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AN ENGINEERING REVIEW OF THE FARM TRACTOR'S EVOLUTION TO A DOMINANT DESIGN

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ABSTRACT

This article explains the origin and performance merits of the conventional farm tractor design, which has endured largely unchanged since the 1940's. The article covers two main themes: first the historical context and external pressures that directed the farm tractor's design evolution; and then an analysis on why the tractor's proportions and force applications points are conducive to good performance. The conventional tractor's weight distribution, wheel proportions, farming implement attachment, and frame construction are discussed.

NOMENCLATURE

p soil (normal) pressure
 c soil cohesion
 k'_c cohesion constant
 γ_s soil bulk density
 k'_ϕ friction constant
 z depth below the surface
 n depth exponent
 s soil shear strength
 ϕ soil friction angle
 k soil shear modulus
 j soil shear deformation
 i slip at tire-soil interface

H tractor traction thrust force
 V vertical soil reaction force
 w tire width
 R tire outer radius at contact point
 P_t tire pressure
 η tractive efficiency
 F pulling force generated by tire
 S actual forward speed of vehicle
 P power delivered to wheel
 P_t net tire pressure
 W weight
 D draft force
 B soil bulldozing force

1 Introduction - The importance of farm tractors

Tractors are an icon of industrialized, modern farming and their presence has been noted as a differentiator between farming in developed versus developing countries [1] [2]. There is high correlation worldwide between farm productivity and available tractor power [3] [4] [5] [1]. In 1950, the USA Census Bureau summarized the benefits of mechanizing American agriculture during the past 50 years [6]: 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, en-

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abling 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 paper aims to facilitate improvements to farm tractors by providing an explanation for the conventional farm tractor design and an analysis framework that can be also be used to evaluate new tractor designs.

2 History of farm tractor evolution to a dominant design

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 [7] [8] [9] [10]. 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 wheels joined by differential axle (front wheel assist sometimes present).
- The braking force at each rear wheel can be controlled independently (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 block and transmission case used as structural components.

Similarly to most 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 and 2.3. They are also summarized in Figure 1.

To emphasize the other design directions the nascent tractor industry could have gone on, Figure 2 shows 24 production tractor layouts from between 1910 and 1920. Layouts varied widely in traction gear (mostly combinations 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 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 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 north-eastern cities. Earnest farmers tilled the wild soil and rapidly expanded the total amount of available arable land [7]. 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 1910’s 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. USA farming land prices were on a sharp rise as farmers had surplus money and looked to increase production by investing in expanding their properties. Farms grew in number and size yet farm labor was more 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 [6].

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 [24]. It still 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 [25] [24]. 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 [7] [26]. The demand for a less expensive, smaller, and lighter tractor was growing louder and manufacturers new and old rushed to fill the void [27] [28].

The first tractor to meet the demands of the common farmer in size and price was offered by the “Bull Tractor Company” in 1913. This lightweight tractor had three wheels with a single drive-wheel and had an initial price comparable to a team of horses. By 1914 it was the best-selling tractor in the country [7]. 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 price and volume that would raise the entry barrier to tractor manufacturing beyond

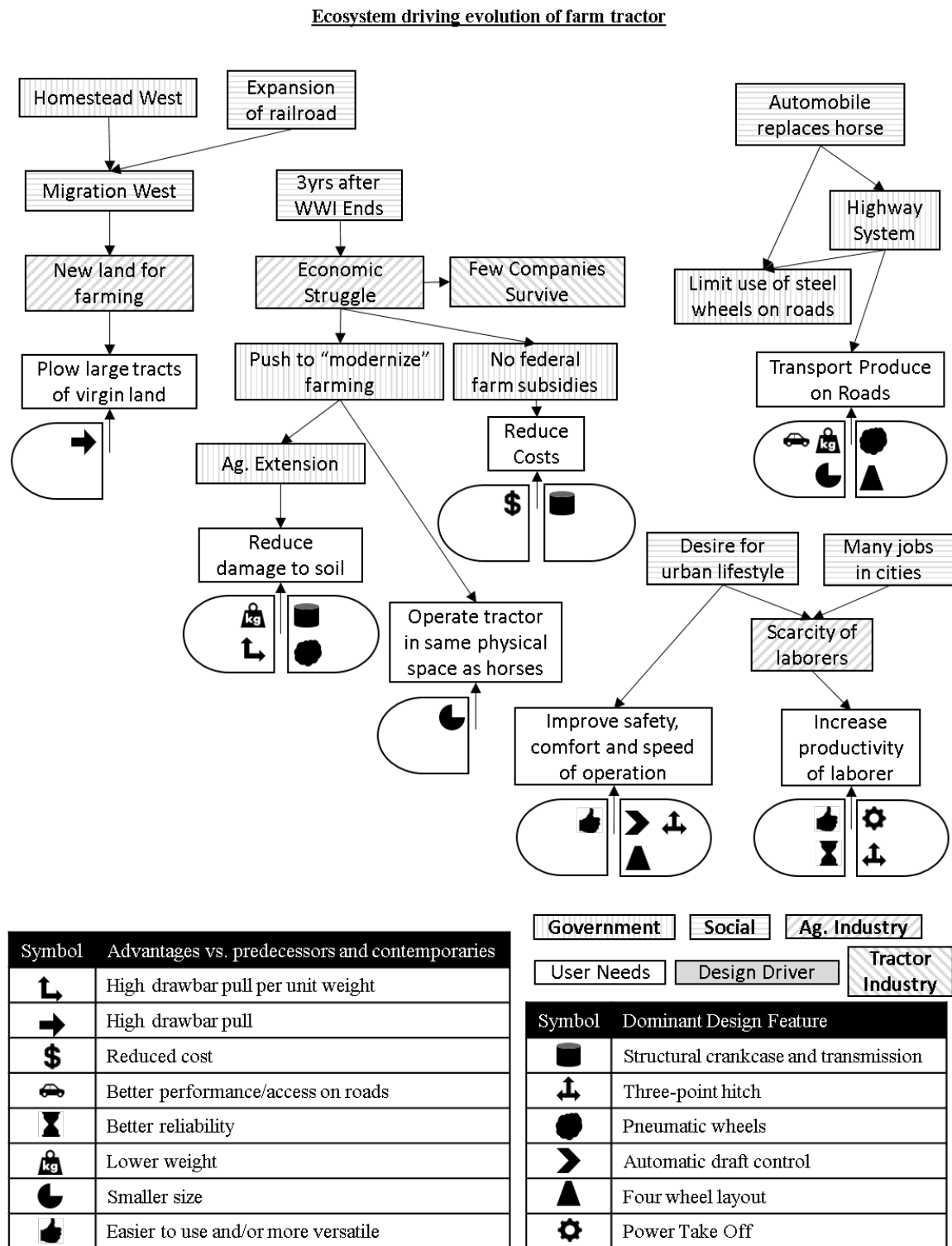


FIGURE 1. GRAPHIC CHRONOLOGY OF TRACTOR EVOLUTION AS DRIVEN BY THE HISTORICAL CONTEXT AND STAKEHOLDER EXPECTATIONS.

