Journal of Mechanical Design. Received December 08, 2019;
Accepted manuscript posted April 13, 2020. doi:10.1115/1.4047001
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Investigation of viability to replace draft animals with all-wheel-drive motorcycles on small farms

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abstract - This paper 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 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, novel balance board attachment, and the ability to attach implements ahead or behind the rear axle. The design was created to address unmet farmer requirements identified during interviews with Indian farming stakeholders. A prototype of the tractor demonstrated the completion of key farming operations in a Massachusetts farm where expert user feedback was obtained. In-person interviews on the tractor's usefulness were then conducted with 24 small and marginal Indian farmers in Karnataka, Gujarat, and Tamil Nadu. The tractor was described to the farmers with help of pictures, videos, and local experts. Farmers generally reported that the prototype tractor would meet their needs and suggested being willing to purchase the vehicle for 123,000 INR, about 22% higher than the price target for 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.

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1 Introduction

This paper 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. 1) [1, 2], but conventional tractors cannot replace animal's small dimensions and low capital cost [3, 4]. 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 [5]. The majority of farms in the world (84%), and particularly in India (86%), are less than 2 ha in size [6, 7], whereas the conventional tractor largely evolved for farms in the US that are at least 30 times larger [8–10].

A tractor layout specialized to the contemporary needs of small farms, called **Bullkey**, has been previously introduced by the authors [17, 18]. *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 [17, 18], Bullkey was shown to generate more drawbar pull per unit mass than conventional tractors. This is important because mass is correlated to both tractor price [17, 18] and drawbar pull [19–21]. 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

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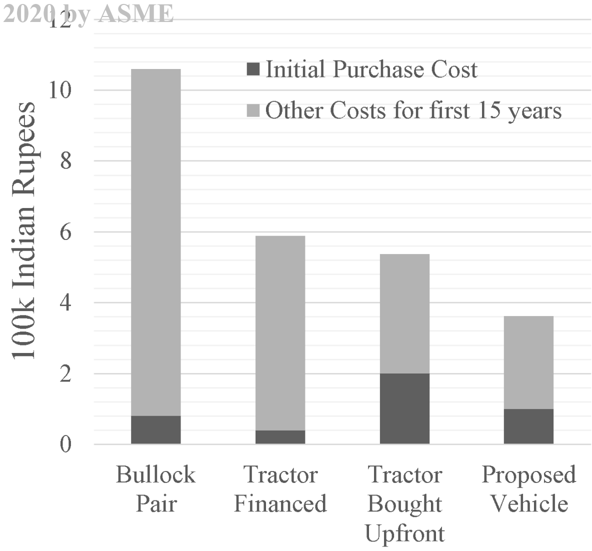

Fig. 1. OWNERSHIP COSTS OVER 15 YEARS FOR A BULLOCK PAIR, A SMALL TRACTOR, AND THE BULLKEY TRACTOR. In addition to purchase price, other costs include fuel/food, and maintenance. An ideal solution would have the low purchase price of bullocks and the low upkeep cost of tractors - shown as Bullkey tractor. Financing or renting may be inaccessible to many farmers. Renters forgo using the tractor for supplemental income work and potentially timeliness of completing operations. [11–16]. A breakdown of the costs shown here is provided in Supplemental Material E.

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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. Bullkey has advantages over other mini tractor solutions, it is less exhausting to use than a power tiller, and has better tractor performance than rear-wheel drive tricycle tractors [18].

Power tillers can have small dimensions and cost but typically require the user to walk behind them, leading to exhaustion and shortening work hours [22]. Very low cost mini tractors with rear wheel drive include the locally made "Saneda" tractor, which is created by combining a motorcycle front-end and a two-wheel rear axle with a manually powered, lever-actuated rear-mounted tool [18]. This tractor is disadvantageous in that it can easily upend due to its drive-wheel and tillage tool location, and it also generates three soil compaction lanes since its front wheel is centered between the two rear wheels.

In its introductory paper, Bullkey was field tested to validate its traction performance and to preliminarily assess its usability with farmers' feedback [17, 18]. This paper expands on that work by demonstrating the design's viability for performing specific and comprehensive agricultural operations key to Indian farmers. Section 2 presents the needs of small Indian farmers elucidated during field interviews and from background research that drove the design of Bullkey. Section 3 describes Bullkey's overall design and how it was engineered to achieve the operations required by Indian small farmers. Section 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. Field testing for this study was only conducted in Massachusetts because of the cost, time, and logistical challenge of importing a prototype vehicle into India - farmers in India were provided with a graphic booklet, videos, and performance numbers describing the tractor while local experts were used for translation. The collected feedback suggests that Bullkey is useful and attractive to the targeted user population.

