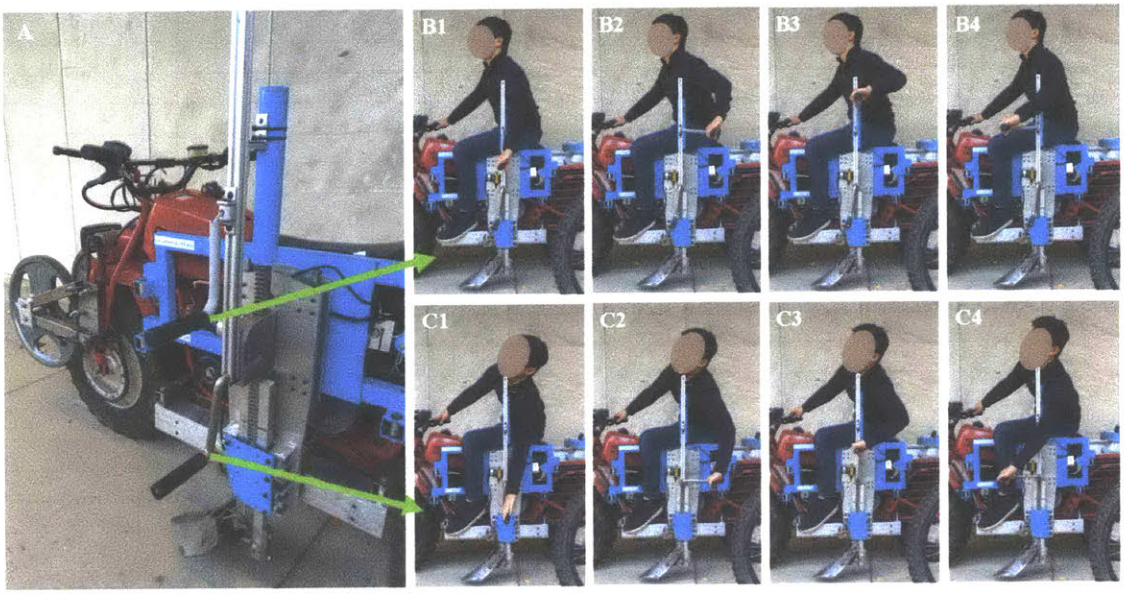

Figure 5-2: Tests to explore crank handle height. (A) a simple device to test crank handle heights up 60 cm higher than the current design. (B) The user's motion with a handle height ~31.5 cm higher than the current design. (C) The user's motion with the current handle height.

during insertion. Therefore the soil drag forces pushing the tool back are now also pushing it down (a similar working principle to a typical door stop). By contrast, a conventional three point hitch inserts the tool down and forward (see Fig. 5-3). An improved tool motion path for small tractors with low lifting strength should do two things: 1) Insert the tool into the soil downward and backward, thus utilizing the torque created by the soil drag force. 2) Lift the tool upward and backward - thus allowing the tool to reverse into the furrow (i.e. the rut it created) during lifting and reducing the amount of soil that must be disturbed to lift. Some strategies for achieving this motion path are discussed in Appendix D.

5.3.2 Next steps for distribution of Bullkey

The current Bullkey prototype has important areas to be improved for mass manufactured and distribution. This areas for improvement mainly revolve around improvements the limitations of the prototype caused by its requirements to be instrumented and viable for being manufactured by the author in a small machine shop. The central tool attachment should be made more compact and the rear tool attachment should be placed closed to the rear axle. As suggested by users, the outrigger arm should have greater adjustability laterally

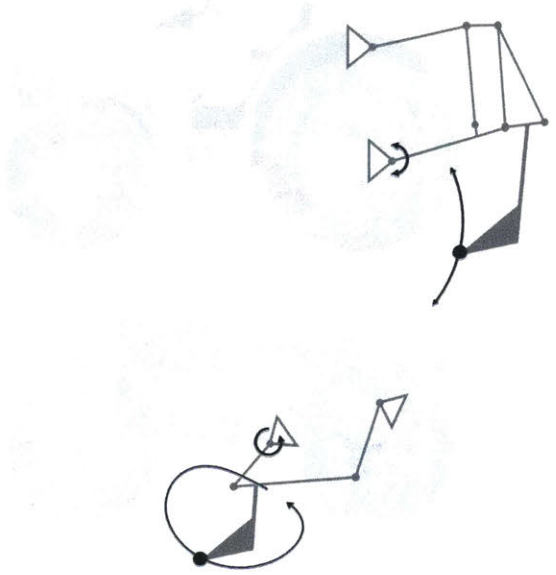

Figure 5-3: The conventional tool motion path (top) compared to the tool path proposed by the authors (bottom). The latter is well suited to very small tractors since it requires less force to operate.

and vertically to suit all crops. The balance board could be improved with an alternative mechanism that still exploits the same principles. Finally, a new vehicle platform should be built from the ground up to consider safety and have a reverse gear.

The current tool attachment mechanisms are unnecessarily large. The central tool attachment currently occupies about half the length of the vehicle, this was to facilitate instrumentation and is unnecessary for production. As discussed in Section 5.3.1, the mechanism could be made very compact by consisting only of a narrow jack. This would liberate more space for the user to comfortably straddle the motorcycle frame with their legs. The rear tool attachment method on the prototype was limited by the attachment points on the base ROKON vehicle. A production attachment system should be moved closer to the rear axle of the motorcycle, this would improve the ease-of-use for heavy rear-mounted tools and make the tractor more compact.

The proof-of-concept balance board shown in this thesis is functional and has high potential to be a viable implementation. However, it is not a formally optimized design in dimensions or mechanical layout - that optimization is left for future work. For discussion of design challenges and freedoms in a balance board, I present an alternative design that improves clearance to the motorcycle frame, eliminates side-to-side motion during turning, and allows reversing without the balance board position being unstable. This alternative design replaces the ball hitch of the implemented design with four to five pin joints. This alternative design has advantages and disadvantages compared to the implemented design. In brief terms, the current design is simpler but its motion is less ideal.

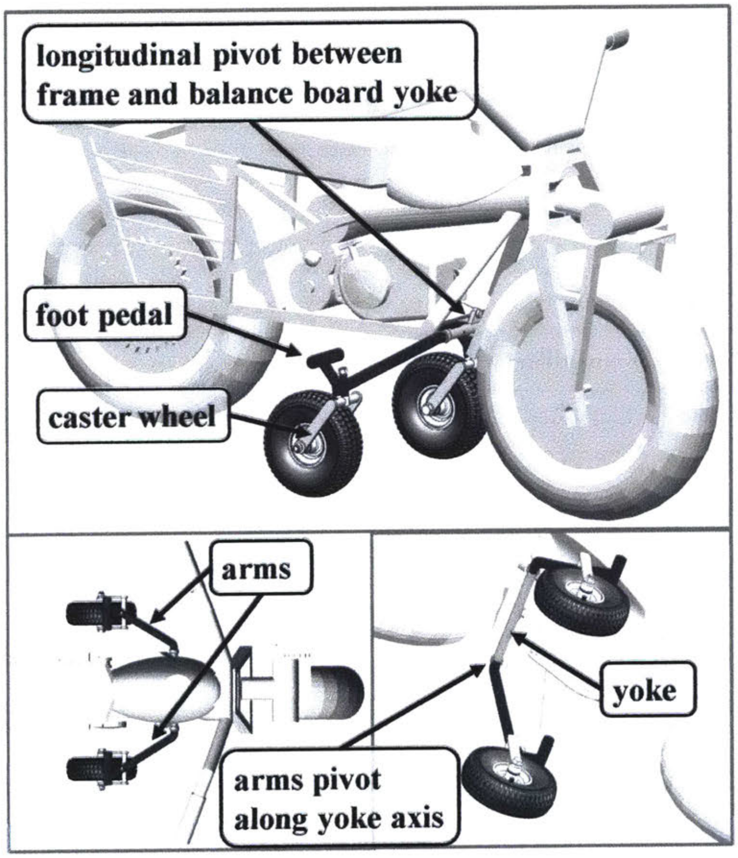

Figure 5-4: AN ALTERNATIVE BALANCE BOARD DESIGN CONCEPT ALSO CREATED BY THE AUTHORS. The two arms could be rigidly coupled to rotate together (four total pin joints) or independent (five total pin joints). The arms are assumed to be rigidly coupled.