Sample of Production Tractor Layout Designs 1910 to 1920

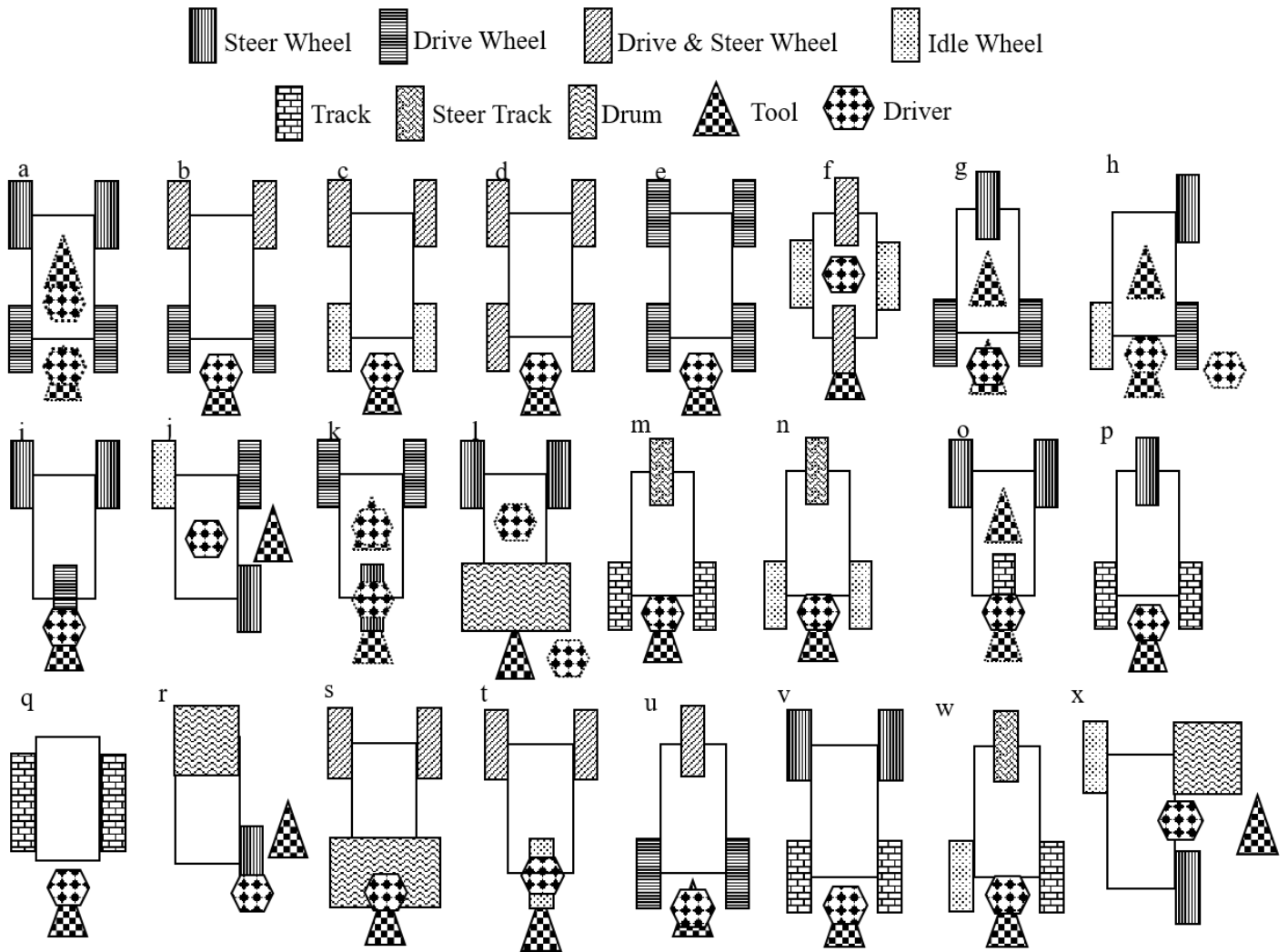


FIGURE 2. SAMPLE OF TRACTOR DESIGN LAYOUTS FROM 1910 TO 1920. COMPONENTS WITH A DOTTED OUTLINE REPRESENT MULTIPLE POSSIBLE LOCATIONS IN OTHERWISE IDENTICAL LAYOUTS. A LIST OF SOME PRODUCTION TRACTORS USING EACH LAYOUT CAN BE FOUND IN APPENDIX A.

what most smaller competitors could muster [7]. 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").

2.3 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 year 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 [29]. 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 Figure 2) [24] [25].

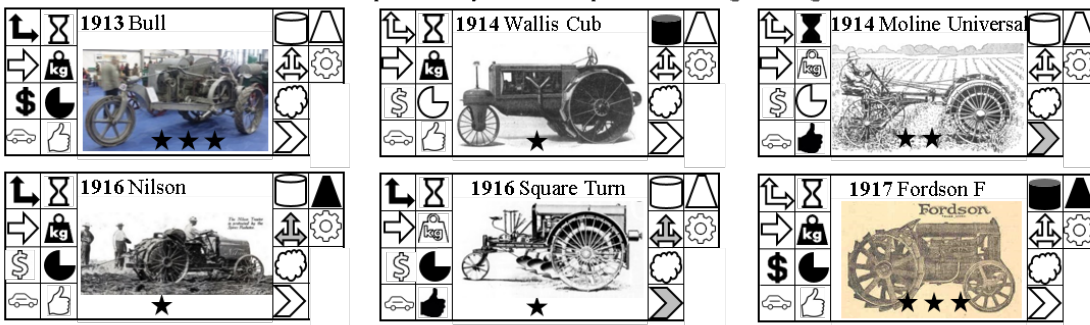
During 1921, a dramatic shift occurred. European and Rus-

Evolution of Farm Tractor to Dominant Design

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	Symbol	Dominant Design Feature
	High drawbar pull per unit weight		Structural crankcase and transmission
	High drawbar pull		Three-point hitch
	Reduced cost		Pneumatic wheels
	Better performance/access on roads		Automatic draft control
	Better reliability		Four wheel layout
	Lower weight		Power Take Off
	Smaller size		
	Easier to use and/or more versatile		

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

Feature is: absent evolving present

FIGURE 3. GRAPHIC CHRONOLOGY OF TRACTOR EVOLUTION INTO CONVENTIONAL SMALL TRACTOR DESIGN. MORE DATA ON VEHICLES MAY BE FOUND IN APPENDIX B. PHOTO CREDITS: 1902 IVEL [11], 1908 HART PARR [12], 1909 AVERY FARM CITY [13], 1913 BULL I [14], 1914 WALLIS CUB [15], 1914 MOLINE [16], 1916 NILSON [17], 1916 SQUARE TURN [18], 1917 FORDSON F [19], 1921 IHC 15-30 [20], 1924 IHC FARMALL [21], 1924 ALLIS CHALMERS U [22], 1939 FORD 9N [23]

sian agriculture had recovered enough from WWI to suddenly make them largely independent of imported food. Farmers in the USA had misjudged international demand and severe 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. Farm tractor production plunged by two-thirds from 203,277 units in 1920 to 68,029 units in 1921 [29].

The Great Depression and Stock Market Crash of 1929 would keep American farmers in a difficult position through the 1920's and 1930's. 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. Over the next 20 years a fiercely price-competitive tractor market would see manufacturers converge on similar designs [7]. 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 [29]. 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 [6].

2.4 Emergence of dominant tractor design features between 1920 to 1940

Some major innovations between 1920 and 1940 that shaped the dominant tractor design are [10]:

1921 - First Nebraska Tractor Test is performed. These tests would go on to become the national, and later international, standard for tractor testing. The test's prominence still makes it a major quantifiable target for tractor manufacturers. Most of the more marketable parts of the test involve towing a braked vehicle behind the tractor, an operation generally better suited to tractors designed to pull heavy tillage tools.