2 Description of Farmer Needs

Fig. 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. 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 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,

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Major design requirements from user needs		Reference Alternative (in gray)		
Aspect	Bullkey	Bullock Pair	Small Tractor	Comment
Purchase cost (INR)	∼100000	80000	265000	Similar to bullock pair [14]
Ownership cost (INR/year)	<12500/Ha	93000 [13]	12500/Ha [16]	Bulls also fed on idle days
Overall Width (m)	1.7	2.1	1.7	Operate safely on road lanes
Required Path Width (m)	<0.7	0.6 to 0.9	1.7	Move between tall row crops
Headland needed (m)	<1.5	1.5	2.6	Reduce field area not farmed
Max. Drawbar Pull (N)	>2800	2800 [23]	4600	Bullocks' max. 3x their avg. [24]
Daily work hours	unlimited	5	unlimited	Walking fatigues animal & user
Top road speed (km/h)	26	4	26	Gov. policy may impact speed

Table 1. MAJOR USER NEEDS IDENTIFIED VIA INTERVIEWS WITH STAKEHOLDERS IN INDIA AND BACKGROUND RESEARCH. Unless otherwise noted, bullock values are from the authors' farmer interviews and tractor values are from the Mahindra Yuvraj NXT 215 (Mahindra Tractors, India [25]) - a market leader in the small tractor segment. Actual Bullkey price will be affected by distribution possibilities. Converting INR to USD at the time of writing for reference, the purchase cost and ownership cost per hectare for Bullkey would respectively be approximately 1400 and 175 USD.

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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 [4] [26] [14].

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 1. Bullkey should be comparable to bullocks in purchase cost (Fig. 1), width, drawbar pull, headland required, and have the ability to traverse unfinished dirt paths. Bullkey should be comparable to conventional small tractors in ownership cost (Fig. 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 [4] [26]. 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.

3 Prototype Vehicle Design

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.

3.1 Prototype vehicle

The Bullkey prototype was built by modifying a ROKON Scout utility motorcycle (ROKON, New Hampshire [27, 28]) 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. 3 and its main dimensions are listed in Table 2. The Rokon was only used as a test platform, and any resulting product would be custom made for the target market. And then you can address his next point to stress that other two-wheel driver motorcycles exist near our target price point, and given the market trends between tractor weight and price [18], a Bullkey of our target weight should be near the target price point. A similar vehicle to the ROKON commercially available at a much lower cost is the Taurus [29]. Repurposing valuable familiar features of local vehicles (in this case motorcycle dimensions and steering) has also been explored in prior work for small Easter European farmers [30].

This design can generate a high tillage drawbar pull for two main reasons: a high proportion of its total mass is sup-