Looking to the future, it would be interesting to consider making this tractor electric if solar panel and battery technologies become capable of sustaining its performance at a low cost. Bullkey's two-wheel drive transmission could be simplified by having two independent electric motors, one for the front wheel and one for the rear wheel. Additionally, this would enable the implementation of a computer-controlled traction control system that further improves Bullkey's drawbar pull capabilities. Batteries could be placed low on the vehicle to achieve a low center of mass and their weight would contribute to improving traction. The tool control systems could also be electrically powered.

5.4 Conclusion

In this thesis a tractor design specialized to small Indian farms was created and prototyped. This tractor is called Bullkey and utilizes inline drive wheels, a centrally located tool, and stabilization fitments that do not interfere with its ability to access narrow spaces between crop rows. The drive wheel and tool locations augment its traction performance, allowing it to maintain a pulling performance comparable to bullocks while being sold at a lower price than conventional tractors. Accessing narrow inter-row spaces is a key advantage of bullocks over conventional tractors; Bullkey's ability to replicate that accessibility increases its value to farmers and enables it to fully replace bullocks.

To study existing tractor designs and explore ways to augment Bullkey's traction performance in a narrow package of dimensions comparable to bullocks, a tractor physics model was implemented. Leveraging the model, the Bullkey design was identified and a proof-of-physics prototype created to test its traction performance and to confirm the modelling behind it. This prototype validated the Bullkey's high drawbar pull per unit mass performance and ability to access narrow inter-row spaces between growing crops.

After validating the performance of the Bullkey, the prototype was modified to improve its overall usability and allow it to perform farming operations key to Indian farmers. After these modification, the Bullkey demonstrated in field tests its ability to perform the required operations. Afterwards, the Bullkey design was discussed one-on-one with 24 Indian farmers in their home villages. The results from these interviews showed that farmers believed Bullkey could replace bullocks in their farming operations and that their suggested purchase price was higher than the sale price Bullkey was designed for.

The Bullkey design has high potential for productization. It is designed to fulfill a well documented user need, it is built on solid engineering principles, and the target users have expressed an understanding of its advantages as well as an interest in purchasing it for a price higher than its initial target sale price.

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Chapter 6

Appendix

Appendix A: Chapter 2 notes

It is the authors' intent that these tables will provide engineers with context to better understand the tractors studied in Chapter 2. Table 6.1 are tractors that were evaluated for their key innovations or historical significance. Figure 6-1 shows images larger images for these tractors. Table 6.2 shows production tractors with the vehicle layouts discussed in Chapter 2.

Manufacturer	Model	Years	Engine	Mass	Price (2017)	Units Made
Ivel	"tractor"	1902-1920	18hp	1814kg	£300 ($43,630)	900
Hart-Parr	30-60	1907-1918	60hp	9120kg	$2,600 ($64,030)	3,798
Ford	T	1908-1927	22hp	660kg	$360 ($5,067)	14,689,525
Avery	Farm & City	1909-1915	36hp	2100kg	$2,500 ($67,750)	N/A
Bull	Little Bull	1913-1915	12hp	1315kg	$335 ($8,450)	3,800
Wallis	Cub	1914-1918	44hp	3855kg	$2,480 ($55,495)	660
Moline	Universal	1915-1918	27hp	1630kg	$1,325 ($18,105)	20,000
Nilson	20-40	1916-1929	40hp	2380kg	$925 ($33,230)	N/A
Square Turn	18-35	1917-1925	35hp	3538kg	$1,875 ($22,900)	approx.700
Fordson (Ford)	F	1917-1928	20hp	1215kg	$395 ($5,760)	755,278
Int. Harvester	15-30	1921-1928	30hp	2653kg	$1250 ($17,905)	157,366
Int. Harvester	Farmall Reg.	1924-1932	20hp	1655kg	$925 ($13,530)	134,647
Allis-Chalmers	U	1929-1952	20hp	2086kg	$125 ($21,240)	19,009
Ford	9N	1939-1942	20hp	970kg	$585 ($10,291)	99,002

Table 6.1: Production data for vehicles in Figure 3 of Chapter 2.

Figure 6-1: Larger images for some tractors that introduced innovations or have historical significance as discussed in Chapter 2.

Appendix B: Chapter 3 notes

Appendix B1: Breakdown of costs for farming with bullocks or conventional tractors in Indian small farms

Aspect	Variable	Tractor	Bullock Pair	Units
Capital Cost	C	200000	80000	INR
Principal on Loan	P	20	N/A	% of C
Interest on Loan	I	16	N/A	% of C
Annual operating cost 1 hectare	O	12500	60000	INR/year
Time before replacement	T	10	13	years
Resale value when replaced	R	50000	0	INR

Layout	Manufacturer	Model	Years	Motor	Mass
A	Twin City	12/20	1919-1926	27hp	2268kg
	Russell	Model C 20/40	1919-1924	40hp	3450kg
	Huber	30/60	1912-1916	60hp	5000kg
B	Hart Parr	20-40	1912-1914	40hp	6000kg
	Samson	Sieve Grip	1914-1918	25hp	2630kg
	Wallis	Cub	1913-1917	44hp	3855kg
C	Bull	Little Bull	1913-1915	12hp	1800kg
	Case	10/20	1914-1918	20hp	2304kg
D	Hart-Parr	Little Devil	1914-1916	22hp	3015kg
	Common Sense	15/25	1914-1918	25hp	2700kg
	Emerson Brantingham	Model L	1916-1918	20hp	2500kg
E	Gray Tractor	Model B	1914-1918	25hp	2500kg
F	Joilet	Bates Steel Mule F	1915-1937	30hp	2200kg
G	Beltrail	Model B 12-20	1917-1920	20hp	1500kg
	Tom Thumb	12-20	1917-1920	20hp	1900kg
	Joilet	Bates Steel Mule C	1911-1919	30hp	2200kg
H	Yuba	20-35	1911-1916	35hp	3500kg
	Blewett	Webfoot 53	1920-1922	53hp	4500kg
	Holt	75	1913-1924	75hp	10432kg
I	Killen Strait	30hp	1917-1919	30hp	2600kg
J	Killen Strait	15-30	1913-1917	30hp	4300kg
K	Lawter	18/38	1914-1918	38hp	2950kg
	Boring	12/25	1916-1922	25hp	2050kg
	Hackney	Auto-Plow	1916-1922	36hp	3630kg
L	S.L. Allen	Planet Jr.	1920-1935	2.31hp	250kg
	Moline	Universal	1914-1918	27hp	1630kg
	Allis-Chalmers	6-12	1919-1926	12hp	1134kg
M	Acme	12-24	1918-1919	24hp	1450kg
N	Rumely	8-16	1917-1919	16hp	2600kg
O	Victor	Victor	1919	34hp	1950kg
P	Bean	Track-Pull 6/10	1918-1920	10hp	1400kg
Q	Samson	Iron Horse D	1918-1923	26hp	850kg
	Olmstead	Four Wheel Pull	1914-1920	50hp	3000kg
R	Fitch Four Drive	20/30	1915-1918	30hp	1360kg
S	Buckeye	Junior	1912-1915	25hp	2500kg
T	Heer	20-28	1912-1916	30hp	2000kg
	Nelson	20-28	1917-1924	30hp	2000kg
U	Rumely	Ideal Pull	1916-1917	16hp	1500kg
V	Post	12-20	1918-1920	20hp	1500kg
W	John Deere	Dain	1918-1919	24hp	2086kg
X	Bullock	Creeping Grip	1916-1919	20hp	3270kg

Table 6.2: Layouts of Chapter 2 matched to production vehicles.