1922 - International Harvester introduces the Power Take Off (PTO), allowing the tractor's engine to power 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. 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

- Was advertised for cultivating, plowing, and cutting.

1927 - John Deere introduces "Power Lift", allowing the farmer to use the engine's power to raise and lower farming implements. This reduced the drudgery of tractor usage and increased tractors' field capacities (actual acres worked per hour).

1932 - Firestone and Allis Chalmers introduce the pneumatic rubber tire. This allowed tractors on the growing network of paved roads (where steel, lugged wheel were not permitted) and enabled farmers to operate at higher speeds more comfortably.

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

3 Analytical modeling of the conventional tractor's design

The modeling of a tractor on soil can be separated into two related parts: calculating the distribution of forces among all tires (the tires hold the tractor afloat and propel it forward) and, given those load conditions, calculating the power consumption and other performance metrics at each individual tire. For force distribution, this article considers only the case of a standard tractor on flat ground, assumes a state of equilibrium, and assumes that all drive wheels are connected via a standard differential axle (i.e. deliver the same torque).

3.1 Conventional tractor dimensions and relevant forces

Calculation of the tractor-applied forces at the tire-soil interface requires modeling of the full tractor and farm implement system. Under the assumption of the tractor being a laterally symmetric rigid body, and all the wheels having their center axes orthogonal to gravity and parallel to each other, the tractor free-body diagram 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 contact points
- tractor orientation with respect to gravity (uphill or downhill slope)

An high-level assessment on the effects of slightly altering conventional tractor dimensions on reaction forces at the tire-soil interface can be obtained from studying Figure 4.

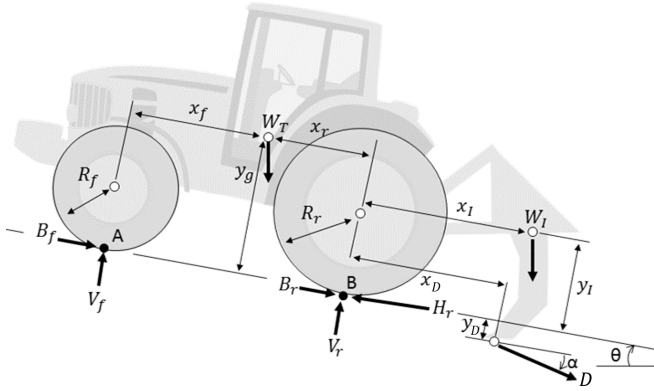


FIGURE 4. FULL BODY DIAGRAM FOR FARM TRACTOR IN 2D.

Overall, the sum of the vertical force on both front wheels is:

$$V_f = \frac{1}{x_f + x_r} (W_T(x_r \cos(\theta) - y_g \sin(\theta)) + D(y_D + \cos(\alpha) - x_D \sin(\alpha)) + W_I(-x_I \cos(\theta) - y_I \sin(\theta))), \quad (1)$$

and the sum of the vertical force on both rear wheels is:

$$V_r = \frac{1}{x_f + x_r} (W_T(x_r \cos(\theta) + y_g \sin(\theta)) + D(-y_D + \cos(\alpha) + x_D \sin(\alpha)) + W_I((x_I + x_r + x_f) \cos(\theta) + y_I \sin(\theta))). \quad (2)$$

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:

$$H = B_f + B_r + D \cos(\alpha) + (W_T + W_I) \sin(\theta). \quad (3)$$

The calculation of the actual wheel torque necessary to achieve H_r and the calculation of resistance forces B_f and B_r , requires an analysis as described in section 3.3.

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% [30].

The two major causes of power loss are soil deformation and slippage at the tire-soil interface [31]. 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 points is faster than the forward speed of the vehicle. Presence of at least minimal slippage is unavoidable because 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 [32] [31]. 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.

3.3 Model for interaction of single drive tire with soil

The tire-soil model summarized here is as described by Wong [31] and is commonly accepted in terramechanics. Research groups have suggested accuracy improvements which sometimes come at the cost of generality or requiring more experimental data. Senatore [33] has provided a good summary of potential improvements to this tire-soil model.

For analytically studying the tire-soil interface, it is helpful to study 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 Figure 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.

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 [34] or Reece’s equations [35]. Reece’s equation is

$$p = (ck'_c + w\gamma_s k'_\phi)(z/w)^n, \quad (4)$$

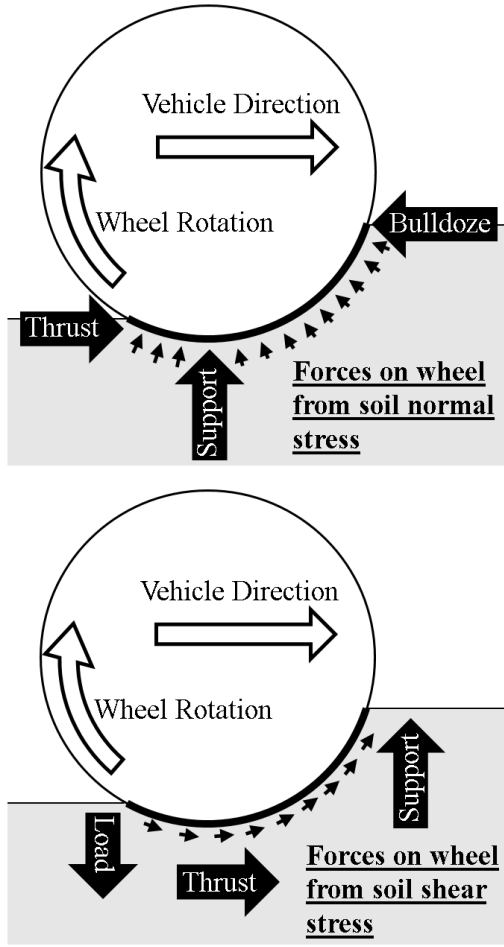


FIGURE 5. STRESS UNDER RIGID DRIVEN WHEELS ROLLING ON DEFORMABLE SOIL. SEPARATED FOR CLARITY INTO NORMAL AND SHEAR STRESS. WHEELS ARE MOVING TO THE RIGHT AND ROLLING CLOCKWISE. NOMENCLATURE ACCORDING TO REACTION FORCE DIRECTION (AS FELT BY WHEEL) ARE SHOWN IN SOIL.

where, p =soil pressure, c =soil cohesion, k'_c =cohesion constant, w =tire width, γ_s =soil bulk density, k'_ϕ =friction constant, z =depth below soil surface, n =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:

$$s = (c + p \tan(\phi))(1 - e^{-j(i)/k}), \quad (5)$$

where, s =soil shear strength, p =soil (normal) pressure, c =soil cohesion, ϕ =soil friction angle, k =shear modulus, j =shear deformation, i =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 tire is compliant and assumed to take the idealized form shown in Figure 6 when deformed, it can be separated into three sections: front circular arc of tire, flat horizontal section at bottom of tire (the depth at which the tire total pressure matches the soil pressure), and rear circular arc of tire. These sections are defined by the angles θ_c , θ_f , and θ_r .

It is often the case that reaction forces are known but not tire slippage or sinkage. In that situation the a suitable combination of tire slippage, and angles θ_c , θ_f , and θ_r can be found via a control strategy as shown by Senatore in [33].