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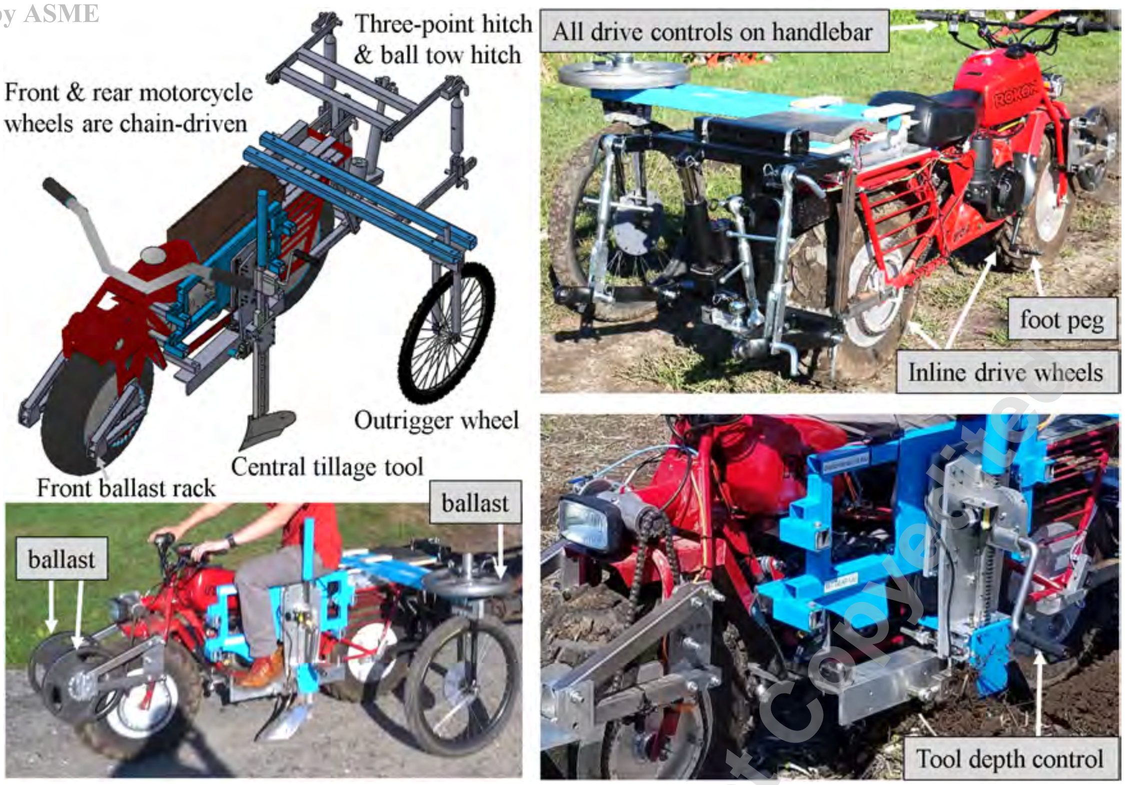

Fig. 3. OVERVIEW OF THE BULLKEY DESIGN. The CAD drawing on top left highlights key features of proposed tractor design. This is supplemented by three pictures of the physical prototype where those features are clearly visible.

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 2. KEY BULLKEY DIMENSIONS.

ported by the front and rear drive tires, and tillage forces from the centrally mounted tool increase the vertical load on both drive tires [17, 18]. 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 [31] [32] [33].

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. 3), and a novel human-powered stabilization design we call a *balance board*. 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 balance board allows Bullkey to retain an overall width comparable to a single bullock, therefore avoiding the need to straddle crop (Fig. 4). It is described in Section 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 [17, 18]. Finally, its tool attachment points make it safe to operate and compatible with the tools needed to complete key tasks mandated by small Indian

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farmers.

3.2 Balance Board

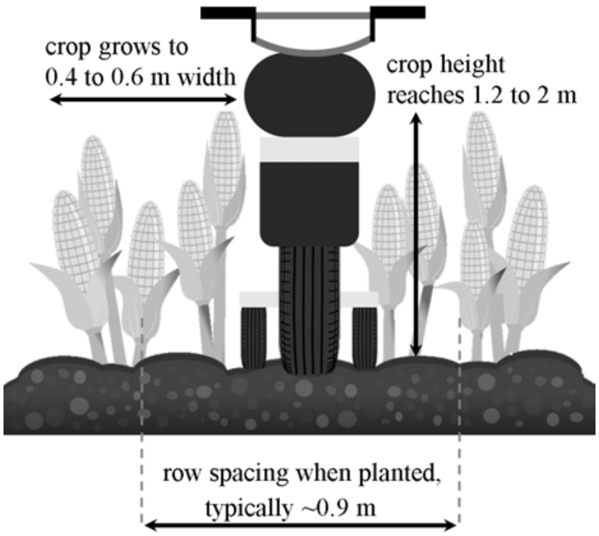

Fig. 4. THE BALANCE BOARD ALLOWS BULLKEY TO OPERATE BETWEEN ROWS OF TALL GROWING CROP BY KEEPING ALL OF ITS GROUND CONTACT POINTS IN A SINGLE LANE NARROWER THAN THE DISTANCE BETWEEN ADJACENT CROPS.

Fig. 5. THE BALANCE BOARD 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.

To enable Bullkey to operate in the same overall space as a single bullock, the balance board stabilization attachment for utilitarian two-wheeled vehicles was created [34]. This device is human-powered 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). 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. 5). The balance board can replace the outrigger arm during spraying of tall crops when the sprayer is towed as seen in Fig, 7. When the balance board is used, the outrigger arm and ballasting weights are stored elsewhere and not attached to the vehicle.

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.

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.