To calculate the costs of ownership for 15 years, the equations below were used with values from Table 6.3. Yearly maintenance costs were assumed to remain constant through time for both tractor and animals. At the end of their useful life as draft animals, bullocks cannot be sold in India [22] but reasonably maintained tractors can be sold for at least 25% of their original value after 10 years [47]. The Bullkey tractor is assumed to have equivalent ownership costs to a conventional tractor but with an estimated capital cost of 100,000 INR and a corresponding resale price of 25,000 INR after 10 years. The capital cost for Bullkey is a target as mentioned by farmers [46], not a final price.

Total ownership costs for tractor or bullock pair bought up front:

ownership cost total for 15 years $= tO + 2C - R$

Total ownership costs for tractor financed:

ownership cost total for 15 years$= tO + 2C - R + 2(C - P)I$

Appendix B2: Average drawbar pull results compared to model predictions

	Avg. Pull (N) [actual(model)] and Model Error (%) at Tire Slip							
Mass (kg)	**10% slip**		**15% slip**		**20% slip**		**25% slip**	
Fr./R	pull	error	pull	error	pull	error	pull	error
95/96	1162(849)	-26.9	1300(1161)	-10.7	1472(1391)	-5.5	1513(1564)	3.3
95/96	1297(849)	-34.5	1333(1161)	-12.9	1350(1391)	-3	1479(1564)	5.7
95/137	1281(1086)	-15.2	1313(1441)	9.7	1478(1697)	14.8	1425(1882)	32
136/96	1360(1096)	-19.4	1461(1448)	-0.9	1495(1698)	13.6	1612(1878)	16.5
136/96	1324(1096)	-17.2	1516(1448)	-4.4	1509(1698)	12.5	1616(1878)	16.2
136/137	1436(1326)	-7.7	1624(1735)	-6.8	1688(2015)	19.4	N/A(2211)	N/A
136/137	1526(1326)	-13.26	1623(1735)	-6.8	1955(2015)	3.1	N/A(2211)	N/A
136/153	N/A(1431)	N/A	1989(1923)	-3.3	2026(2148)	6	2158(2347)	8.8
136/153	1825(1431)	-21.5	2009(1923)	-4.3	2056(2148)	4.5	2141(2347)	9.6
152/153	1999(1653)	-17.3	2056(1968)	-4.3	2065(2262)	9.5	2317(2463)	6.3
152/153	1568(1653)	5.4	1694(1968)	16.2	2092(2262)	8.1	2110(2463)	16.7

Table 6.4: Summary of results from field test experiments compared to model predictions. For reference, 64% drawbar pull to mass ratio for all configuration masses is 191 kg : 1199 N, 232 kg : 1456 N, 273 kg : 1714 N, 289 kg : 1814 N, 305 kg : 1914 N

Appendix B3: Common Indian Tractor Sale Prices and Size

Make	Model	Mass	Motor	Min. Price
Jyoti	Sanedo	450 kg	12 hp	120k INR
Madhav Agro	DI 510	515 kg	10 hp	215k INR
Blue Chemp Agro	MS-120	520 kg	12 hp	170k INR
VST Shakti	MT 180 D JAI 2W	645 kg	19 hp	295k INR
VSt Shakti	MT 180D	645 kg	18.5 hp	295k INR
Kubota	NeoStar B2741 4WD	650 kg	27 hp	545k INR
VST Shakti	MT 224 1D AJAI 4WD	740 kg	22 hp	356k INR
Captain	120 DI	780 kg	15 hp	250k INR
Mahindra	Yuvraj 215 NXT	780 kg	15 hp	200k INR
VST Shakti	MT 171 DI Samraat	800 kg	13 hp	275k INR
Sonalika	GT 20 RX	820 kg	20 hp	300k INR
Sonalika	GT 22	850 kg	22 hp	343k INR
Swaraj	717	850 kg	15 hp	260k INR
Captain	200 DI	885 kg	17 hp	265k INR
Captain	200 DI 4WD	940 kg	17 hp	310k INR
Farmtrac	Atom 26	990 kg	26 hp	480k INR
John Deere	3028 E	1070 kg	28 hp	565k INR
John Deere	3036 E	1295 kg	36 hp	740k INR
Farmtrac	60	1400 kg	50 hp	630k INR
TAFE	30 DI Orchard Plus	1400 kg	30 hp	420k INR
Swaraj	724 XM Orchard	1430 kg	25 hp	395k INR
Massey Ferguson	1035 dI Maha Shakti	1700 kg	39 hp	495k INR
Eicher	364 Super DI	1710 kg	32 hp	471k INR
Massey Ferguson	1035 DI	1713 kg	35 hp	490k INR
Massey Ferguson	1134 MAHA SHAKTI	1720 kg	34 hp	470k INR
Eicher	242	1735 kg	25 hp	355k INR
John Deere	5005	1750 kg	33 hp	470k INR
John Deere	5039 D PowerPro	1760 kg	41 hp	570k INR

New Holland	3032	1760 kg	35 hp	520k INR
Mahindra	275 ECO	1760 kg	35 hp	455k INR
John Deere	5042 D PowerPro	1810 kg	44 hp	625k INR
Powertrac	439 Plus	1850 kg	41 hp	530k INR
Kubota	MU4501	1850 kg	45 hp	715k INR
John Deere	5205	1870 kg	48 hp	690k INR
Swaraj	735 FE	1895 kg	39 hp	550k INR
Powertrac	ALT 4000	1900 kg	41 hp	530k INR
Farmtrac	Champion 39	1940 kg	39 hp	490k INR
Massey Ferguson	7250 Power	1950 kg	47 hp	620k INR
Massey Ferguson	241 4WD	1950 kg	42 hp	620k INR
John Deere	5050 D - 4WD	1975 kg	50 hp	800k INR
Eicher	371 Super Power	1995 kg	37 hp	475k INR
John Deere	5045 D - 4WD	2010 kg	45 hp	770k INR
Mahindra	475 DI	2019 kg	42 hp	545k INR
Swaraj	855 FE	2020 kg	52 hp	710k INR
Mahindra	Yuvo 575 DI	2020 kg	45 hp	628k INR
Mahindra	Yuvo 415 DI	2020 kg	40 hp	570k INR
Eicher	380 Super DI	2045 kg	40 hp	530k INR
New Holland	3600 Tx Heritage Edition	2055 kg	47 hp	650k INR
New Holland	3630 TX Plus	2080 kg	55 hp	725k INR
Mahindra	585 DI Power Plus BP	2100 kg	50 hp	600k INR
John Deere	5310	2110 kg	55 hp	789k INR
Digitrac	PP 43i	2140 kg	47 hp	585k INR
Powertrac	Euro 50	2170 kg	50 hp	610k INR
Swaraj	963 FE	2200 kg	60 hp	790k INR
Kubota	MU5501	2200 kg	55 hp	870k INR
Farmtrac	45 EPI Classic Pro	2245 kg	48 hp	590k INR
New Holland	Excel 4710	2255 kg	47 hp	660k INR
John Deere	5405 GearPro	2280 kg	63 hp	850k INR

Digitrac	PP 46i	2470 kg	50 hp	630k INR
Sonalika	WT 60 SIKANDER	2520 kg	60 hp	790k INR

Table 6.5: Common tractors sold in India with their mass, engine power, and lowest typical sale price. The tractors are sorted by mass. Data collected by authors from online tractor sale websites [65, 96].