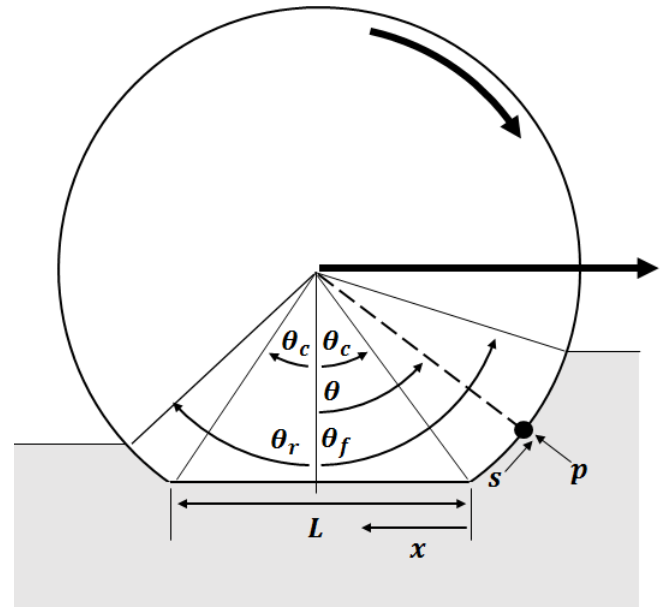


FIGURE 6. PARAMETERS OF TIRE PERIMETER FOR CALCULATION OF FORCES AT INTERFACE.

The net vertical force may then be mathematically expressed as

$$\begin{aligned} V = & wR \int_{\theta_c}^{\theta_f} [p(\theta) \cos(\theta) + s(\theta, i) \sin(\theta)] d\theta \\ & + w2RP_f \sin(\theta) \\ & + wR \int_{\theta_c}^{\theta_r} [p(\theta) \cos(\theta) - s(\theta, i) \sin(\theta)] d\theta \end{aligned} \quad (6)$$

The horizontal force will be expressed as

$$\begin{aligned}
H = & wR \int_{\theta_c}^{\theta_f} [-p(z)\sin(\theta) + s(\theta, i)\cos(\theta)]d\theta \\
& + w \int_0^{L(\theta_c, R)} s(\theta)dx \\
& + wR \int_{\theta_c}^{\theta_r} [p(\theta)\sin(\theta) + s(\theta, i)\cos(\theta)]d\theta
\end{aligned} \quad (7)$$

For both equations variables are defined as H =drawbar pull, V =vertical ground reaction, w =tire width, R =tire radius, P_i =net tire pressure. The angles θ_c , θ_f , and θ_r define the tire shape and sinkage into the soil as shown in Figure 6.

3.4 Validation of Tractor Model with Published Data

The model discussed in Section 3 may be used to evaluate and inform design of farm tractors. To verify the model's accuracy as implemented, in this section its outputs are compared to published data on production tractors [36] [37].

Experimental data were obtained from Battiato, Diserens, and Sartori [36] [37], where four different-sized production tractors were tested in various soil conditions. To test a tractor's drawbar pull performance, it would tow a "braking" tractor behind it via an instrumented cable. The braking tractor would be 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.

4 Analytical model insights into tractor dominant design

This summarizes why the dominant tractor design is a good engineering product. The historical evolution of the tractor was elaborated on in Section 2.

4.1 Advantages of conventional tractor wheelbase length and weight distribution

Modeling and experimental data agree that for a conventional small tractor (four wheels, rear wheel drive, trailing farm implement) the ideal weight distribution for efficient drawbar pull occurs at about 30% weight on the front wheels and 70% weight on the rear wheels. This is for an operation on flat ground and in a straight line. This weight distribution is what is usually found on the dominant tractor design.

Figure 8 summarizes model results for the effect on tractive efficiency of weight, weight distribution, and draft magnitude. The weight distribution shown in Figure 8 is a statically measured weight distribution at zero drawbar pull. The effective weight distribution during operation is accounted for during simulation calculations, however. 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. Placing more than 80% of a conventional tractor's weight on its rear wheels is not recommended. Doing so does not improve efficiency but does increase the risk of the tractor tipping backwards.

The Nebraska Tractor Tests are a standardized testing method to evaluate the performance of farm tractors. Test results have are often used by manufacturers when promoting their tractors. One of the more marketable parts of the test involves the maximum generated drawbar pull force when towing a braked vehicle behind the tractor, an operation generally better suited to tractors designed to pull heavy tillage tools. Before 1950 the tests were performed on soil instead of the concrete track now used. During that earlier period, it was also more common to test vehicles under 30hp. These two facts make the Nebraska prior to the 1950s the most informative ones for this work. Farm tractors below 25hp tested between 1941 and 1950 were selected for comparison to Figure 8.

For tests, engineers employed by the manufacturer whose tractor was being tested were allowed to set up the 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 Figure 9, it can be observed that the engineers would generally setup 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 in agreement with the outputs the Section 3 model. The mass increase would increase maximum drawbar pull as predicted by the model. The weight distribution seen in the Nebraska tests is at the point where its benefits asymptote in modelling as shown in Figure 8.

4.2 Advantages tillage tool rigid mounting behind rear axle

Tillage tool mounting is a critical feature of the dominant tractor design. The utilization of draft forces to increases the vertical load on the 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. In this section, historical context is provided along with engineering insights.

4.2.1 Usage of towed tillage tool to increase tractor's maximum drawbar pull

In 1916 Nilson Tractor Company introduced their "Fulcrum and Lever" hitch system. The goal was to use the draft force from the implement being towed to increase the downward force on the drive wheels. This would in turn increase the maximum pulling force the drive wheels could generate (the relationship between normal pressure on soil and

