

A Novel Traction Mechanism Based on Retractable Crampons to Minimize Soil Compaction and Reduce Energy Consumption

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Abstract

Tired and tracked tractors on agricultural soil have the inherent limitation of needing considerable ballast to gain traction and have low tractive efficiency due to slip and tire flexing. These limitations contribute to soil degradation and reduce the possibility to intensify mechanical field management. To address these disadvantages, we introduce a novel traction mechanism which combines inching or push-pull locomotion with retractable tines or crampons which penetrate the soil every few meters. Once inserted into the soil, relatively thin and short crampons provide sufficient motion resistance to pull tillage implements through the soil, with no need for additional ballast.

Optimal crampon design depends on the width, depth in the soil, rake angle, and inter-crampon spacing. A hinged design allows for reliable crampon insertion and extraction. The pull/weight ratio of the vehicle can be controlled by placing the hinge low and by separating the crampon from the hinge by an arm. Travel reduction and tractive efficiency can be controlled through the actuation length of the push-pull mechanism. Experimental results show that crampons can achieve a high pull/weight ratio, travel reduction of less than 10%, and a tractive efficiency of over 90% on agricultural soil.

Keywords: Crampons, push-pull locomotion, inching locomotion, soil compaction, travel reduction, tractive efficiency

1. Introduction

Tractors with tires (and tracks) need ballast to generate pull. When power is supplied to a tire without sufficient ballast, the tire slips excessively, generating no or little traction. As the weight on the tire increases, they compact the soil under the tire, the soil particles interlock and resist the shear force, and the tractor moves forward. Optimal tractive efficiency is achieved at a pull/weight ratio of about 0.4 (Zoz and Grisso, 2003). For every Newton N of draft which acts horizontally on the surface between tire and soil, the ballasted vehicle needs to apply 2.5 N of weight to the same surface. The combined force vector measures about 2.7 N for every N of draft and presses diagonally downward into the soil at the rather steep angle of 68° from horizontal. Even at maximum tractive efficiency, there is some slip, which shears the soil under the tire horizontally and increases the damage to soil structure (Söhne, 1952).

Soil compaction has several undesirable effects. The soil under the tire is compressed into a continuous rut which is a pathway for water erosion. The compacted soil has lost fertility because of reduced root penetration (Bengough et al., 2011), reduced soil aeration (Whalley et al., 1995), reduced

water infiltration and reduced water storage (Ankeny et al., 1990), and due to erosion from excess runoff (Fullen, 1985). Compacted soil requires significantly stronger and deeper tillage, which increases machinery costs and energy consumption, and leads to a cycle of ever bigger machinery to till soil which is compacted to ever-increasing degree and depth (Håkansson and Reeder, 1994).

Even though these problems have been studied and published for well over 60 years, the solutions offer only partial respite, and never abandon the fundamental principle of locomotion by ballasted surface interaction. Tracks spread the weight over a longer section of the rut, which somewhat decreases the volume of compressed soil, but shear the soil badly when steered (Hamza et al., 2005). Controlled traffic aims to limit compaction to permanent ruts in the field, sacrificing a significant portion of the soil. No-till can avoid some tractor traffic, but not all, while the associated dependency on herbicides leads to other problems like herbicide resistance and environmental degradation. There is a need for a device that can generate traction while minimizing the loading that causes soil compaction.

2. A new traction mechanism based on crampons and push-pull

2.1 The design idea

Narrow tent pegs and fence stakes are widely used to exert force with a major horizontal component in soft soil. We propose to use the same principle to anchor traction (Bover, 2011), to drive narrow stakes or tines periodically into the soil to form a static anchor from which an agricultural device can be pulled. We use the term “crampon” for a narrow stake or tine used for traction by soil penetration. A crampon driven into the soil and linked to a push-pull mechanism may propel a machine in an alternative motion pattern. Once half the motion pattern of the push-pull is complete, a second crampon provides anchorage and the first crampon is pulled from the soil.

The concept of traction with static crampons and a push-pull mechanism poses the following design questions:

- what is the proper shape and configuration of crampons to penetrate the soil easily while providing maximum draft,
- how to insert and extract a crampon from the soil,
- how to integrate a crampon into a complete vehicle design, and
- how to configure the push-pull mechanism of the vehicle?

2.2 Crampon shape and configuration

A crampon in soil subject to horizontal pull will exhibit a passive force with horizontal and vertical components, both of which depend on the depth of the crampon in the soil, its rake angle, its distance to other tines in the soil, its width, and the soil conditions. The horizontal or draft component is directed away from the pulling force and should be maximized. The vertical component is much weaker than the horizontal component in most configurations and can either force the crampon up or down, depending on the configuration. Godwin (2007) and Godwin and O’Dogherty (2007) showed that the draft force of a narrow tine increases with depth, while depth has little effect on the vertical force. The rake angle has a strong effect on both the draft force and the vertical force. A rake angle smaller than approximately 70° will produce a downward vertical force, and a rake angle greater than approximately 70° will produce an upward vertical force that needs to be counterbalanced by implement weight or weight

transfer. The distance between the tines has a diminishing effect on the draft force, as does the width of the tine. Until a width of about 10mm the draft increases in proportion to width, and thereafter the effect decreases. The width has very little effect on the vertical force. Whiteley and Dexter (1981) showed the force required to drive a cone into the soil grows linearly with the cone area. We assume a similar relationship will hold for a cone-shaped crampon.