Appendix B4: Soil properties and sensors used for tests

	Soil Type		
Property	**Weak**	**Strong**	**Actual**
n	1.1	0.79	1
Cohesion (kPa)	0.6	20	3.3
Friction angle (deg)	28	18	33.7
k'_c (kN/m^2)	0.990	2354	74.6
k'_ϕ (kN/m^3)	1528	-4130	2080
Bulk density (kg/m^3)	1310	1580	1557

Table 6.6: Soil properties used to generate plots. Soils properties for limit conditions are the upper and lower strength limits of soils published soil traction parameter tables [108][9]. Actual soil strength for field tests is from matching soil type, cone penetromenter data, and soil moisture data from field test to the most appropriate soil parameters in [108].

String Potentiometer (Tool Position)	
Sensor[15]	CALT CWP-S
String Length	500 mm
Resistance Range	0-500 kOhm
Force (Tool Loads)	
Sensor[19]	DYLY 104-500
Load Range	±500 kg
Sensitivity	2.0 ± 0.05 mV/V
Non-Linearity	±0.03≤%F·S
Hysteresis	±0.03≤%F·S
Amplifier[93]	Tacuna EMBSGB200
Amplification	1&2 @550x, 3 @220x
Magnetic Proximity (Wheel Rotations)	
Sensor[6]	MAFM1-A0-1H
Switching Freq.	5 kHz
Magnets	Neodymium 10x3 mm
Magnets per rotation	10
sensor to magnet	5 mm
Acceleration (Vehicle Motion)	
Sensor[2]	Adafruit ADXL335
Range	±3 g
Bandwidth	50 Hz
Data Acquisition (All Sensors)	
Device[23]	DATAQ DI2108
Resolution	16 bit
Capture Rate	10 kHz

Table 6.7: Overview of electronics used for data collection.

Appendix B5: Data processing from experiments

Processing of the collected sensor data was performed in MATLAB. First, the drawbar force components were calculated at every instant. To define the drawbar components and their point of application, soil force D and center-of-pressure position x are calculated from Eqns 6.1, 6.2 and 6.3.

$$D = \sqrt{(R_A - R_B)^2 + R_C^2} \tag{6.1}$$

$$\alpha = tan^{-1}\left(\frac{R_C}{R_A - R_B}\right) \tag{6.2}$$

$$x = \frac{-R_A * (d + l + q) + R_B * (d + 2l + q)}{(R_A - R_B * sin(\psi) - R_C * cos(\psi)} \tag{6.3}$$

Where, in reference to Figs. 3-12 and 3-3, R_A is the tension force on Load Cell 1, R_B is the tension force on Load Cell 2, R_C is the tension force on Load Cell 3, l is the vertical distance from Load Cell 1 to Load Cell 2, q is the vertical vertical distance from Load Cell 2 to the origin of distance x when d = 0, d is the distance the tool jack has been lowered from its storage position, and γ is the angle of attack for the plow.

After the data was loaded into MATLAB, the resulting time-force signals were processed through a 1 Hz low pass filter, selected at this frequency because 1 second is the time it takes the tool to travel three characteristic lengths. Then, the distance traveled by all wheels was calculated by summing the new distance traveled each time a magnet was detected ($2\pi/10 * R_{effective}$) and using linear interpolation to fill in gaps when no magnet was detected. The three (one per wheel) distance-travelled vectors were then processed through another 1 Hz low pass filter. The highest drive tire slip was selected at each instant, along with its corresponding drawbar pull. This matrix was then rearranged so that all drawbar pull instances were assigned to the closest integer slip (i.e. all slip instances between 13.5% and 14.5% were assigned to the 14% slip bin). Finally, the drawbar pull values in each slip bin were averaged.

Appendix C: Chapter 4 notes

Appendix C1: Tool dimensions table

	Plow	Rotavator	Discs	Planter	Sprayer	Cultivator	Trailer
Balancing	Outrig.	Outrig.	Outrig.	Outrig.	Outrig. or Board	Board	Outrig. or Board
Attachment	Central	Pin	3-Point	3-Point	pin or moto frame	3-Point	Ball
Mass	1kg	120kg	69kg	137kg	9kg (sprayer) 11kg (trailer) <60kg (water)	21kg	225-425kg
Tool Width	0.20m	1.02m	1.37	1.5m	0.68m (trailer) 0.59cm (tank) 1.68m (boom)	0.51m	1.4m
Net Length	2.17m	3.78m	2.69m	3.60m	3.61m (trailer) 2.17m (frame)	2.64m	5.4m
Speed	1-3km/h	1-4km/h	3-4km/h	3km/h	3-6km/h	2-3km/h	5-20km/h
Depth	5-18cm	10cm	8-14cm	3-6cm	N/A	3-10cm	N/A

Table 6.8: Basic dimensions for tools used.

Central Attachment	
Mass	32 kg
Jack axis to rear axle	0.6 m
Jack axis to centerline	0.32 m
Vertical travel range	0.3 m
Three-Point Hitch	
Mass	36 kg
Overall width	0.51 m
Vertical travel range	0.38 m
Lower pins to rear axle	0.45 m
Ball/Pin Hitch	
Height	0.3 m
Dist to rear axle	0.35 m

Table 6.9: Basic dimensions for attachment systems.

Appendix C2: Breakdown of costs for farming with bullocks or conventional tractors in Indian small farms

Mass of one Bullock	500 kg
Purchase cost of one Bullock	40000 Rs.
Usable animal life	10 years
Lifetime of animal	13 years
Number of Bullocks	2
Daily feed	0.04 kg of food per kg of animal
Cost of feed	6 Rs./kg
Other costs (medical etc.)	3000 Rs. per bull per year
Purchase cost of ride-on bullock cart	30000 Rs.
Bullock cart maintenance	6000 Rs./year
Cart life	10 years

Table 6.10: Breakdown of costs to an Indian farmer for bullock ownership.

Capital Cost	200000Rs./Tractor
Principal on Loan	20%
Interest on Loan	16%
Tenure of Loan	5 years
Resale value after 10 years	40000Rs.
Annual operating cost per acre	5000Rs./year/acre
Tractor rent per hour	800Rs./hr
Hours per acre	20hrs/acre/year%

Table 6.11: Breakdown of costs to an Indian farmer for purchasing (financed and upfront) or renting a tractor. A farmer may rent a tractor if they do not own one or own one that is too small for the task. A farmer who owns a tractor can rent it and themselves out to others for profit.

Appendix C3: Questions and booklet for farmer interviews

-

A) Farm

1) What is a typical row length for you?

2) What is typical row spacing for you?

3) What are your main crops?

4) How would you describe your soil?

B) Demographic

1) What is your experience in agriculture (approximate years, locations)?

2) How would you describe your role in a farm?

C) Farm Tools

1) How do you work the land? (bullocks, tractor number of people, who are the people?)

2) As applicable: How often do you use a farm tractor or bullock? What do you typically use each for?

3) Do you purchase farm mechanization tools? What do you look for?

4) What difficulties do you have with your current bullocks, tractors or related tools?