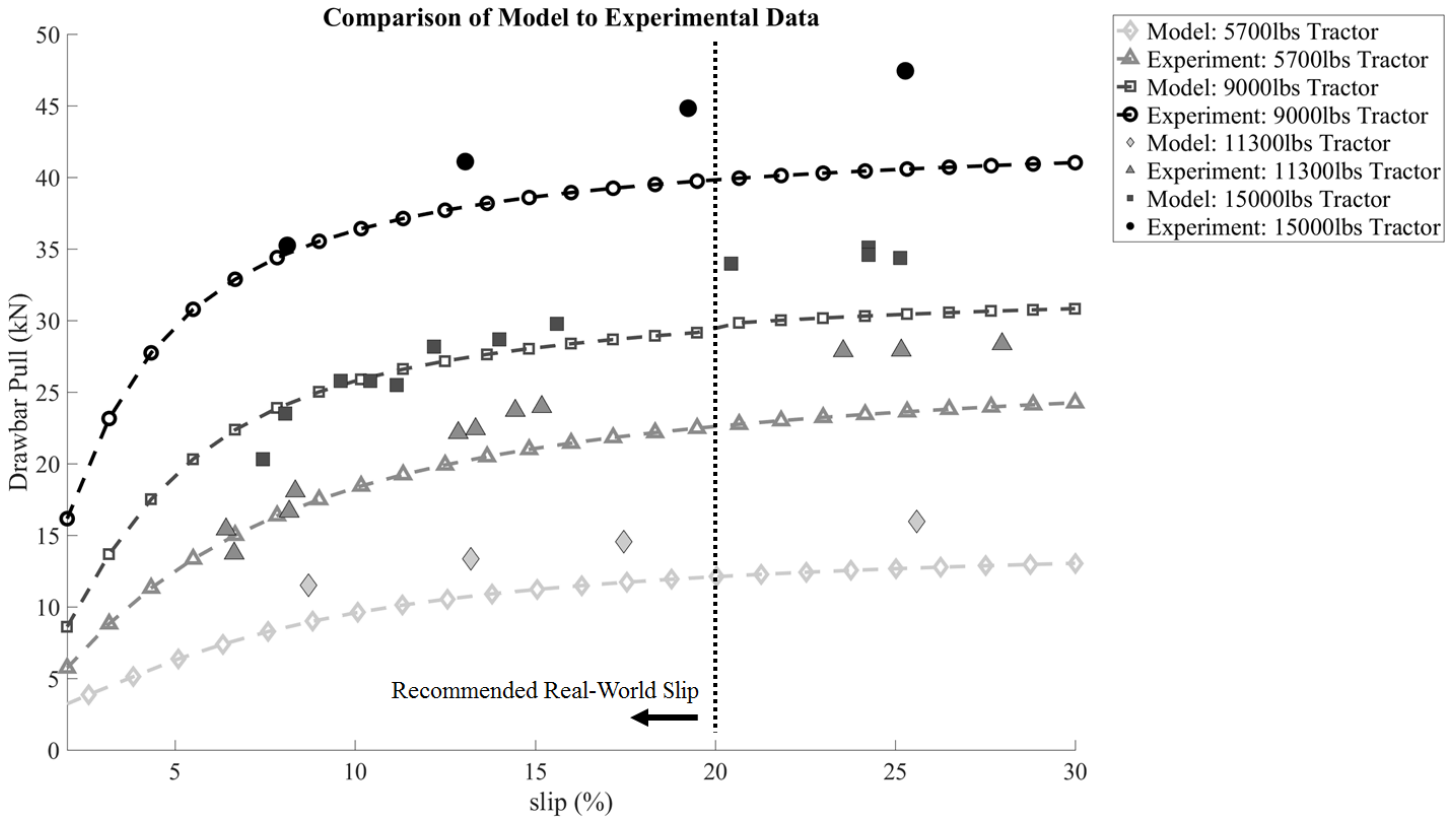


FIGURE 7. COMPARISON OF TRACTOR MODEL AS DESCRIBED IN SECTION 3 TO PUBLISHED TRACTOR EXPERIMENTS. EXPERIMENTAL DATA FROM THE WORK OF BATTIATO, DISERENS, and SARTORI [36] [37]. MODEL HAS ITS BEST ACCURACY BETWEEN 5% AND 20% SLIP, WHICH IS THE RANGE RECOMMENDED FOR FARM TRACTOR OPERATION [31] [30] [32] [38].

shear strength at the tire-soil interface is better described in Section 3).

Nilson's system attached an implement-towing chain, much higher above the ground than other similar sized tractors had before. The effects of this design change on the vertical load at the rear wheels can be quantified from the free body diagram in Figure 10.

Several important mechanical design observations can be made about raising the towing attachment point y_T on the tractor, as Nilson did:

It will likely increase traction. Raising the attachment point will increase the vertical reaction force on the rear tire V_R , which in turn increases the maximum shear strength of the soil and usually increases the maximum drawbar pull (Maximum drawbar pull usually limited by traction and not engine torque. See Section 3). The 1916 Nilson tractor featured three rear wheels: a wide drum-wheel with a narrow wheel on each side. This large contact patch helps reduce the risk of increasing the ground pressure on the rear wheels to

the point where it is detrimental to maximum drawbar pull.

It will worsen safety of operation. Raising the attachment point will decrease the vertical reaction force on the front wheels V_F . This reduces the steering authority of the front wheels and increases the risk of the tractor flipping backwards during operation.

It will reduce the drag of the trailing tool. When a tillage tool is towed by a tractor (instead of carried), the tool will usually have wheels or skids to control the depth of the tilling operation. The tractor must then overcome the horizontal tillage force in addition to the horizontal force generated by pulling the implement wheels or skids in soil. Raising the tractor attachment point y_T decreases vertical loading on the idle front wheels of the tool trailer V_{FT} , which in turn reduces wheel sinkage and therefore bulldozing resistance H_{FT} (see Section 3).

Carrying a tillage tool is more efficient than towing it. It may be observed that rigidly mounting the tillage tool behind the tractor would eliminate the need for implement wheels and would place the implement's weight and the ver-