As a first working test and based on the above information related to the performance of crampon-like tines and cones, we used 1.5 to 2 times the depth of the crampon in the soil as a working distance between crampons. We also decided that while a steep rake angle is desirable for a strong draft force, 70° is an upper limit to avoid an upward lift, and we set 70° as a first working value. This leaves crampon depth as a free variable that can be used to dynamically adjust the draft force to the operational needs. As Godwin investigated draft forces in the tilled A horizon where overburden stress will be lower than in untilled soil, a greater draft should result from penetration of soil below the tilled layer.

2.3 A hinged design for crampon insertion and extraction

To avoid a dedicated set of actuators which drive a crampon into the soil, extract it from the soil, and regulate its depth in the soil according to the required draft force, we propose a mechanism as illustrated in Figure 1 whereby the crampons benefit from the relationship between rake angle and vertical forces as described above. In this design, the crampons are fixed to the rear of a moving frame by a horizontal hinge and are shaped such that when resting on the ground, the tips of the crampons are pointing backward at the ground, initially at a rake angle which is significantly less than 70° . When the frame moves backward, the tip of the crampon penetrates the soil, partly under its weight and partly due to the motion resistance of the soil, which at a rake angle of less than 70° has a downward force component. The more the crampon penetrates the soil, the stronger the motion resistance, which forces it deeper and deeper into the soil until its draft force is higher than the draft force of the tillage implement it must move. As the crampon rotates around the hinge the rake angle increases and with that the horizontal draft force. When the motion of the frame is reversed, the rake angle is reversed: 70° becomes 110° , motion resistance results in a strong upward force, and the crampon is quickly pulled out of the soil.

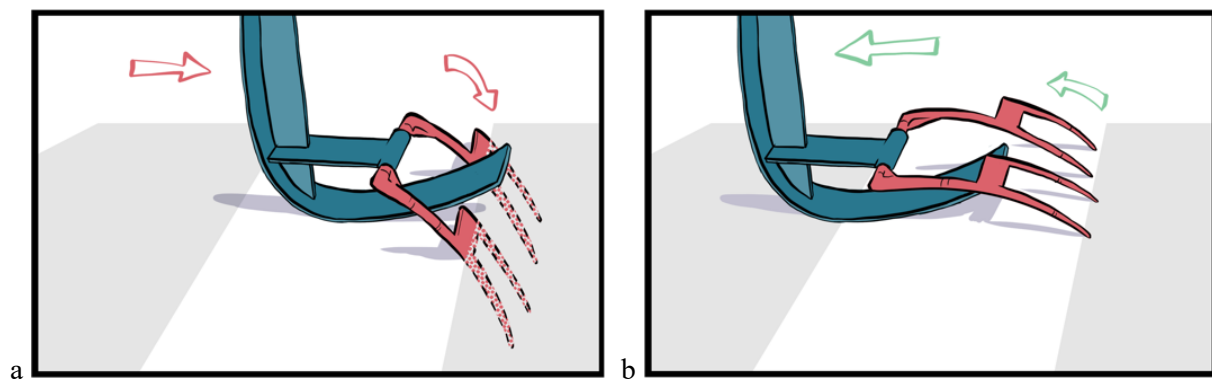


Figure 1. A hinge allows relatively simple crampon placement. Vehicle motion is from right to left, such that when a frame is pushed or pulled back, it moves from left to right. (a) Crampons are pushed into the soil. (b) Crampons are pulled out of the soil.



Figure 2. Empirical crampon designs. In each photo, there is a vertical shaft that connects the crampon to its implement frame. At the base of the shaft, there is a horizontal hinge to which the crampons are connected, allowing them to swing up and down. The straight crampons in (a) and (b) penetrate the soil to a depth of 10cm and 20cm respectively, the curved crampons in (c) penetrates to about 5cm. (a) and (b) also have a tillage implement (a sweep) connected to the base.

Since the strength of agricultural soil has high spatial variability (Watts et al. 2006), once the crampon is anchored and the tillage implement it pulls or pushes moves forward, the soil strength encountered by the tillage implement can increase significantly within a meter or less, such that the draft force of the tillage implement becomes greater than the original draft force of the anchor. When this happens, the insertion mechanism as described here pushes the crampon even deeper into the soil, until the draft force of the crampon is again greater than the draft force of the tillage implements. Because of this self-regulating mechanism, the crampon will be pushed only as deep into the soil as is needed for a given stretch of soil, which is energy efficient and avoids unnecessary disturbance of the subsoil. We find that crampons that are designed as in Figure 2 penetrate the soil efficiently and reliably. In each case, the crampons will initially enter the soil at an angle of about 45° , which generates a strong downward force, and then rotate into a position of about 70° .