Note: Vehicle is referred to as Bullkey in the following questions.

D) On a scale of 1 (least) to 5 (most):

How likely would you be to use Bullkey for the following:

1) for plowing?

2) for secondary tillage?

3) for planting?

4) for cultivating?

5) for spraying?

6) for trailer?

E) Open Questions

1) Looking at pics what do you think of the vehicle width? Follow ups: Does a narrower vehicle facilitate farming operations? If so, for which operations? Which advantages would you expect?

2) Does the vehicle look light enough for your needs? Follow ups: Would a lighter vehicle facilitate farming operations? If so, for which operations? Which advantages would you expect?

3) Are there task you do on your farm that you are not sure if Bullkey could manage? Follow ups: Are there tasks you are concerned Bullkey would not be able to do? If so, which operations? Why?

4) Are there farming operations you feel Bullkey is better suited to than any existing alternatives? Why?

5) What would you like to change about Bullkey? Why?

6) If you had a Bullkey, what operations would you use it for?

7) If Bullkey was available to buy, what, if anything, would you pay for it?

F) Additional conversation points

1) Would you prefer the outrigger arm or balance board? Why?

2) Would you prefer a diesel engine or a petrol engine? Why?

3) Would you use Bullkey as a motorcycle? If so, what is the lowest acceptable top speed.

Appendix D: Chapter 5 notes

Introduction

The author's suggested mechanism for attaching a tool near the tractor's center is a modified linear motion jack, as discussed in Chapter 5. However, if one were interested in achieving the elliptical tool path motion shown in Fig. 5-3, a different mechanism would be required. In this appendix, three mechanisms for achieving this motion will be briefly discussed. It is the author's intention to provide the reader with a starting point for mechanism design ideation. It is not the author's intention to suggest a specific mechanism as the best solution, that is left for future work.

Pin joints mechanism for elliptical path

A four bar mechanism is a well understood device for generating elliptical motion. It requires only pin joints and rigid links, which enables it to be made robust for outdoor applications without many complications. Using the nomenclature in Fig. 6-8 for a four bar linkage, the tillage tool's location and orientation can be calculated from Eqn. 6.4.

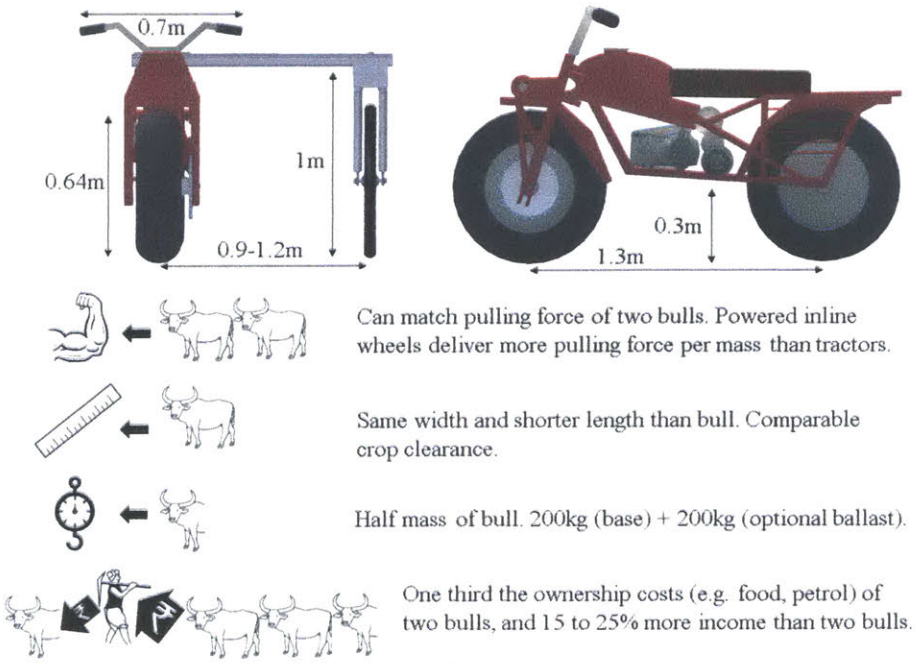
$$q\begin{bmatrix} cos(\gamma) \\ sin(\gamma) \end{bmatrix} + r\begin{bmatrix} sin(\mu) \\ cos(\mu) \end{bmatrix} - s\begin{bmatrix} cos(\varphi) \\ sin(\varphi) \end{bmatrix} - t\begin{bmatrix} cos(-\theta) \\ sin(-\theta) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{6.4}$$

Where q crank length, r is rocker length , s is follower length, t is frame link length, θ is frame link angle to horizontal, μ is crank link angle to horizontal, and φ is follower angle to horizontal

An example implementation of this concept is shown in Fig. 6-9. In that implementation the drive link CD is located near the output shaft of the engine and low in the motorcycle frame. This would facilitate using either the engine power or an electric motor (where being low is beneficial to CG location) to drive the mechanism. The mechanism can also be driven manually. This can be achieved by extending the rear guiding link BA past point A, turning it into a lever, or by adding a second mechanism that applies a force directly at one of the mechanism pivots. The latter would turn the mechanism into a six bar linkage and is shown in Fig. 6-9.

The mechanism shown in Fig. 6-9 was designed in MATLAB. The design space where the following equation is true was explored for desirable motion paths using Eqn. 6.4.

1



Can match pulling force of two bulls. Powered inline wheels deliver more pulling force per mass than tractors.

Same width and shorter length than bull. Comparable crop clearance.

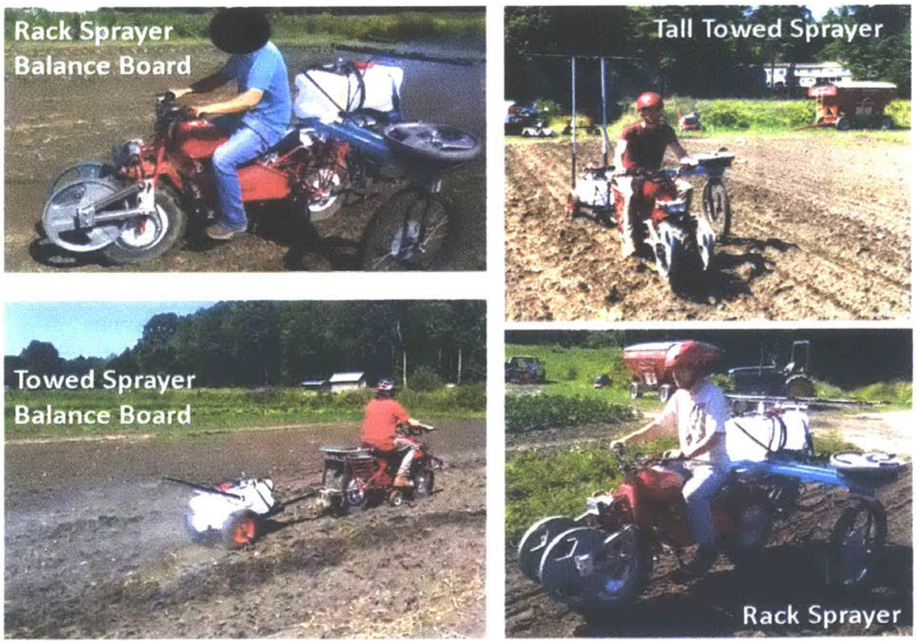
Half mass of bull. 200kg (base) + 200kg (optional ballast).

One third the ownership costs (e.g. food, petrol) of two bulls, and 15 to 25% more income than two bulls.