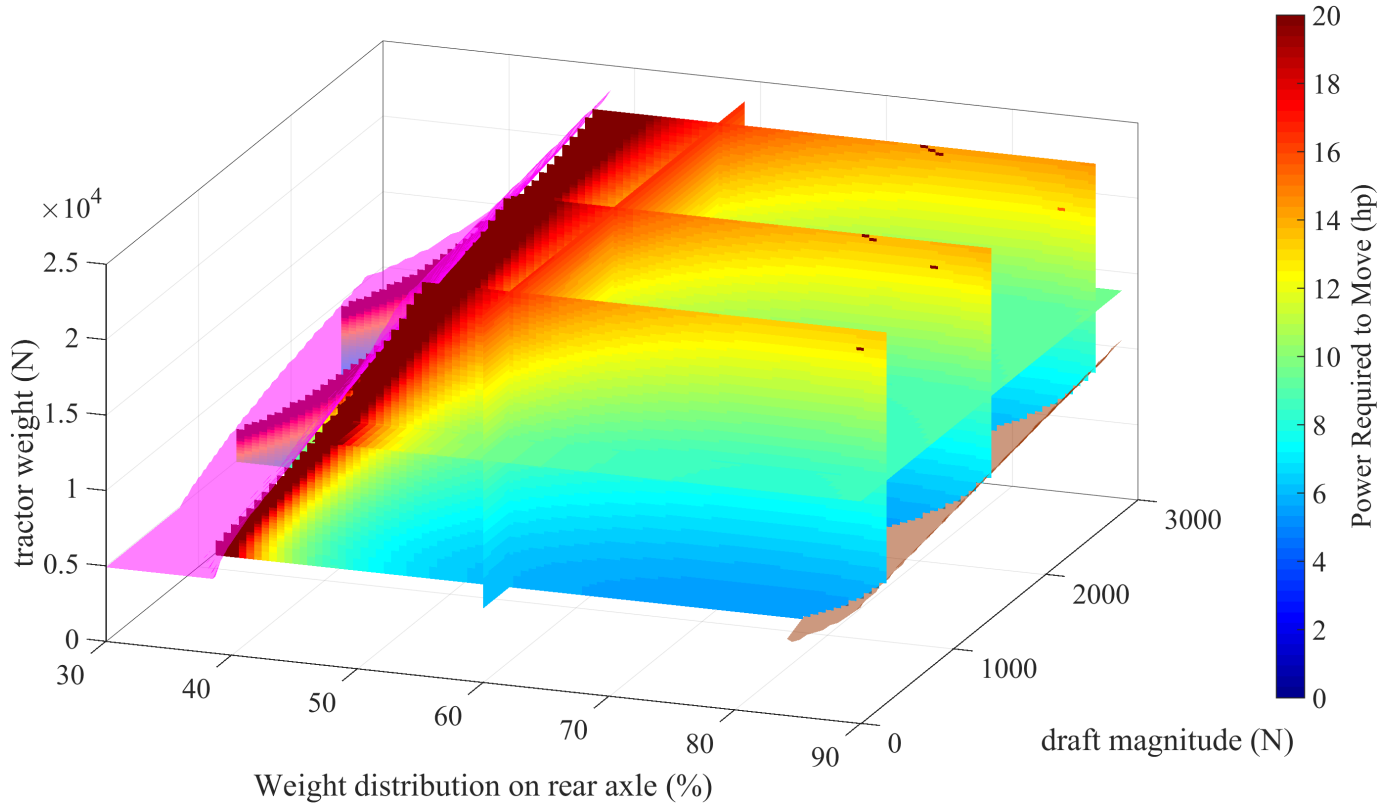


FIGURE 8. SIMULATION DATA FOR ONE MILLION TRACTOR CONFIGURATIONS. DEMONSTRATES THAT OPTIMAL WEIGHT DISTRIBUTION FOR DRAWBAR PULL IS ABOUT 70% TO 80% OF VEHICLE MASS ON THE REAR WHEELS. THE SEMI-TRANSPARENT PURPLE FRONTIER ON THE LEFT ON LEFT REPRESENTS WHERE TRACTOR WHEELS SLIP FULLY WITHOUT GENERATING PROGRESS OR WHERE ANY WHEEL SINKS PAST ITS RADIUS. THE SEMI-TRANSPARENT BROWN FRONTIER ON THE RIGHT REPRESENTS WHEN THE TRACTOR FLIPS BACKWARDS.

tical component of draft D directly on the tractor's wheels. This has several important benefits to the tractor's drawbar pull performance:

- Eliminating the implement wheels eliminates the terms H_{FT} and H_{RT} from the calculation of the magnitude of chain tension T , thus reducing the required drawbar pull of the tractor.
- Placing the implement's weight W_T directly on the vehicle would increase the magnitude of W and reduce the distance x_R . This can then increase the vertical load on the rear drive wheels V_R (increasing it is usually beneficial) without increasing the vertical load front idle wheels V_F (increasing it is usually detrimental).
- Likewise, the downward component of draft force D can increase V_R without increasing V_F .

The case of the implement being rigidly attached to the tractor will be further examined in Section 4.2.2.

4.2.2 Usage of carried tillage tool to increase tractor's maximum drawbar pull

In 1939 Ford released the 9N tractor which featured the "Three-Point Hitch" trailing tool attachment system patented by Harry Ferguson. An updated version of this tractor with the same attachment system, the Ford 8N released in 1948, would go on to become the best selling single tractor model in the USA in history. The "Three-Point Hitch" is now the standard implement attachment system for tractors.

In 1948, a much lighter tractor was also released: the Allis-Chalmers Model G. The Model G was an anomaly among its contemporaries; it featured a tubular frame, an engine mounted behind the rear wheels, and a tool attachment point in front of the driver seat between the front and rear axles.

Table 1 shows a comparison of the specifications for both these tractors.

Free body diagrams are shown in Figure 11 to aid the comparison between rigidly attaching the tillage tool behind (the now

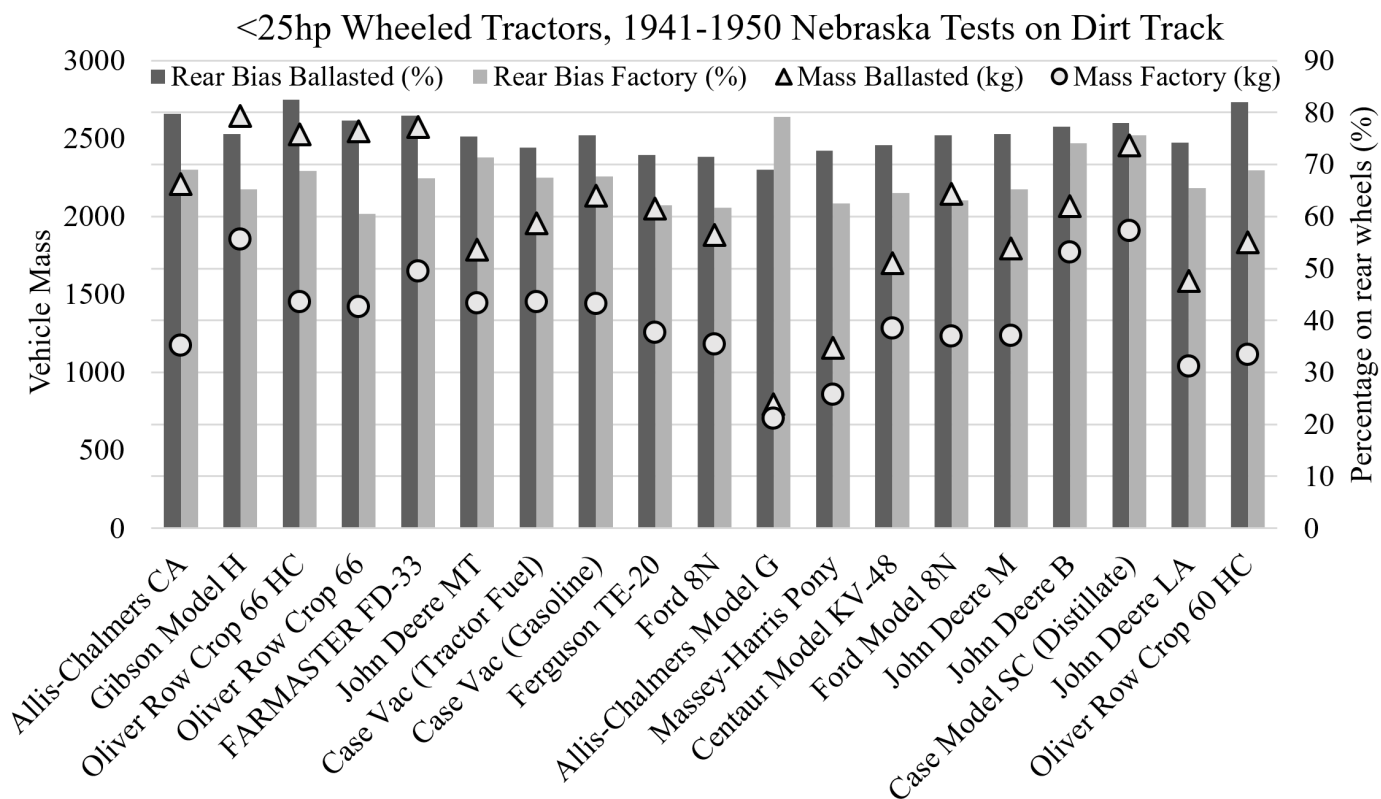


FIGURE 9. DATA COMPILED FROM NEBRASKA TRACTOR TEST ARCHIVES [39]. NOTICE THAT, FOR TESTING, COMPANY ENGINEERS WOULD BALLAST THEIR TRACTORS TO HAVE ABOUT 70 TO 80% OF THE TOTAL VEHICLE MASS ON THE REAR WHEELS.