2.4 Forces acting upon the crampon, the resulting pull/weight ratio, and implications for vehicle design

The pull/weight ratio is a fundamental property of any traction device as it has many implications for the damage it will do to the soil, the type of terrain it can navigate, and the energy it will consume. The pull/weight ratio is also referred to as the net traction ratio, P/W, dynamic traction ratio, or coefficient of traction (Zoz and Grisso, 2003). To understand the pull/weight ratio for crampons at the maximal penetration depth when the rake angle has reached 70° , consider a traction device as shown in Figure 3. This device has a rear and a front crampon. The rear crampon has reached a rake angle of 70° in the soil while the front crampon is outside the soil. The device has a central horizontal shaft with wheels to stabilize it. The wheels and the front crampon which is sliding over the ground create motion resistance F_R . The rear crampon is attached with a hinge H to a frame that is moving with respect to the horizontal shaft by a motor. When power is supplied to the motor, the motion resistance forces F_R and the force from the anchored rear crampon meet at the hinge of the rear crampon, and it is convenient to discuss the different forces as they act on this point. It is also convenient to discuss the forces acting on the rear crampon as if they were concentrated at the tip of the crampon which is deepest in the soil, since the motion resistance is strongest at the tip and since any weight that suffices to balance the forces acting on this point will also balance forces acting on a point higher up.

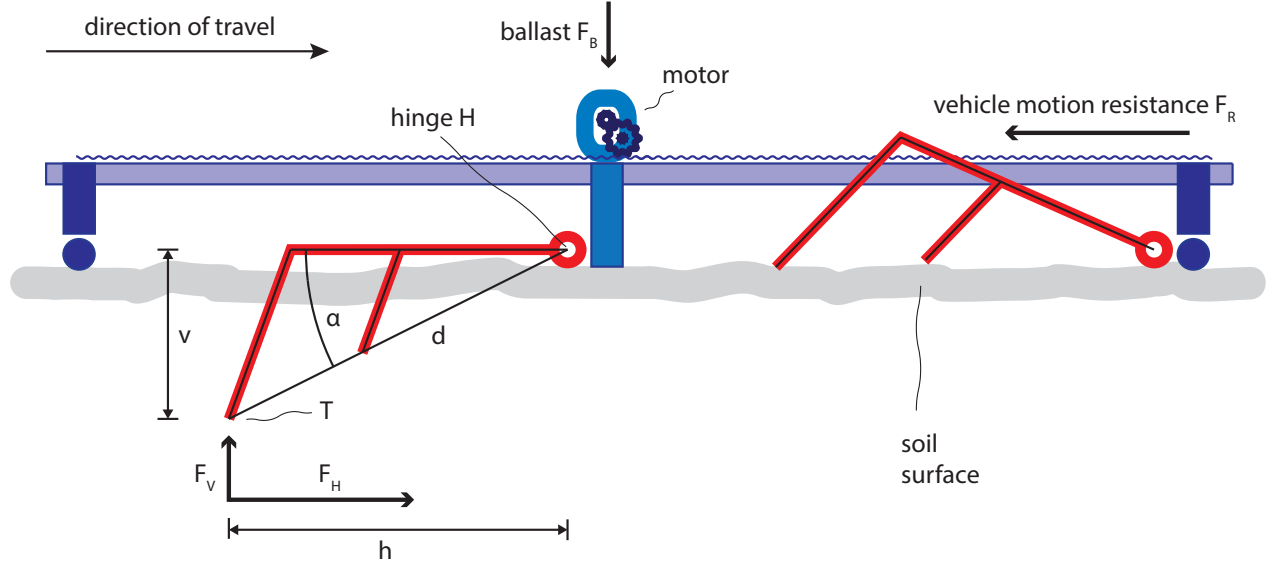


Figure 3. Dynamic forces in a push-pull device with crampons.

When the motor is under power, the crampon presses into the soil at an angle α along the diagonal d . While the horizontal draft force F_H of the crampon matches the horizontal motion resistance F_R ,

$$(1) \quad F_H = -F_R,$$

the vertical force F_V of the crampon quantifies the ballast force F_B needed to prevent the crampon from moving out of the soil,

$$(2) \quad F_B = -F_V = -F_R * \frac{v}{h},$$

where v is the vertical distance between H and the tip of the crampon T and h is the horizontal distance between H and T , and $v/h = \tan(\alpha)$.

