



Article

Mass Impact of a Mounted Sprayer on the Operational Balance of an Agricultural Tractor

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Abstract

The operational stability of agricultural tractors is directly influenced by the mass distribution between axles, particularly when using mounted implements with variable loads. This study aimed to evaluate how different masses of a mounted sprayer (550 kg, 850 kg, and 1150 kg) and tire inflation pressures (151.7–193.1 kPa) affect the load distribution between axles, tire contact area, center of gravity (CG) displacement, and tractor lead ratio. A 3×4 factorial design was adopted with a statistical analysis of key parameters across 12 experimental combinations. The results demonstrated that increasing implement mass significantly shifted the load toward the rear axle, reducing the front axle load by up to 46% and displacing the CG rearward by more than 11 cm, thereby compromising stability. Tire pressure, as well as the interaction between mass and pressure, also exhibited statistically significant influence on load distribution and CG positioning while modulating the tire contact area. The lead ratio increased linearly with mass, exceeding the recommended 5% threshold when the sprayer was at full capacity. These findings indicate that while the implement mass exerts a dominant effect, tire pressure management represents a statistically relevant factor for stability, requiring integrated management that considers the interaction between ballasting and tire inflation to mitigate operational risks.

Keywords: mass distribution; operational stability; tire pressure; lead ratio; center of gravity



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1. Introduction

The performance of a vehicle in straight-line motion is influenced by its ability to accelerate, decelerate, and overcome slopes. This ability depends on the balance between the tractive or braking effort transmitted by the tires and the resisting forces acting on the system [1]. The operational efficiency of an agricultural tractor depends directly on the proper mass distribution between axles and internal tire pressure, as inadequate adjustments to these conditions can increase slippage, increase fuel consumption, and compromise the uniformity of field applications [2]. This control becomes even more critical in the face of dynamic load variations and adverse topographic conditions, which influence mass distribution, center of gravity geometry, and traction effects on the stability and operational safety of tractors [3].

Despite tractors being widely employed in soil preparation, crop establishment, fertilizer distribution, and spraying operations, the adoption of ballasting strategies frequently considers total system mass or tire pressure separately, without considering the interaction between these factors in a real working environment and integrated manner. Studies on mass distribution in tractors demonstrate that proper ballasting is fundamental for maximizing traction capacity and controlling wheel slippage, particularly on low-resistance soils. Ref. [2] observed that the absence of adequate ballast causes excessive slippage under low soil cohesion conditions, reducing the tractor's energy efficiency.

Weight distribution on conventional tractor axles occurs primarily through the addition of counterweights. In most cases, these weight modifications involve artificial mass increase or decrease based on the operator's empirical knowledge. Few cases exist of innovative systems employing actual prototypes for this purpose. Three main problems emerge from this approach. The first refers to the absence of clearly established criteria for determining adequate weight distribution between front and rear axles. The second problem relates to the fact that adding a single counterweight frequently results in irregular weight distributions between axles. The third challenge involves the lack of accessible control systems and appropriate control strategies, which contributes to inadequate variations in loads supported by tractor axles [4].

Furthermore, ref. [5] showed that lower diagonal tire pressures during subsoiling operations result in reduced slippage, lower fuel consumption, and higher operational efficiency, indicating the importance of combined adjustment between mass and tire pressure. Ref. [6] demonstrated that in 4×2 tractors with front-wheel drive, optimal performance condition is achieved when the front axle supports between 40% and 45% of the total mass and the speed ratio between front and rear wheels remains between 1% and 5%. However, the authors do not consider dynamic load variations occurring during the use of implements whose mass changes throughout operation, as is the case with sprayers having reservoirs at different fill levels.

Internal tire pressure exerts a significant impact on rolling resistance, sidewall deformation, and soil compaction. Ref. [7] described that excessively low pressures increase the contact area, reducing the lead ratio and aggravating compaction, while excessively high pressures elevate slippage. Additionally, ref. [8] pointed out that excessive tire deformation, caused by a misadjusted ballast, alters axle height relative to the ground, impairing uniformity in fertilizer and pesticide distribution. These findings indicate that tire pressure should be adjusted considering not only soil characteristics but also the dynamic mass of the tractor–implement system.

The three-point hydraulic system and ISO standards associated with implement hitching are fundamental for system stability and safety. ISO 730:2009 defines geometric parameters for three-point hitching but does not quantify how the tractor center of gravity displacement varies when the mounted implement changes its weight during operation. In this regard, ref. [9] recorded that mounted sprayers with flexible reservoirs dynamically modify mass distribution, but few studies have measured the effect of this variation on the stability, lead ratio, and traction loss under real field conditions.