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3.3 Implement Utilization

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, as outlined in Section 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. 6 and tool dimensions are provided in Supplemental Material A.

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 [35]) 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 [36]), with 0.92 m tillage width, 0.3 m diameter blades, and powered by a 208cc Briggs & Stratton (Briggs & Stratton, Wisconsin [37]) 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 [38]) 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 [39]) 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 3 cm 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 [40]) 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 [41]) 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 Field Validation of Operations and Assessment Interviews

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 [17, 18]. Field testing for this study was only conducted in Massachusetts because of the cost, time, and logistical challenge of importing a prototype vehicle into India.

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 [42], 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 Supplemental Material A 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 [19] [20]) and generally operate the tires at 10 to 20% slip. These tests are discussed in detail in [17, 18].

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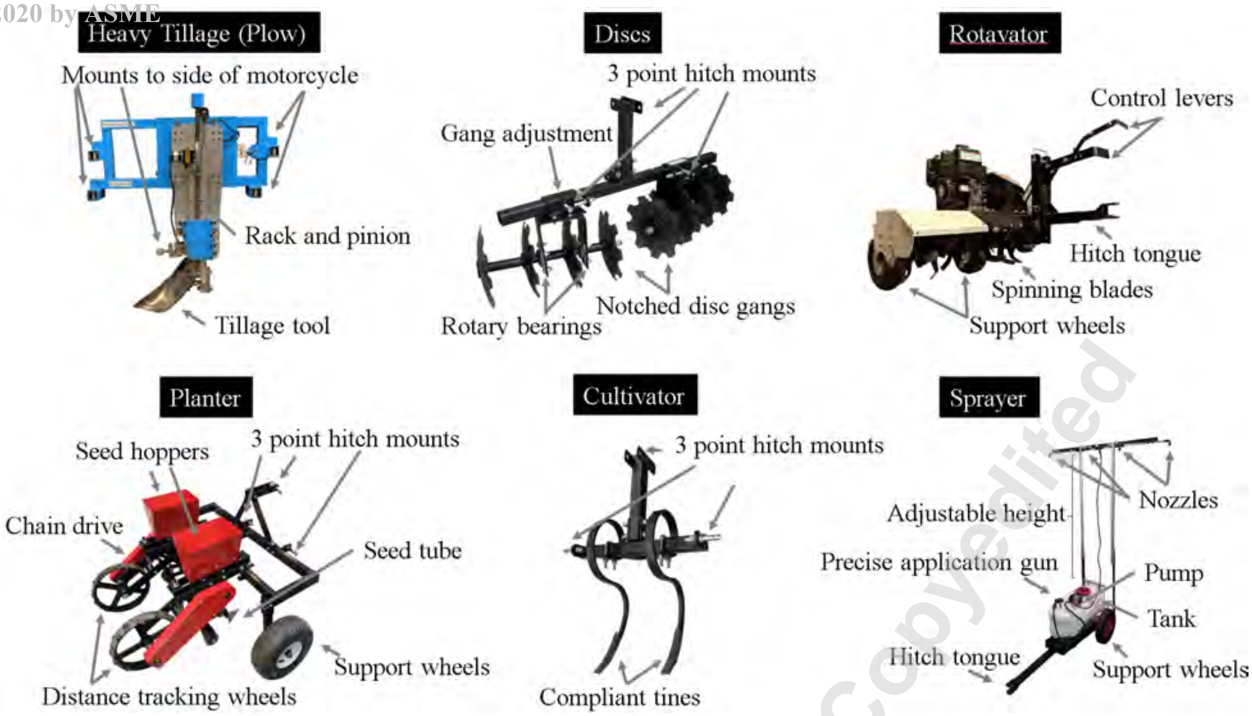

Fig. 6. CLOSE UP VIEWS AND KEY COMPONENTS OF THE FARMING IMPLEMENTS USED DURING FIELD TESTING.

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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 50 m 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. 6). 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 inserted into the 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.

4.2 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 (see Supplemental Material C) 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.

4.3 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 in-

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Fig. 7. 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.

terviews 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 [43].

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 Supplemental Material C.

Given the inability for us to test a physical prototype in India, to explain the functionality of Bullkey, farmers 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 Supplemental Material D.

5 Results - Field Validation of Operations and Assessment Interviews

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 [42], demonstrating that it can do the operations identified in Section 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

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Journal of Mechanical Design. Received December 08, 2019;
Accepted manuscript posted April 13, 2020. doi:10.1115/1.4047001
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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.