Crampons turn the optimal pull/weight ratio into a geometric question. Given that a traction device will have some weight, the need for additional ballast can be eliminated by placing the hinge as close to the ground as possible, and by making the horizontal distances between the hinge and the crampon tips as large as needed for the load. Therefore, the crampons in Figure 2 and 3 comprise rods which penetrate the soil, and of arms which connect the rods to the hinge. The arms allow a low placement of the hinge without compromising the ability of the rod to rotate from 45° to 70° during penetration, and the length of the arm controls the pull/weight ratio. In over 20 prototypes that we built and tested at the farm Son Duri in Mallorca, Spain, we have successfully placed the crampon hinge 20–30 mm above the soil.

Consider a straight tine as in Figure 2b with an arm of 400 mm length and a rod of 260 mm length, which we found to provide good motion resistance for most applications. When the arm is in the horizontal and the rod has reached a rake angle of 70° , we have $v = 244$ mm, $h = 489$ mm, and a pull/weight ratio of 2.0, which is five times more than the recommended pull/weight ratio of 0.4 for a tired or tracked vehicle on similar soil.

2.5 Push-pull mechanism

To move a device from a static anchor point, the traction mechanism needs to use a push-pull mechanism, resulting in what is known as inching locomotion. Most versions of inching locomotion expand and contract the wheelbase of a wheeled vehicle. To the best of our knowledge, the idea to insert narrow retractable rods or tines into the ground to push or pull a vehicle forward by inching locomotion has not previously been studied.

Spanski (1963) described experiments for the US Army where the front and rear units of a vehicle are connected by a hydraulic cylinder. Starting in the contracted or minimum length position, the operator brakes the rear unit and applies power to the front unit. Power is also applied to the inching cylinder between units. Thus, the first unit develops its normal tractive effort, plus getting a push from the rear unit. The functions of the two units are then reversed and the second unit is drawn up behind the first. Spanski found that there was a tendency for the wheels of the front unit to "dig in" faster than the unit could be pushed forward. Inching locomotion was subsequently abandoned for over 50 years until Moreland et al. (2011) studied it for the exploration of extraterrestrial terrain, finding that static wheels provide about twice as much tractive force as rolling wheels on soft soil.

The simplest push-pull mechanism comprises two independent frames, one behind the other, which are connected by a rigid extensible shaft. Each frame can be provided with crampons, such that when the front frame is anchored, the rear frame is pulled forward, and when the rear frame is anchored, the front frame is pushed forward. Figure 4 illustrates a complete motion cycle of a cultivator which uses push-pull and crampons.

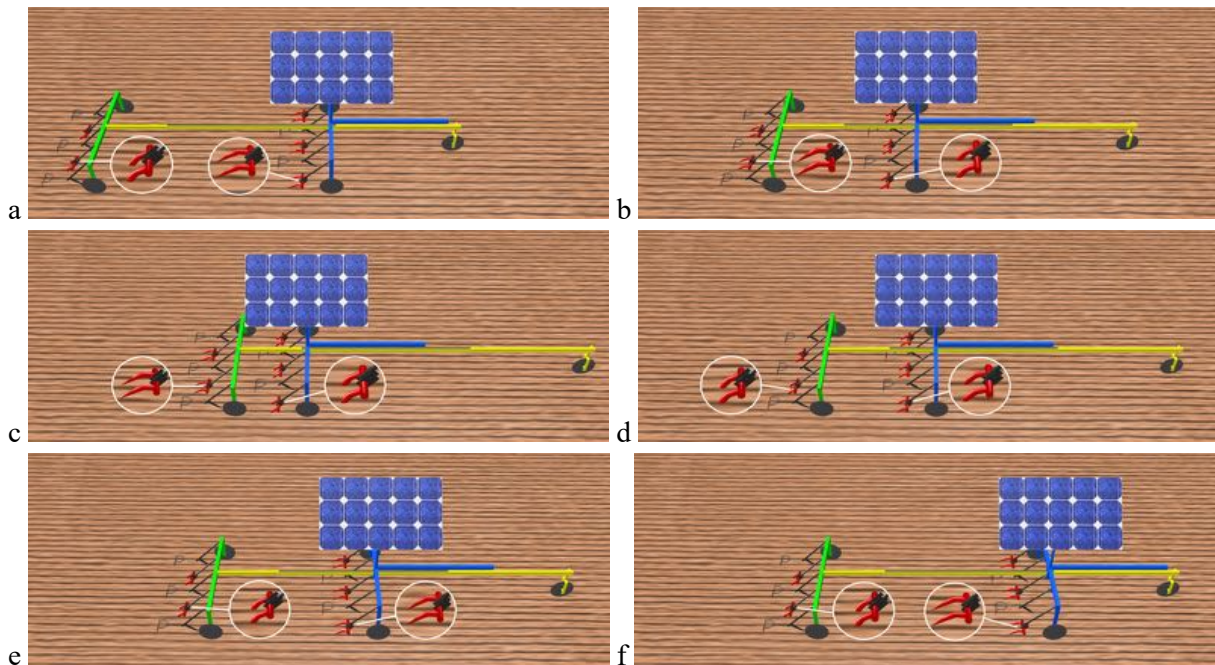


Figure 4. The crampons on two frames are inserted into and extracted from the soil in an alternating push-pull motion pattern. The vehicle in this figure moves from left to right. (a) The vehicle is fully extended. The left frame is anchored and the right frame is at the extended position but not yet anchored; (b) Right frame is anchored and left frame is pulled to the right; (c) The vehicle has fully contracted; (d) Left frame is anchored right frame is pushed to the right; (e) Continuation of motion in middle right image; (f) At the end of the push phase, the vehicle is fully extended.