Despite advances, there remains a gap in the literature regarding the simultaneous evaluation of mounted implement mass variation and the influence of different tire pressures on the load distribution between axles, center of gravity displacement, tire contact area, and lead ratio. This absence hinders the development of practical recommendations for ballasting and tire inflation pressure in operations where implement weight varies continuously, compromising safety, energy efficiency, and soil conservation.

Consequently, this study aims to quantify mass distribution between the front and rear axles of an agricultural tractor coupled to a sprayer at three fill levels (550 kg; 850 kg;

and 1150 kg) and subjected to different tire pressures (151.7 kPa; 165.5 kPa; 179.3 kPa; and 193.1 kPa), evaluate variations in front and rear tire contact areas resulting from these configurations, calculate horizontal displacement of the system's center of gravity for each experimental condition, and determine the lead ratio obtained as a function of sprayer mass and tire pressure combinations.

2. Materials and Methods

This experiment was conducted at the physical store of Alvorada Sistemas Agrícolas, located in the municipality of Cachoeira do Sul, Rio Grande do Sul, Brazil. The experiment composition was based on the interaction between two factors: implement mass (Factor 1) and tire pressure (Factor 2). These factors were combined according to treatments described in Table 1, resulting in 12 system configurations (treatments). Implement masses were chosen to represent the sprayer with a full, half-full, and empty tank. Tire pressures were chosen based on the load-bearing capacity of the tires.

Table 1. Description of experimental factors and respective levels.

Levels	Sprayer Mass (kg)		Tire Pressure kPa (psi)
	Water Mass (kg)	Total Mass * (kg)	
1	600	1150	151.685 (22)
2	300	850	165.474 (24)
3	0	550	179.264 (26)
4	-		193.053 (28)

* = Equipment shipping mass is 550 kg.

The experimental design utilized was completely randomized blocks, with a combination of studied factor levels, resulting in a 3×4 factorial. Twelve treatments were evaluated, considering the following variables: front axle mass and rear axle mass, front and rear tire contact area, lead ratio, and horizontal center of gravity displacement. Each treatment was replicated 5 times for all variables, except for tire contact area, where collection was performed on one wheel from each axle. Factor interaction was analyzed through an F-test to verify the factor correlation on variables of interest. The description of the experimental treatments is shown in Table 2.

Table 2. Description of experimental treatments, combining implement mass levels (kg) and different tire pressures (kPa and psi) applied in each treatment.

Treatment	Implement Mass (kg)	Tire Pressure kPa (psi)
1	1150	151.685 (22)
2	1150	165.474 (24)
3	1150	179.264 (26)
4	1150	193.053 (28)
5	850	151.685 (22)
6	850	165.474 (24)
7	850	179.264 (26)
8	850	193.053 (28)
9	550	151.685 (22)
10	550	165.474 (24)
11	550	179.264 (26)
12	550	193.053 (28)

The tractor used was a John Deere 5080 E, with 58.84 kW (80 cv) of power, a 2.05 m wheelbase, a Class 2 three-point hydraulic system, equipped with Alliance Farm Pro 18.4–30 rear tires with a maximum supportable load of 2948.35 kg at 158.579 kPa (23 psi), and Pirelli

R-1 12.4–24 front tires with a maximum supportable load of 1200 kg at 165.474 kPa (24 psi). The mounted implement was a 550 kg (empty) Greensystem PV1006 sprayer with a 600 L tank capacity. The second gear of group B was used with a rotation fixed at 1700 rpm (540 rpm at PTO). Figure 1 shows the machine-implement assembly described above.



Figure 1. John Deere 5080E tractor coupled to Greensystem PV1006 sprayer used in the experiment. The person shown in this figure is the first author of the manuscript.

The established tractor mass distribution was 60% on the rear axle and 40% on the front axle (due to the system containing a 4×2 tractor with auxiliary front-wheel drive and a mounted implement), resulting in a total weight of 3190 kg. The tractor was weighed with Presenti-Smart Farming[®] pad scales. The tractor weight was standardized without any implement attached. Figure 2 shows the tractor being weighed by pad scales.



Figure 2. Obtaining tractor weight using pad scales.

Tire inflation pressure was modified using an air compressor and measured with a pressure gauge. To determine contact area, the team lifted the desired axle using a hydraulic jack and positioned a wooden plate below the tire. After plate positioning, the tractor was lowered, resting on the plate, and lime was added. Finally, the tractor was lifted again, and digital images were captured for contact area measurement using AutoCAD[®] software 2022. Figure 3 shows the measurement of tire contact area.