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. 8).

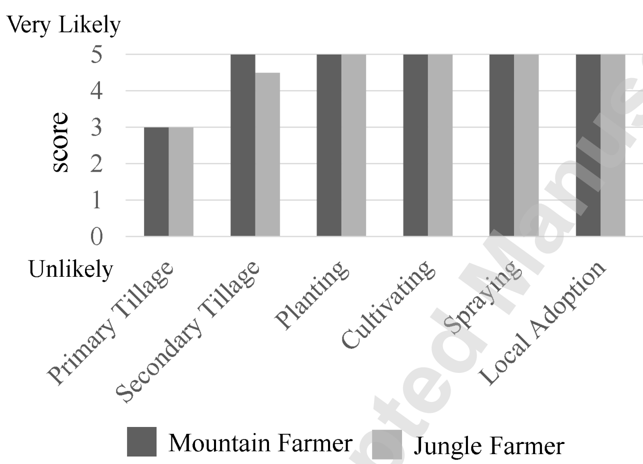

Fig. 8. SELF-DESCRIBED LIKELIHOOD OF TWO INTERVIEWED PERUVIAN FARMERS FOR DOING AN ACTIVITY WITH BULLKEY. These farmers were present to observe while Bullkey performed every operation described in this paper. "Local Adoption" refers to the likelihood that they and their neighbors would use the tractor for farming in Peru.

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 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. 8) 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.

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 tractor 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.

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Indian farmers saw a financial value in Bullkey. On average, they said they would be willing to pay 123,000 INR (aprox. 1720 USD) 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 approximately 100,000 (aprox. 1400 USD). 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. 9). 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%).

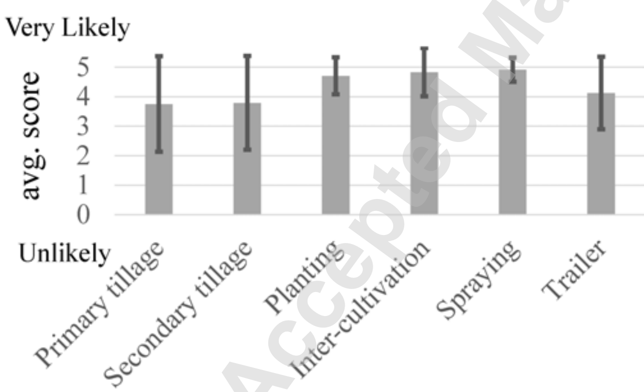

Fig. 9. SELF-DESCRIBED LIKELIHOOD OF INTERVIEWED INDIAN FARMERS FOR DOING AN ACTIVITY WITH BULLKEY TRACTOR.

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 1.4 m instead of the current range of 0.9 to 1.2 m.

6 Discussion

6.1 Satisfying user needs

Originally, the major design requirements identified (Table 1) were related to drawbar pull, purchase and ownership cost, device 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 [17, 18]. 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.

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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 [17, 18], where it is shown Bullkey can pull more per unit mass than conventional tractors. Farmers also mentioned on this point that with easier access to renting a tractor for primary tillage (which is done on an open field with no obstructions), they are feeling reduced pressure to own a tillage solution. 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 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.

In future work, it will be desirable to import or locally build multiple additional prototype units of the Bullkey tractor for use in India. Farmers interviewed in India expressed interest in drive testing the prototype. We are motivated to invest in local testing by the good alignment between the positive responses from the Peruvian farmers in Massachusetts who observed the tractor operating and the small Indian farmers who were only shown graphic media along with performance data.

7 Conclusions

This paper describes 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 authors, 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 yield 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.

Acknowledgements

This work was sponsored by Mahindra Tractors and the MIT Tata Center. Thank you to Gwyndaf Jones, Dan Dorsch, Elliot Donlon, and Jeffrey Costello for assisting with field tests. Thank you to Clark Farm for providing us with farm land for testing. Thank you to Aravind Bharadwaj, Vivek Gupta, Nagendra Pansare, Sameer Deo, Ravindra Shahane, Muthiah Saravanan, Ashwinikumar Parhate, Ganesh Sadkar, and others at Mahindra Tractors for sharing their expertise in

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Supplemental Material is provided next

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Supplemental Material A: Tool dimensions table