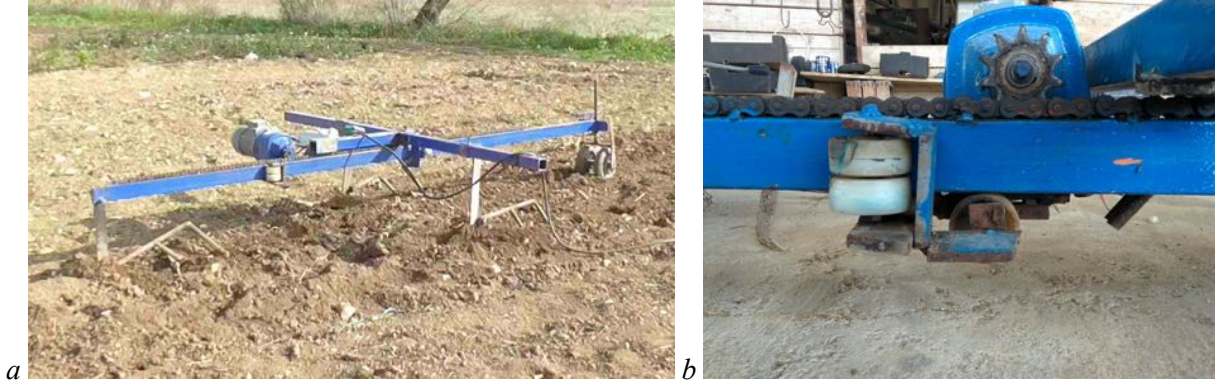


Figure 5: Drive train with cogwheel and chain welded to the central shaft.

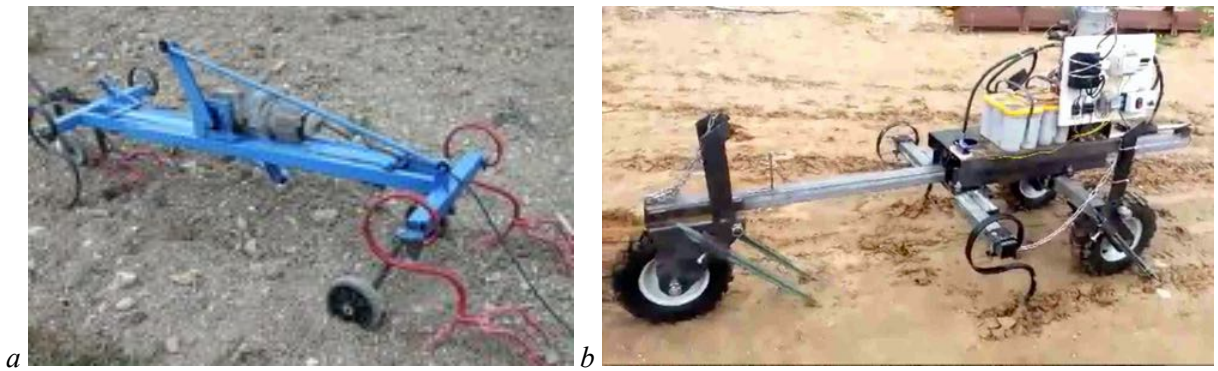


Figure 6: Left: Crankshaft drive train. Right: Hydraulic drive train.

Figures 5 and 6 show different implementations of the extensible shaft: a cogwheel which interlocks with a chain on the extensible shaft, a crankshaft, and a hydraulic system.

3. Motion dynamics, travel reduction, and tractive efficiency

Travel reduction is a reduction in distance traveled because of losses because of tire flexing, slip between surfaces, and shear within the soil (Zoz and Grisso 2003). The travel reduction ratio TRR is expressed as

$$(3) \quad TRR = 1 - \frac{v_a}{v_t},$$

where v_t is the theoretical or ideal velocity which could be achieved if there were no losses, and v_a is the actual velocity as measured. Crampons do not have travel reduction because of tire flexing but have some travel reduction because of the hinged design which drives a crampon backward into the soil under backward pressure. Once inserted, an increase in pull will force the crampon deeper into the soil, resulting in some slip and shear.