Figure 3. Tire contact area collection. The person shown in this figure is the first author of the manuscript.

Center of gravity displacement was calculated based on Equation (1), where “b” was isolated. Figure 4 shows the parameters adopted for center of gravity calculation.

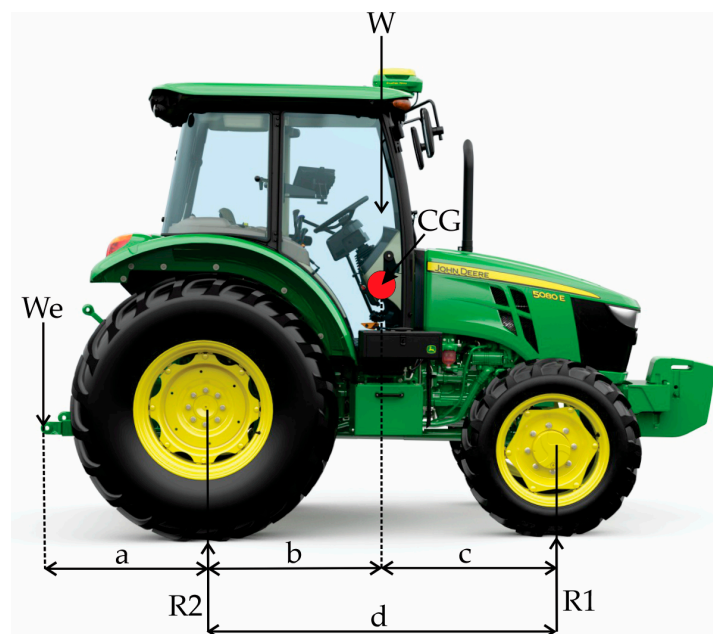


Figure 4. Parameters adopted for center of gravity calculation.

Equation (1). Tractor weight

$$W \times b = R_1 \times a + W_e \times d \quad (1)$$

where

W = tractor weight;

W_e = mounted implement weight;

R_1 = soil reaction on front axle;

a = wheelbase distance;

b = distance between rear axle and center of gravity;

d = distance between rear axle and hitch point on hydraulic system arm.

In addition to statistical analysis, a safety analysis was performed, considering the weight transfer between rear and front axles and their limits, based on Equations (2) and (3).

Equation (2). Weight transfer from front axle to rear axle (ISO/TC 22—Road vehicles)

$$T_p = (P_e \times d)/a \quad (2)$$

where

T_p = weight transfer by 3-point hitch (kgf);

P_e = weight at 3-point hitch (kgf);

d = distance between rear axle and tractor 3-point hitch (mm);

a = tractor wheelbase (mm).

Equation (3). Maximum weight transfer from rear axle to front axle (ISO/TC 22—Road vehicles)

$$T_{pmax} \leq 0.8 \times P_1 \quad (3)$$

where

T_{pmax} = weight transfer by 3-point hitch (kgf);

P_1 = front axle weight of tractor (kgf).

Five replications of the lead ratio were performed for each treatment, with each replication consisting of two passes over the same route on flat terrain, one with front-wheel drive (FWD) disengaged and another pass with FWD engaged. For lead ratio calculation, the following Equations (4) and (5) were used:

$$NTG: (NV \times NG) + NGVI \quad (4)$$

where

NTG: total number of lugs at end of displacement;

NV: total number of turns made by front tire;

NG: number of front tire lugs;

NGVI: number of excess lugs from incomplete turn.

$$A = (TGCT - TGST) \times 100 / TGST \quad (5)$$

where

A : lead ratio;

TGCT: total lugs with traction;

TGST: total lugs without traction.

3. Results

3.1. General Analysis

Statistical analyses and F-tests for each configuration are presented in Table 3, with mean values of loads recorded on the front and rear tractor axles as a function of implement (sprayer) mass variation and different tire inflation pressures. It is observed that increasing sprayer mass coupled to the tractor rear causes significant load transfer from the front axle to the rear. With the implement at 550 kg ("empty tank"), the front axle load was 866.75 kg, while the rear axle load was 2912.25 kg. When the mass was increased to

1150 kg (“full tank”), the front axle load was reduced to 470.25 kg and the rear axle load increased to 3889.75 kg. This transfer represents a 45.8% reduction in weight supported by the front axle and a 33.6% increase in the rear axle. Additionally, the two-way ANOVA (F-test) demonstrated that both individual factors (mass and pressure) and their interaction (mass $\times$ pressure) had a statistically significant effect ($p < 0.01$) on axle loads. This interaction suggests that both implement mass and tractor tire pressure should be adjusted jointly, seeking to preserve system efficiency, reduce soil compaction risk, and maintain tractor stability.