	Plow	Rotary Tiller	Disc Harrow	Planter	Sprayer	Cultivator	Trailer
Balance System	Outrigger	Outrigger	Outrigger	Outrigger	Outrigger or Board	Board	Outrigger or Board
Attachment	Central	Pin	Three-Point	Three-Point	pin or on moto frame	Three-Point	Ball
Mass	1kg	120kg	69kg	137kg	9kg (sprayer) 11kg (trailer) 20-60kg (water)	21kg	225-425kg
Implement Width	0.20m	1.02m	1.37	1.5m	0.68m (trailer) 0.59cm (tank) 1.68m (boom)	0.51m	1.4m
Overall Length	2.17m	3.78m	2.69m	3.60m	2.17m (on moto) 3.61m (trailer)	2.64m	5.4m
Forward 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

Supp. Table 1. 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

Supp. Table 2. BASIC DIMENSIONS FOR ATTACHMENT SYSTEMS.

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Supplemental Material B: 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 INR (aprox. 560 USD)
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 INR (aprox. 0.10 USD) per kg
Other costs (medical etc.)	3000 INR (aprox. 42 USD) per bull per year
Purchase cost of ride-on bullock cart	30000 INR (aprox. 420 USD)
Bullock cart maintenance	6000 INR (aprox. 84 USD) per year
Cart life	10 years

Supp. Table 3. Breakdown of costs to an Indian farmer for bullock ownership.

Capital Cost	200000 INR (aprox. 2800 USD) per Tractor
Principal on Loan	20%
Interest on Loan	16%
Tenure of Loan	5 years
Resale value after 10 years	40000 INR (aprox. 560 USD)
Annual operating cost per acre	5000 INR (aprox. 70 USD) per year per acre
Tractor rent per hour	800 INR (aprox. 11 USD) per hr
Hours per acre	20hrs/acre/year%

Supp. Table 4. 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.

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Supplemental Material C: Questions asked to farmers

-

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.

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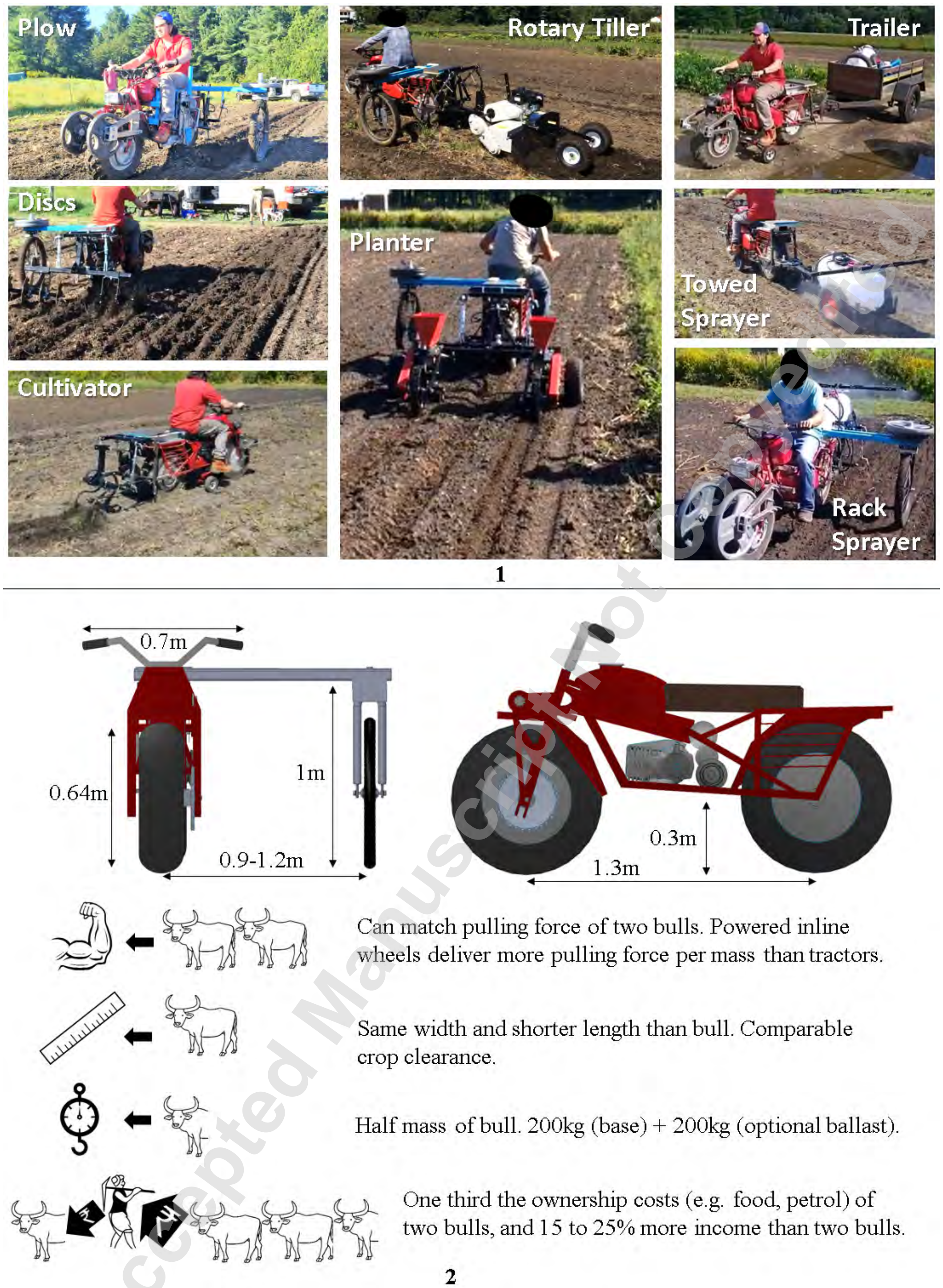
Supplemental Material D: booklet supplied to dealers and farmers for interviews