To discuss the travel reduction during the motion cycle of a push-pull device with crampons, consider the basic vehicle design in Figure 5. Two frames move independently from each other and are connected by an extensible shaft which is a metal bar to which a chain is welded. The front frame (a vertical shaft at the left end) is welded to the front of the extensible shaft. The rear frame, a horizontal shaft at a right angle with the central shaft, moves freely along the central shaft. An asynchronous

electrical motor with cogwheel is mounted on the rear frame such that the cogwheel interlocks with the chain on the central shaft. The cogwheel needs a fixed number of rotations to extend and contract the shaft fully. The actuation length d_a by which this shaft extends and contracts fully is a principal factor in the calculation of the resulting motion.

During the pull phase, the rear frame A advances by a distance d_a toward the front frame B and during the push phase, the front frame B moves by a distance d_a ahead of the rear frame A . Let t_m be the duration of a single pull or push phase when the motor is driven at nominal frequency and load. We find that the theoretical velocity of the vehicle is

$$(4) \quad v_t = \frac{d_a}{2 t_m}.$$

The actual velocity is lower because the crampons slide a certain distance backward through the soil when they are driven into the ground: at the beginning of a push phase, the rear frame A slides backward by a distance s_b while the back crampons penetrate the ground. Likewise, at the beginning of a pull phase, the front frame A slides backward by a distance s_a while the front crampons penetrate the ground, see Figure 7. The slip distances s_a and s_b depend on local soil conditions and are variable. The actual distance d_c covered during a complete motion cycle of the vehicle is $d_c = d_a - (s_a + s_b)$. The actual velocity v_a can be calculated as

$$(5) \quad v_a = \frac{d_a - (s_a + s_b)}{2 t_m},$$

and the travel reduction ratio is

$$(6) \quad TRR = \frac{s_a + s_b}{d_a}.$$

We note that the effective velocity v_e of the vehicle is lower than v_a because the electric motor needs time t_s to reverse direction and to ramp up when controlled by a variable frequency drive. t_s is constant and is the same for the pull and push phase:

$$(7) \quad v_e = \frac{d_a - (s_a + s_b)}{2 t_m + 2 t_s}.$$

The tractive efficiency TE measures the ratio of output power to input power or output energy to input energy over a given time. It is usually expressed in percent. With a push-pull vehicle with crampons, all energy needed to move the anchoring frame backward and drive its crampons into the soil can be considered as lost. The energy which moves a frame forward is doing useful work while covering distance d_c but is lost when recovering the distances s_a or s_b , which is the distance the frame moved backward during the alternating motion phase when it was being anchored. We calculate tractive efficiency

$$(8) \quad TE = \frac{2 * F_R * (d_a - (s_a + s_b))}{(F_C + F_R) * (s_a + s_b) + 2 * F_R * (d_a - (s_a + s_b))},$$

where F_R is the motion resistance of a frame which is being moved forward and F_C is the motion resistance of a frame which is being moved backward. As with travel reduction, tractive efficiency will increase with the actuation length d_a of the push-pull mechanism.

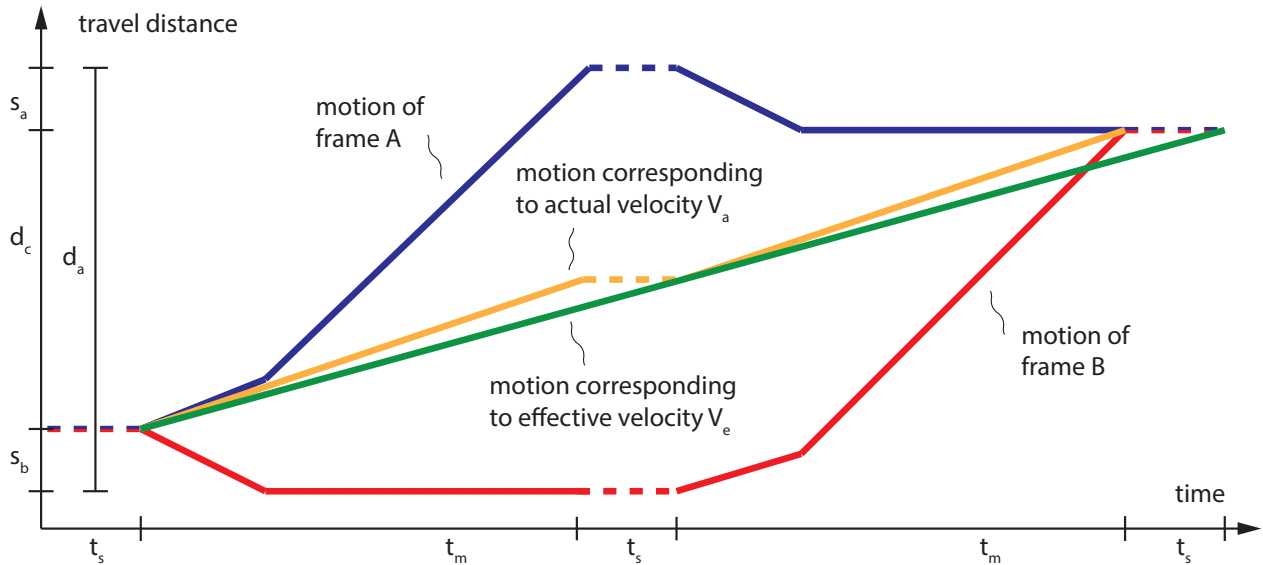


Figure 7. Diagram of the motion dynamics. The upper blue line illustrates the motion of frame A and the lower red line illustrates the motion of frame B. The frames slip back by distances s_a and s_b at the start of a push or pull phase. The switching time t_s is the time lost when the motor reverses direction.