Table 3. Statistical analysis of implement mass distribution $\times$ tire pressure (means and F-test).

Mass (kg)	MF (kg)	MR (kg)	AF (cm ²)	AR (cm ²)	Lead Ratio (%)	CG (cm)
550	866.75	2912.25	0.94	4.75	4.55	61.57
850	679.50	3374.75	0.83	5.29	5.57	55.32
1150	470.25	3889.75	0.58	5.42	7.45	48.49
Pressure (kPa)						
151.685	671.00	3395.33	0.94	6.27	6.11	55.07
165.474	679.33	3389.33	0.83	5.07	5.84	55.43
179.264	663.33	3398.67	0.73	4.86	5.84	54.71
193.053	675.00	3385.67	0.63	4.41	5.62	55.31
CV (%)	24.38	11.87	25.11	15.22	23.98	9.84
F-test						
Mass	7074.17 **	48,030.47 **	-	-	89.83 **	3500.20 **
Pressure	6.24 **	5.15 **	-	-	1.27 ns	6.11 **
Mass * Pressure	4.42 **	3.91 **	-	-	0.44 ns	4.39 **

** Significant at 1% probability ($p < 0.01$); MF (front axle mass); MR (rear axle mass); AF (front axle tire contact area); AR (rear axle tire contact area); CG (center of gravity displacement). ns: non-significant. * is the interaction of mass and pressure.

3.2. Mass Impact

The behavior of front axle mass changes as implement mass increases, illustrated in Figure 5, evaluates four different front tire inflation pressures (151.685; 165.474; 179.264; and 193.053 kPa). The results showed a consistent decreasing linear trend, regardless of the adopted pressure, expressed by the equation $f(x) = 1233.8750 - 0.6608x$ ($R^2 = 0.9958$), configuring consistency in measured physical behavior. Numerically, for every 100 kg added to the implement, an average reduction of approximately 66 kg occurs in the front axle load. This behavior and the negative curve slope confirm the load transfer from the front axle to rear, a direct consequence of implement coupling to the tractor rear via the three-point hydraulic system. It is important to highlight that the pressure variation in tires, despite presenting a statistically significant effect according to Table 3, had a visibly smaller effect magnitude than the mass, demonstrating that in this pressure range, the determining factor for front load is indeed the mass coupled to the implement.

Figure 6 analyzes rear axle mass response as a function of implement mass increase under the same tire pressures evaluated in Figure 5. Data show a growing linear relationship, modeled by the equation $f(x) = 2007.4583 + 1.6292x$ ($R^2 = 0.9986$), indicating that for every 100 kg added to the implement, the rear axle load increases about 163 kg.

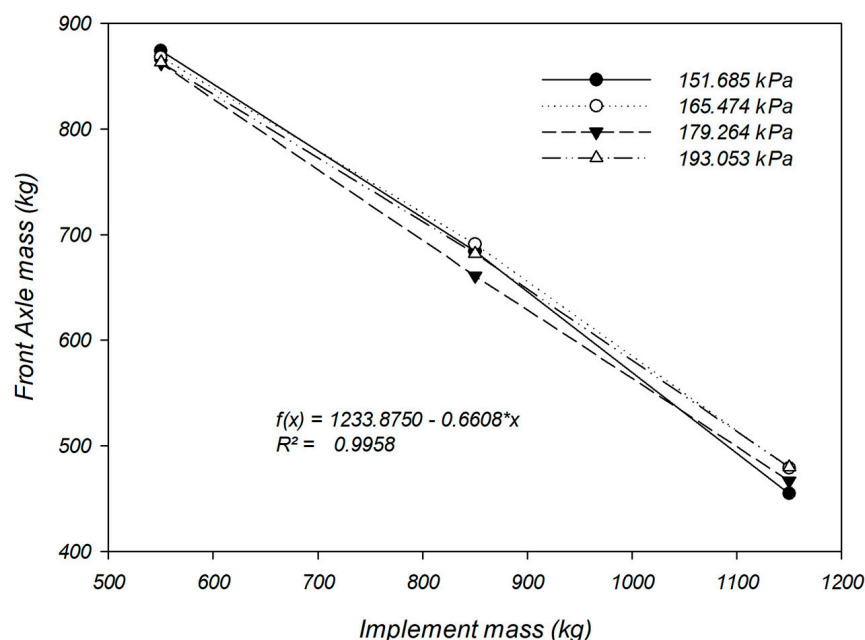


Figure 5. Front axle mass as a function of implement mass for different tire inflation pressures.