Supp. Fig. 1. PAGES 1 AND 2 OF BOOKLET USED TO INTERVIEW FARMERS IN INDIA.

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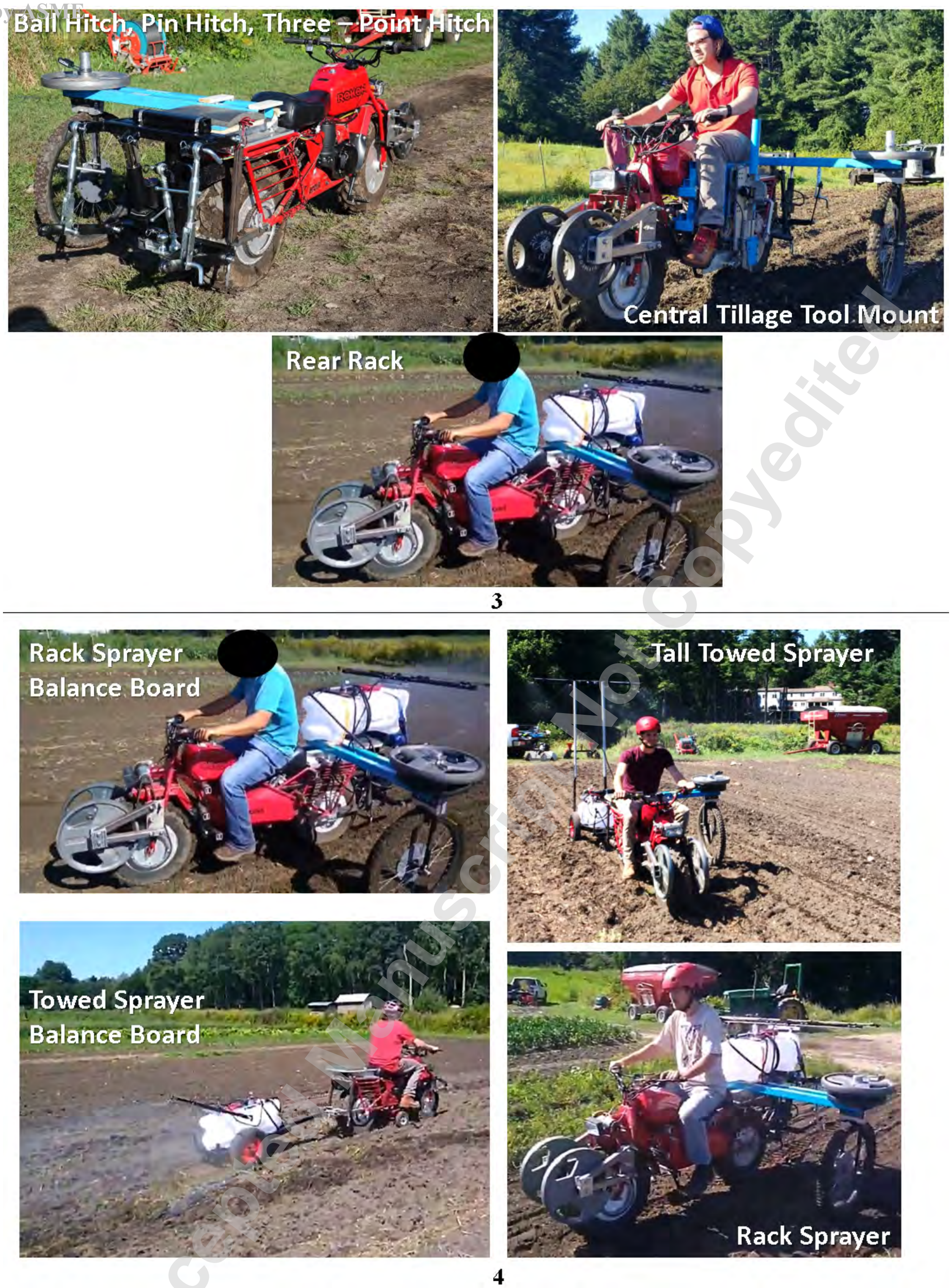