4. Experimental evaluation

To assess the efficiency of traction with crampons we conducted two experiments under realistic conditions on agricultural land in Vilafranca de Bonany, Mallorca, Spain. The device was configured for secondary tillage with sweeps at 5 cm depth. The first experiment was done on very soft soil. It had been cultivated a month earlier and little weed had established. The second experiment was done on harder soil which had not been cultivated for over two months, where a duricrust had formed, and where weed was well established. The soil was dry and comprised 19% sand, 50% silt, and 31% clay.

The machine was powered by an electric asynchronous motor and controlled by a variable frequency drive. The motor powered a cogwheel which moved a central frame with respect to the central extensible shaft. A digital Wattmeter (a SEM 16+, produced by Nordwestdeutsche Zählerrevision, NZR) allowed the measurement of electric input power every 0.83 seconds at a precision of 1%. Since the motor properties were known, we were able to calculate the mechanical load on the motor. The average load is shown in Figure 8.

The central shaft had frames with tillage tools (sweeps) attached at the front and rear, with a total tool width of 120 cm. We will call this frame the 120 cm frame. To provide traction, the central shaft was fitted with three straight crampons as in Figure 2b and two curved crampons as in Figure 2c. The central frame, which moved with respect to the central shaft, had sweeps with a total tool width of 140 cm and was provided with two straight crampons and two curved crampons as in Figure 2b and 2c. We will call this frame the 140 cm frame. The dimensions of the straight crampons were as discussed at the end of Section 2.4. The total machine weight was 196 kg. From ASABE (2006) the sweeps of the 120 cm frame were expected to have a draft of about 1.7 kN and the sweeps of the 140 cm frame were expected to have a draft of 2 kN, so the average pull/weight ratio was expected to be 1.0 or less. Soil resistance is highly variable, deviations of 50% from the mean being common, so a traction device should be prepared to handle higher drafts.