2

Figure 6-2: Pages 1 and 2 of booklet used to interview farmers in India.

3



4

Figure 6-3: Pages 3 and 4 of booklet used to interview farmers in India.

Figure 6-4: Pages 5 and 6 of booklet used to interview farmers in India.

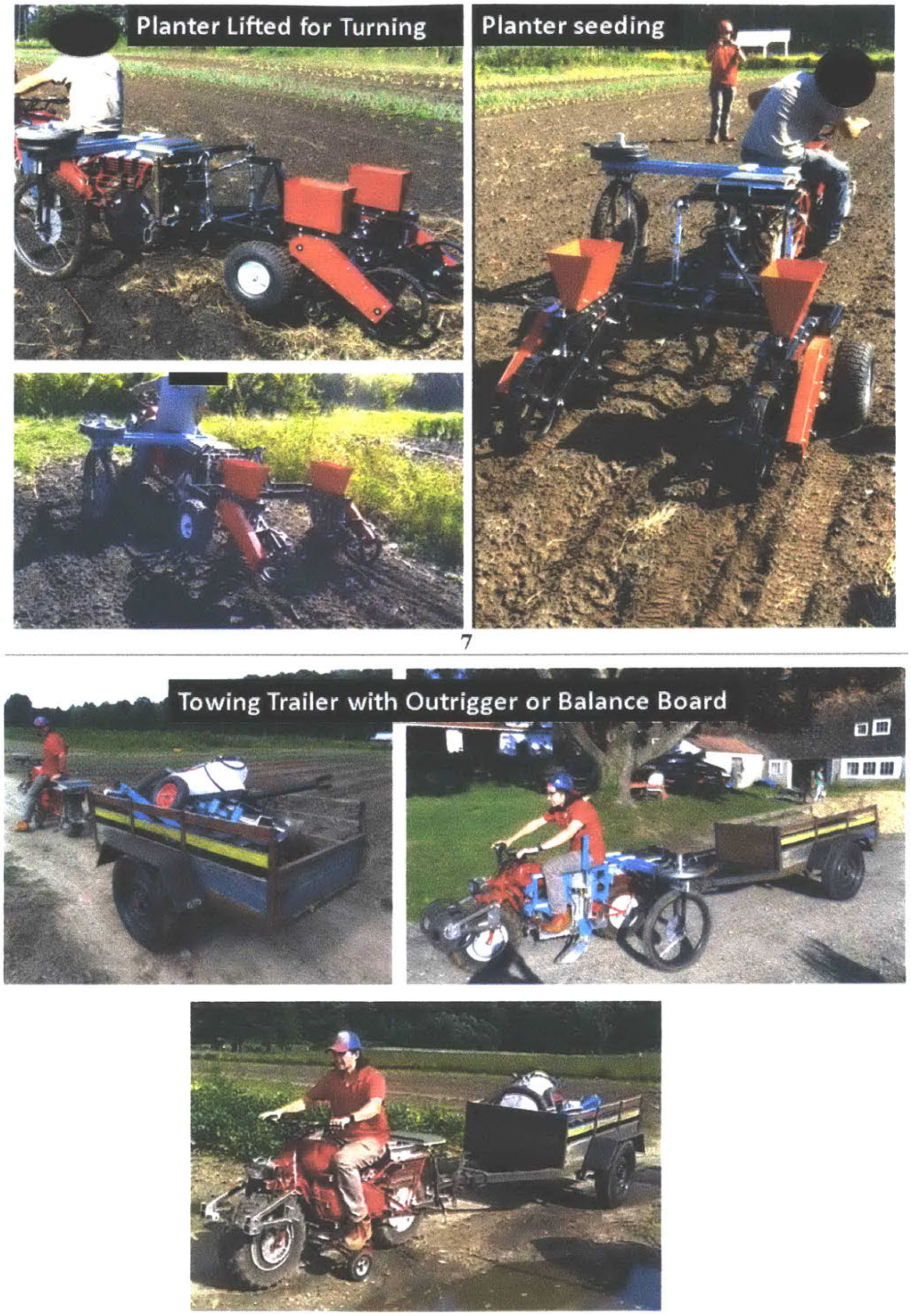
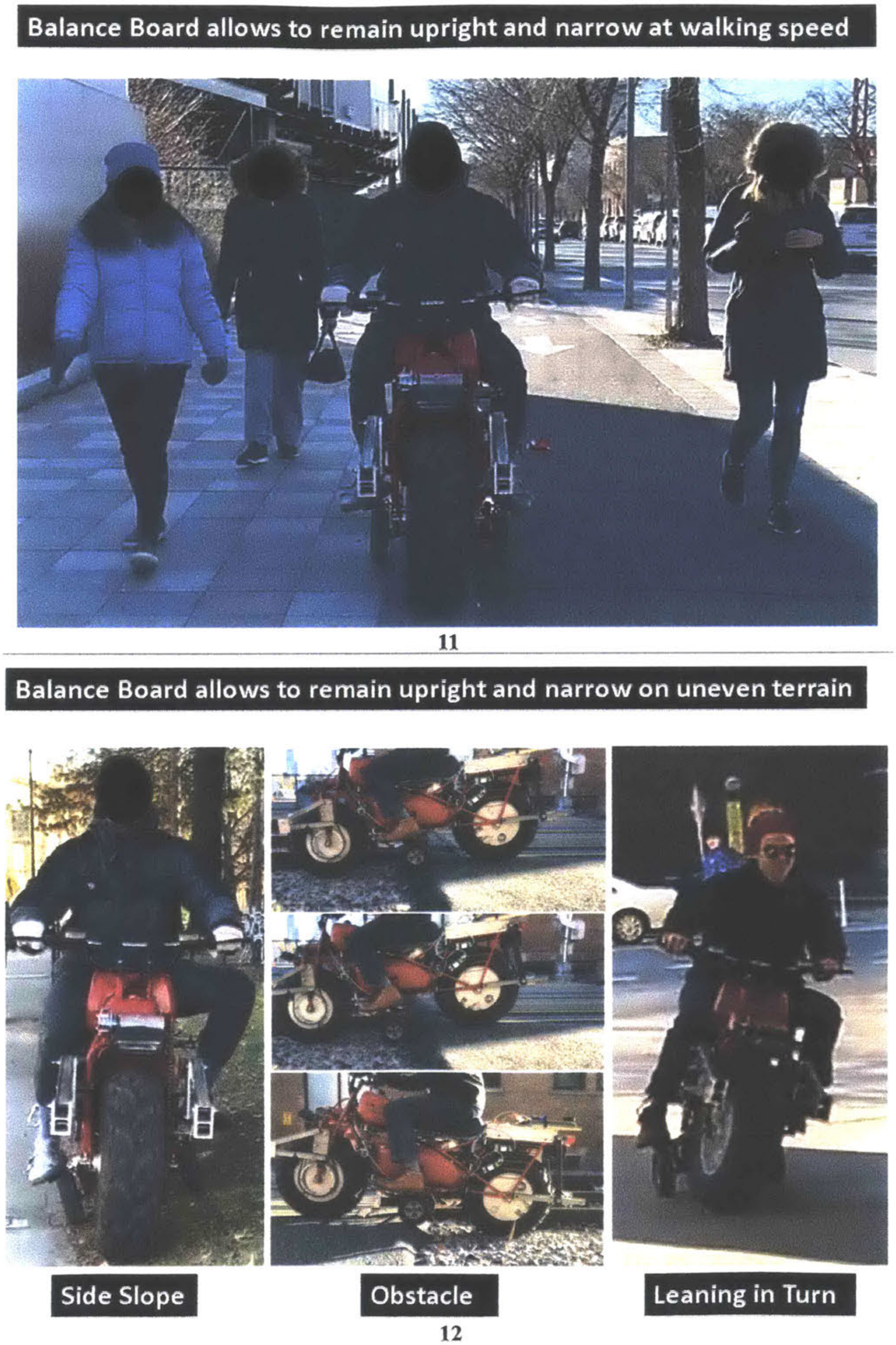


Figure 6-5: Pages 7 and 8 of booklet used to interview farmers in India.