Supp. Fig. 2. PAGES 3 AND 4 OF BOOKLET USED TO INTERVIEW FARMERS IN INDIA.

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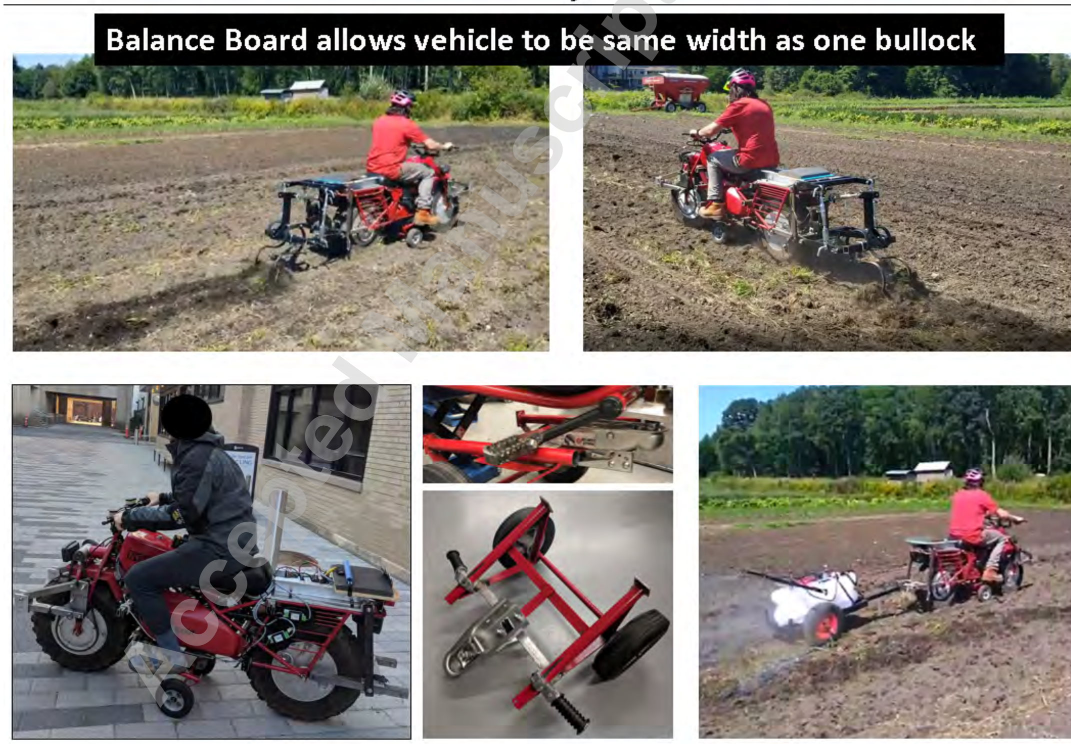

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Supp. Fig. 5. PAGES 9 AND 10 OF BOOKLET USED TO INTERVIEW FARMERS IN INDIA.

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Supp. Fig. 6. PAGES 11 AND 12 OF BOOKLET USED TO INTERVIEW FARMERS IN INDIA.

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