	Ford 8N	Allis Chalmers G
Mass	1,232kg	702kg
Engine Power	27hp	10hp
Weight Front/Rear %	35/65	18/82
Tool Control	Hydraulics	Manual Lever
Engine Location	On/Behind Front Axle	Behind Rear Axle
Tool Location	Behind Rear Axle	Between Axles
Operator Location	Ahead of Rear Axle	Ahead of Rear Axle
Construction	Structural Drivetrain Castings	Welded Tubular Frame
Selling Price (2017)	\$1,404 (\$12,900)	\$970 (\$8,830)

TABLE 1. A comparison on key characteristics of the 1948 to 1952 Ford 8N and the 1948 to 1955 Allis Chalmers G

standard “Three-Point Hitch”) or ahead (the unusual Model G) of the rear axle on a rear wheel drive tractor. The reaction forces at the tires (V_{F_s} , V_{R_s} , H_{F_s} , and H_{R_s}) can then be used to predict tire-soil interaction at each wheel as described in Section 3. Using

the terramechanics theory from Section 3 the following conclusions are drawn:

Effect of horizontal draft force in all cases. Regardless of if the tool is mounted ahead or behind the rear axle, the

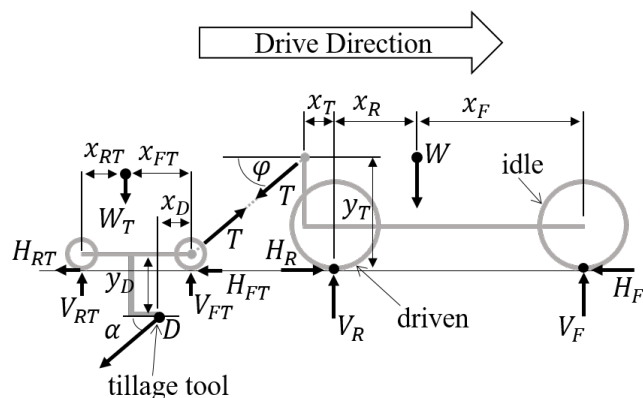


FIGURE 10. WHEN A TRACTOR TOWS A HIGH DRAFT TOOL, THE ANGLE AND POSITION OF THE TOWING CHAIN CAN HAVE A SIGNIFICANT EFFECT ON PERFORMANCE.

horizontal component of draft force W increases the vertical reaction force at the front tires V_F . This has the benefits of increasing steering authority and reducing the risk of the tractor flipping backwards. It also has the important disadvantage of increasing sinkage at the front idle wheels and therefore the magnitude of the progress-opposing force H_F .

Effect of vertical draft force in rear mounted tool case.

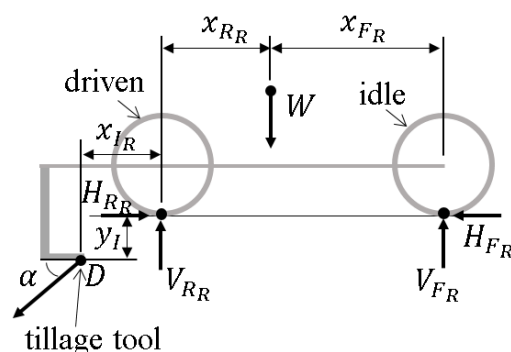
When the tool is mounted behind the rear axle, the vertical component of the draft force P increases the rear vertical reaction force V_{RR} and decreases the front vertical reaction force V_{FR} . This has the benefit of decreasing the progress-opposing force H_{FR} while also usually increasing the progress-favoring thrust force H_{RR} , these two effects improve the tractor's drawbar pull. The disadvantage is that reducing V_{FR} has a negative effect on steering authority and increases the risk of the tractor flipping backwards.

Effect of vertical draft force in central mounted tool case.

When the tool is mounted ahead the rear axle but behind the front axle, the vertical component of the draft force P increases the vertical reaction force at both front wheels V_{FC} and rear wheels V_{RC} . If x_{IC} is greater than x_{RC} , then the effective weight distribution will be shifted forward and vice versa. To maximize drawbar pull it is preferable to minimize x_{IC} . So long as draft force P acts in front of the rear axle, the vertical reaction on the front wheels V_{FC} will not be reduced from its nominal value. This reduces the risk of the tractor flipping backward but also does not reduce the progress-opposing force H_{FC} . Additionally, it may be noted that for a given vertical draft force, the increase in vertical reaction force at the rear tires will be higher for the rear mounted tool.

Tool location affects the fulfillment of stakeholder expectations beyond just tractor performance. Insights into this are presented next.

Rear Tool (Conventional) Tractor



Central Tool Tractor

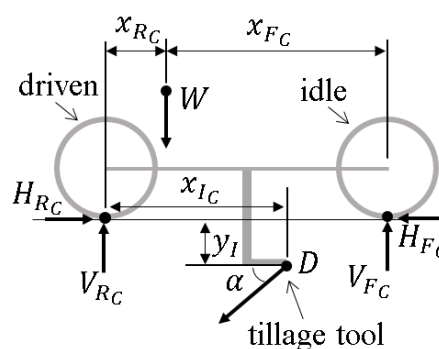


FIGURE 11. LABELED STANDARD CONVENTIONAL TRACTOR LIKE THE FORD 9N (FOUR WHEELS, REAR WHEEL DRIVE, AND RIGIDLY ATTACHED TRAILING TOOL) AND A TRACTOR WITH CENTRALLY MOUNTED TOOL LIKE THE ALLIS CHALMERS G. THIS IS A SIDEVIEW OF TRACTORS FACING RIGHT.

tations beyond just tractor performance. Insights into this are presented next.

User experience advantages of tool behind rear axles

- Placing the implement (tillage tool) behind the rear axle, especially in combination with hydraulics, makes it easier to pick up and drop off many farming implements. The driver need only reverse the implement-less tractor towards and implement, lock the implement attachment points, and use the hydraulics to lift the implement and drive away. When selling the 8N, Ford advertised that an implement could be mounted in less than one minute.
- Placing the implement behind the rear axle does not constrain the length of the implement. This is an important advantage for more powerful tractors that can pull several ground engaging "bottoms" at once.
- Placing a ground-engaging implement behind the rear axle (and therefore behind the driver) minimizes the amount of

dirt that is kicked up into the driver and into the tractor.

- Placing the implement behind the driver places the driver further away from the moving parts of the implement. This can be especially important for implements that have moving parts powered by the engine.

User experience advantages of tool between axles

- Placing the implement (tillage tool) in between both axles, in front of the operator (especially in a tubular frame that allows good ground visibility) makes it easier for the operator to keep a close eye on the quality of the operation without needing to look over their shoulder. This visual advantage also facilitates the operator having manual control over the tool's position since they can more easily supervise it and make small adjustments.

- Placing the implement between both axles can reduce the total length of the vehicle. This can be beneficial for operations in close quarters.

- Placing the implement between both axles enables mounting the engine behind the rear axle while still maintaining good weight distribution. Putting the engine behind the operator (who usually sits ahead of the rear axle in modern tractors) allows better forward visibility and prevents engine heat, fumes, and noise from being blown into the operator's face while driving.

Comments on manufacturing when the farming implement is placed behind the rear axle or between axles.

- Placing the implement (tillage tool) behind the rear axle makes it beneficial for weight distribution to have the engine near the front axle. Since power is delivered to the ground at the rear wheels this often means the engine crank case and transmission case together span the full length of the tractor. Using the engine and transmission cases as the structural "frame" of the tractor minimizes the amount of components, which facilitates fabrication and reduces mass, both of which help lower production costs and the latter can improve performance [7].