Figure 6-6: Pages 9 and 10 of booklet used to interview farmers in India.



Balance Board allows to remain upright and narrow at walking speed

11

Balance Board allows to remain upright and narrow on uneven terrain

Side Slope

Obstacle

Leaning in Turn

12

Figure 6-7: Pages 11 and 12 of booklet used to interview farmers in India.

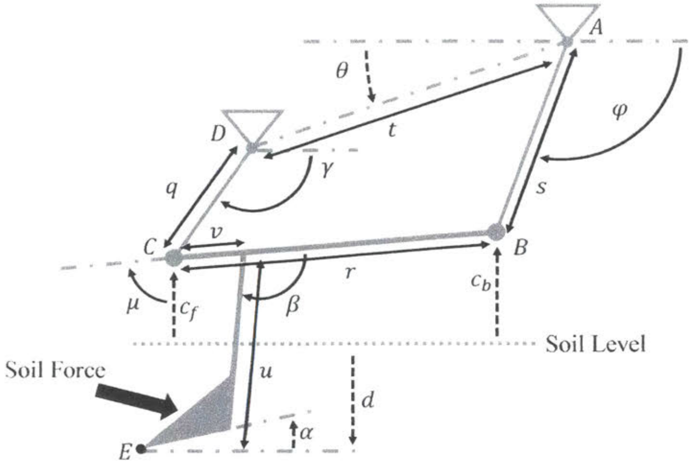


Figure 6-8: Four bar mechanism with variables used in equations labeled.

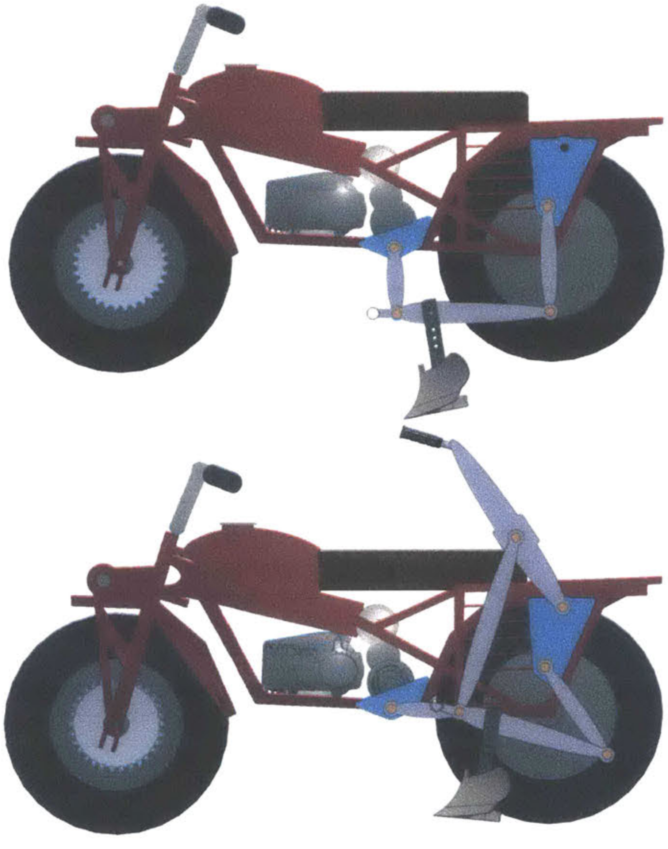


Figure 6-9: Examples of implementation of four bar linkage (top) and four bar linkage with handle for manual control (bottom). More instants in the mechanism motion are shown in Fig. 6-10.

From this equation, after setting the crank arm angle γ, the angles of the rocker arm (μ) and follower (φ) can be solved for.

The magnitude of t and the angle θ were set to constants that matched well to viable attachment points on the current prototype's frame. The lengths of the links q, r, and s were then explored for arrangements where Eqn. 6.5 is met. Desirable designs will keep rocker angle μ approximately constant while the tool is being lowered into the soil. An example of a viable motion path is shown in Fig. 6-10.

$$s + r - q \leq t \tag{6.5}$$

Concepts with other joint and link types

A mechanism that achieves the motion Fig. 5-3 could also use sliding contacts or cable links. These components provide advantages like facilitating keep a constant tool angle through the whole motion cycle without being limited to a circular motion path (as would be the case with a four bar linkage) and decoupling tool depth from the orientation of the rigid links in the mechanism.

The mechanism shown in Figs. 6-11 and 6-12 has parallel sliding circular rails rigidly mounted to a structure that connects the outrigger arm to the motorcycle frame. On these rails a submechanism slides that is effectively a four bar linkage which would otherwise simply achieve a circular motion while keeping the tool at a constant angle of attack. The tool still maintains a constant angle but is motion path shape has been favorably altered by the rails.

The mechanism itself is driven by the light green slotted link shown in Figs. 6-11 and 6-12. This drive link does not fully constrain the location of the tool, instead the tool's location is also determined by the forces applied to it. This degree of freedom allows the drive link to have a longer lever arm while the tool is on the ground than when the tool is raised. It also changes the ratio of vertical to downward motion of the tool throughout its stroke, allowing a shallower insertion angle into the soil.

Another design alternative is shown in Fig. 6-13. This design uses a pin-slot joint and a cable link. The location of the pin in the slot limits the maximum depth the tool can reach. In an implementation of this design, the pin should lock at the top of the slot (for