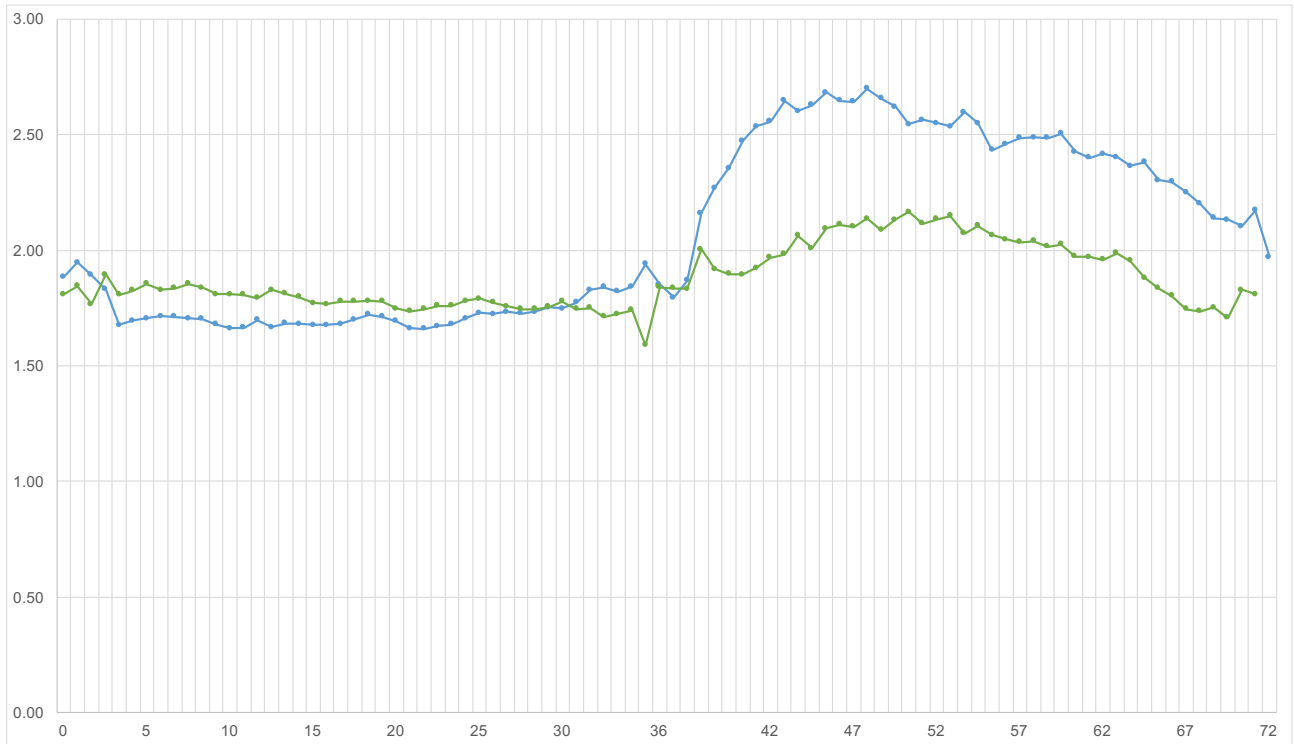


Figure 8. Average load or draft calculated from electric input power over a complete motion cycle. The blue line: first experiment. The green line: second experiment. The x-axis shows the average 72 seconds of a motion cycle. The y-axis shows motor load in kN. The first 36 seconds show the draft of the 120 cm frame. The second 36 seconds show the draft of the 140 cm frame. The high draft of the 140 cm frame during the second motion phase is likely because of an incorrect depth setting of the tillage tools on the respective frame. The motor switches direction at second 0 and 36, and crampon insertion is mostly accomplished within the first three seconds thereafter.

During the experiments, the highest single reading of mechanical load as calculated from input power was 3.1 kN, corresponding to a pull/weight ratio of 1.6, well within the margin of the pull/weight ratio of 2.0 which we calculated for the straight crampons in Section 2.4. During the first experiment on soft soil, the straight crampons penetrated the soil to a depth of up to 20 cm while during the second experiment on harder soil they usually penetrated to a depth of about 5 cm. The curved crampons always penetrated to a depth of 5 cm by design.

Travel reduction because of the slip of the crampons in the soil can be measured by comparing the distance traveled by the cogwheel on the chain to the actual distance covered by the machine. For each contraction and each expansion, the cogwheel traveled exactly 4.026 m on the chain. During the first experiment, 15 motion cycles were measured with a total travel distance of 55m, resulting in an average slip of 18 cm per motion phase and 36 cm per motion cycle. During the second experiment, 12 cycles were measured with a total travel distance of 45.2 m, resulting in an average slip of 13 cm per motion phase and 26 cm per motion cycle. This is a travel reduction of between 6% and 9% on tilled soil.

As for tractive efficiency, we note that during the first three seconds of the pull and the push phase the mechanical load on the motor is about 1.90 kN during the first experiment and 1.85 kN during the second experiment, which we take to be the force F_C needed to anchor the crampons. Using Equation 8

we calculate a tractive efficiency of 91.5% for the first experiment and 93.5% for the second experiment. The results are summarized in Table 1.

Table 1. Results from two field experiments.

	First experiment	Second experiment
Soil	Recently cultivated, few weeds	Two months untreated, crust, some weeds
Depth of straight crampons in soil	20 cm	5 cm
Number of full motion cycles	15	12
Distance traveled	55.0	45.2
Expected draft of sweeps (120 cm frame / 140 cm frame)	1.7 kN / 2.0 kN	1.7 kN / 2.0 kN
Average mechanical load (120 cm frame / 140 cm frame)	1.73 kN / 2.42 kN	1.79 kN / 1.98 kN
Maximal mechanical load	3.10 kN	2.91 kN
Average pull/weight ratio (120 cm frame / 140 cm frame)	0.9 / 1.3	0.9 / 1.0
Maximal pull/weight ratio measured	1.6	1.5
Average slip of crampons	18 cm	13 cm
Vehicle travel reduction	9%	6%
Average load during the first three seconds of pull and push phase	1.90 kN	1.85 kN
Estimated tractive efficiency	91.5%	93.5%

5. Discussion

We observed a fundamental difference between the calculation of the pull/weight ratio, travel reduction, and tractive efficiency of wheeled (or tracked) vehicles and a push-pull mechanism with crampons. With crampons, the pull/weight ratio, travel reduction, and tractive efficiency can be controlled by vehicle geometry. The need for ballast is proportional to the length of the arm which connects the soil-penetrating part of the crampon to the hinge. Travel reduction is inversely proportional to the actuation length of the extensible shaft of the push-pull mechanism. Tractive efficiency increases with the same actuation length.

Further research is needed to establish how reliably the technology can generate traction on different soils and in different terrains, and if the efficiency can further be improved, for example by forcing the crampons faster into the soil. Various methods of steering and turning the vehicle are possible and need to be further developed. A push-pull vehicle is not comfortable for a human driver, and a commercially viable design will probably need to include autonomous navigation.

We have tested a variety of different prototypes and found that the principle of crampons with push-pull allows for a broad range of design options for the crampons, the drive train, and the energy supply. Videos of the various prototypes at work can be found at <http://www.sedewa.com/utopus.html>.

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