- Placing the implement (tillage tool) between the axles makes it beneficial for weight distribution to have the engine near the rear axle (assuming rear wheel drive). This can reduce the structural demands on the tractor since torque is being generated where it is needed (the rear axle). This then can lighten the tractor frame ahead of the rear axle.

- Placing the implement (tillage tool) behind the rear axle can facilitate packaging. The drive axle, hydraulics, and power take-off (PTO) shaft are all around the same location where engine power is being delivered. Additionally, the space behind the rear axle can be fully dedicated to the implement, its attachment linkages, and its power sources (hydraulics and PTO). The space between both axles must be shared with other objects including the operator, the op-

erator controls (along with their transmission lines), and the tractor frame.

4.3 Advantages of conventional rear wheel drive

Driven side-by-side rear wheels connected via a differential axle are well suited the farm tractors, some of their advantages over other options are:

Tighter turning. This happens in a conventional layout for two reasons: smaller front wheels, and ability to steer with brake pedals. For a tractor to take best advantage of equal-torque drive wheels, all drive wheels must be of similar size. In a conventional four wheeled tractor, the front wheels are usually a small diameter to prevent them from hitting the tractor frame during tight turning (during a steered turn, the rearmost part of the inside front tire swings toward the tractor). Making the front wheels larger to match the size of the rear wheels would increase the tractor's turning radius if nothing else was changed. Most tractors are equipped with a rear differential and the two rear drive wheels can be braked separately. Applying the brake on just one wheel causes the tractor to make a tight turn around that wheel.

Simpler construction. Side-by-side drive wheels allow easy use of a standard differential and a drivetrain layout similar to automobiles. When front (steered) wheels are driven, additional linkages must be added to the driveline to enable steering. Since most implements are attached closely behind the rear axle, having all torque delivered to that axle shortens the load path between the implement and the traction force.

Well suited to weight transfer from rear mounted tool. 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.

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 in-line with each other, as are the left wheels.

More than four wheels would increase manufacturing and maintenance complexity (cost). Less than four wheels decreases the stability of the tractor [40] [41].

In four wheeled farm tractors the front axle is usually mounted on a roll rotation pivot (a longitudinal axis pivot), allowing the front wheels to move up and down as a rigid axle (if the left wheel goes down, the right one must come up). This degree of freedom allows the tractor to be statically determinate under

most operating conditions despite having four wheels (support points). This may also make it seem like the front axle would not contribute to lateral rollover stability but that is not the case. Raising the pivoting point for the front axle increases rollover stability [40]. In a “tricycle” tractor (typically one idle wheel or two idle adjacent wheels centered in the front, two conventionally spaced drive wheels in the back), the pivoting point is effectively at ground level. In a four wheeled tractor the pivoting point is usually at least at a height matching the front tires’ radius.

There are two key advantages a rectangular wheel layout from a terramechanics perspective:

- 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 rear and drive 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 [42] [43] [44] [45] [46] [47].
- 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 [48] [31] [49].

5 Conclusion

This article has described 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 major results shown in this article are:

- 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 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.

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Appendix A: 1910 to 1920 Production Vehicles Matched to Layouts Discussed in Figure 2 of Section 2

Layout A				
Manufacturer	Model	Years	Engine	Mass
Twin City	12/20	1919 to 1926	27hp	2268kg
Russell	Model C 20/40	1919 to 1924	40hp	3450kg
Huber	30/60	1912 to 1916	60hp	5000kg
Layout B				
Manufacturer	Model	Years	Engine	Mass
Fitch Four Drive	20/30	1915 to 1918	30hp	1360kg
Layout C				
Manufacturer	Model	Years	Engine	Mass
S.L. Allen	Planet Jr.	1920 to 1935	2.31hp	250kg
Moline	Universal	1914 to 1918	27hp	1630kg
Allis-Chalmers	6-12	1919 to 1926	12hp	1134kg
Layout D				
Manufacturer	Model	Years	Engine	Mass
Heer	20-28	1912 to 1916	30hp	2000kg
Nelson	20-28	1917 to 1924	30hp	2000kg
Layout E				
Manufacturer	Model	Years	Engine	Mass
Samson	Iron Horse D	1918 to 1923	26hp	850kg
Olmstead	Four Wheel Pull	1914 to 1920	50hp	3000kg
Layout F				
Manufacturer	Model	Years	Engine	Mass
Post	12-20	1918 to 1920	20hp	1500kg
Layout G				
Manufacturer	Model	Years	Engine	Mass
Hart Parr	20-40	1912 to 1914	40hp	6000kg
Samson	Sieve Grip	1914 to 1918	25hp	2630kg
Wallis	Cub	1913 to 1917	44hp	3855kg
Layout H				
Manufacturer	Model	Years	Engine	Mass
Bull	Little Bull	1913 to 1915	12hp	1800kg
Case	10/20	1914 to 1918	20hp	2304kg
Layout I				
Manufacturer	Model	Years	Engine	Mass
Hart-Parr	Little Devil	1914 to 1916	22hp	3015kg
Common Sense	15/25	1914 to 1918	25hp	2700kg
Emerson Brantingham	Model L	1916 to 1918	20hp	2500kg
Layout J				
Manufacturer	Model	Years	Engine	Mass
Rumely	Ideal Pull	1916 to 1917	16hp	1500kg
Layout K				
Manufacturer	Model	Years	Engine	Mass
Lawter	18/38	1914 to 1918	38hp	2950kg
Boring	12/25	1916 to 1922	25hp	2050kg
Hackney	Auto-Plow	1916 to 1922	36hp	3630kg
Layout L				

Manufacturer	Model	Years	Engine	Mass
Gray Tractor	Model B	1914 to 1918	25hp	2500kg
Layout M				
Manufacturer	Model	Years	Engine	Mass
Killen Strait	15-30	1913 to 1917	30hp	4300kg
Layout N				
Manufacturer	Model	Years	Engine	Mass
Bean	Track-Pull 6/10	1918 to 1920	10hp	1400kg
Layout O				
Manufacturer	Model	Years	Engine	Mass
Bean	Track-Pull 6/10	1918 to 1920	10hp	1400kg
Layout O				
Manufacturer	Model	Years	Engine	Mass
Beltrail	Model B 12-20	1917 to 1920	20hp	1500kg
Tom Thumb	12-20	1917 to 1920	20hp	1900kg
Layout P				
Manufacturer	Model	Years	Engine	Mass
Yuba	20-35	1911 to 1916	35hp	3500kg
Blewett	Webfoot 53	1920 to 1922	53hp	4500kg
Holt	75	1913 to 1924	75hp	10432kg
Layout Q				
Manufacturer	Model	Years	Engine	Mass
Bullock	Creeping Grip	1916 to 1919	20hp	3270kg
Layout R				
Manufacturer	Model	Years	Engine	Mass
Victor	Victor	1919	34hp	1950kg
Layout S				
Manufacturer	Model	Years	Engine	Mass
John Deere	Dain	1918-1919	24hp	2086kg
Layout V				
Manufacturer	Model	Years	Engine	Mass
Acme	12-24	1918-1919	24hp	1450kg
Buckeye	Junior	1912-1915	25hp	2500kg
Layout X				
Manufacturer	Model	Years	Engine	Mass
Killen Strait	30hp	1917-1919	30hp	2600kg
Layout Y				
Manufacturer	Model	Years	Engine	Mass
Rumely	8-16	1917-1919	16hp	2600kg

Appendix B: Evolution Steps, matched to vehicles in Figure 3 of Section 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