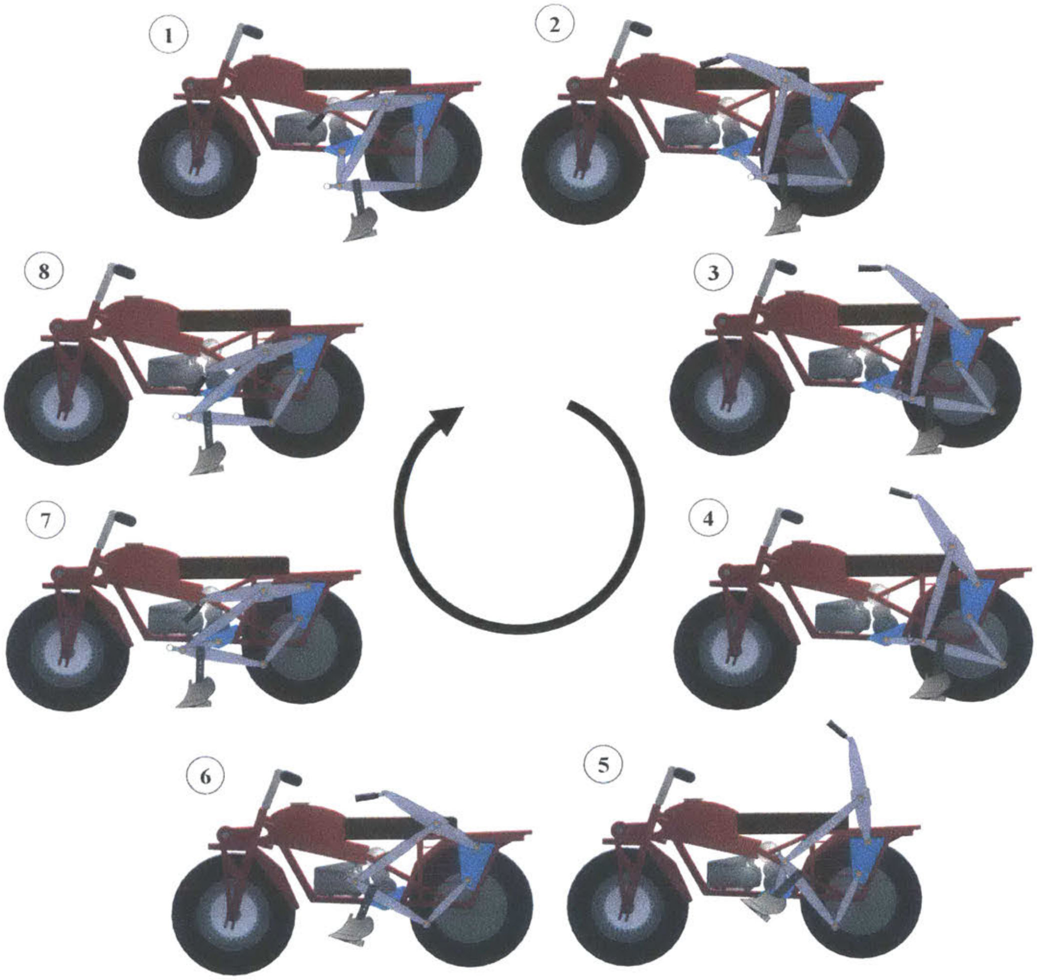


Figure 6-10: Instants in the mechanism motion. Between instants 5 and 1, the tool is coming down so the user does not need to apply force at the handle and can let go of it. A foot support can be placed on the rocker link (shown) to allow the user to press down on the tool during initial insertion into unusually hard soil.

Figure 6-11: Views of concept sliding rail mechanism on motorcycle.

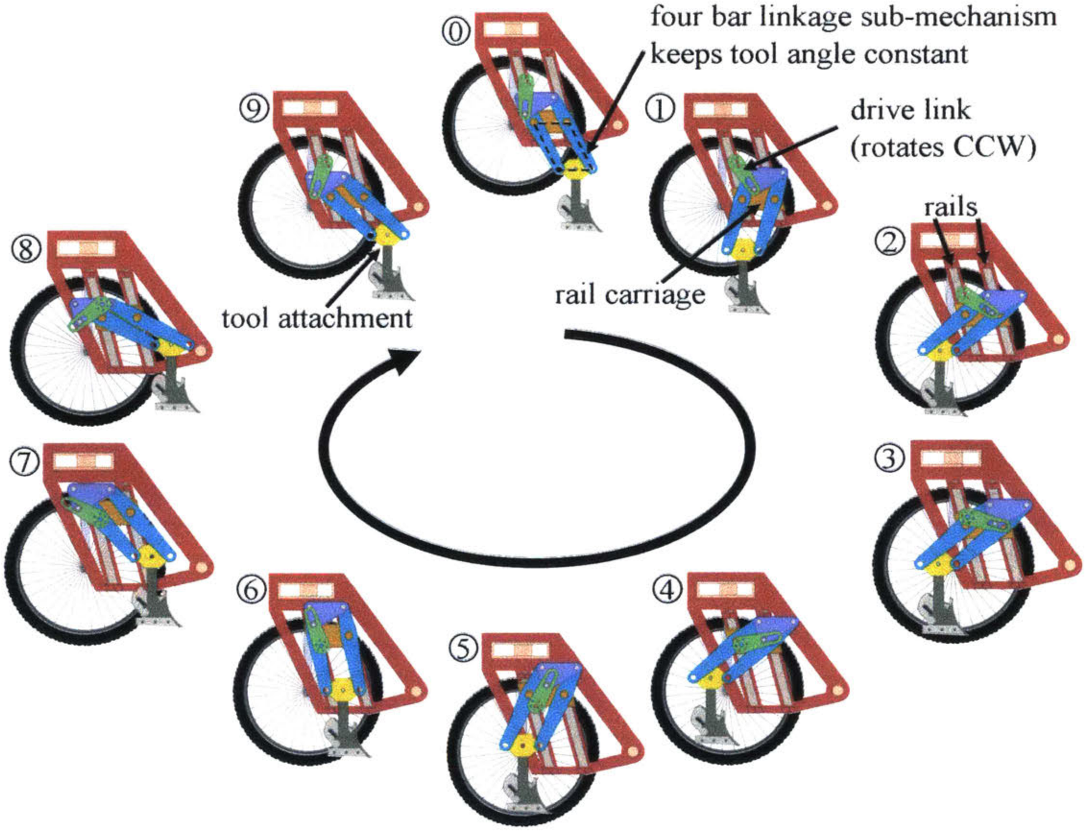


Figure 6-12: Instants in sliding rail concept mechanism motion.

tool transportation) until released by the user. The pin should then fall in the slot to a maximum depth set by the user (not necessarily the bottom of the slot). This maximum depth could be set obstructing the pin's travel along the slot. The cable link allows the pin the tool to be laid on the soil before insertion and then the soil to naturally pull the tool down via its drag forces during forward motion. In other words, the cable limits the tool maximum depth but not its minimum - similar to a conventional tractor hydraulic system.

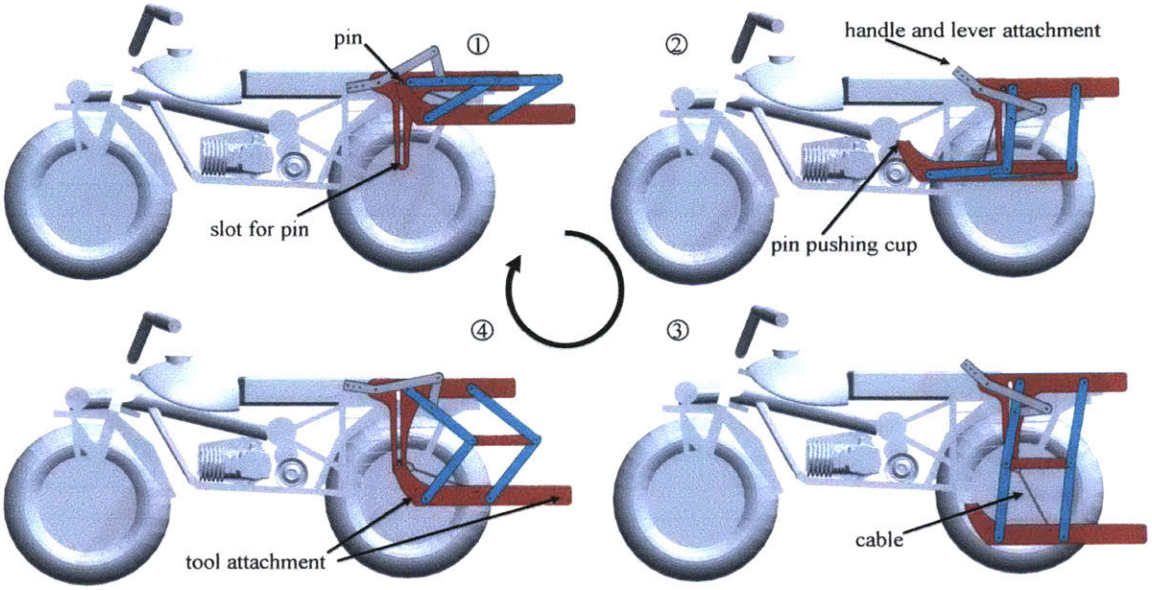


Figure 6-13: Instants in the mechanism motion.