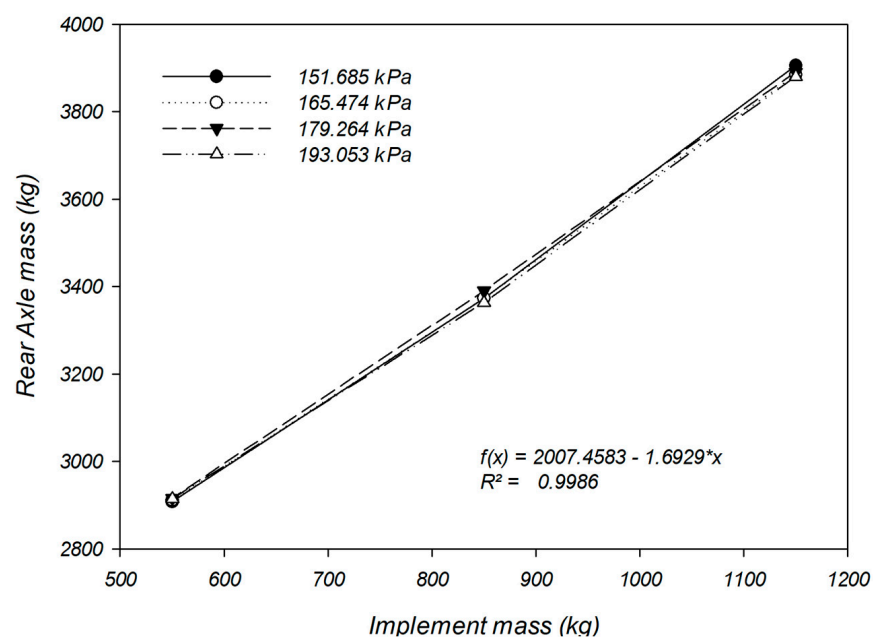


Figure 6. Rear axle mass as a function of implement mass for different tire inflation pressures.

The results in Table 4 demonstrate the percentage mass distribution over the front and rear tractor axles for different treatments, considering combinations between the sprayer mass (550, 850, and 1150 kg) and tire inflation pressures (151.685 to 193.053 kPa). With the sprayer at maximum load (1150 kg), the front axle participation in total system weight varied from 10.44% to 11.01%. For intermediate mass (850 kg), this participation was between 16.32% and 17.00%, and with the empty sprayer (550 kg), the range was 22.82% to 23.11%. Although the percentage variations between different pressure levels are numerically small for each mass condition, the analysis of variance (ANOVA) presented in Table 3 revealed that the pressure effect and mass–pressure interaction on absolute load distribution (in kg) was statistically significant.

Table 4. Mass distribution over tractor axles in each treatment.

Treatment	Mass (kg)	Pressure (kPa)	Mass on Front Axle (%)	Mass on Rear Axle (%)
1	1150	151.685	10.44	89.56
2	1150	165.474	10.98	89.02
3	1150	179.264	10.72	89.28
4	1150	193.053	11.01	88.99
5	850	151.685	16.86	83.14
6	850	165.474	17.00	83.00
7	850	179.264	16.32	83.68
8	850	193.053	16.86	83.14
9	550	151.685	23.11	76.89
10	550	165.474	22.97	77.03
11	550	179.264	22.82	77.18
12	550	193.053	22.85	77.15

The weight transfer magnitude between axles can be better understood from the Table 5 results, which show absolute values calculated for each treatment combination. When the sprayer had a full tank (1150 kg), the weight transfer to the rear axle reached 560.98 kgf, exceeding operational safety limits, which varied from 364 kgf to 384 kgf depending on the treatment. In intermediate scenarios (850 kg) and with an empty tank (550 kg), the transferred values were 414.63 kgf and 268.29 kgf, respectively. In these two scenarios, the weight transfer remained within established limits, since the greater residual weight over the front axle resulted in a considerably higher safety threshold (varying from 528 kgf to 699 kgf). This evidences that the most critical condition is not only the one generating the greatest load transfer but also the one that most reduces the safety limit itself by mitigating the front axle.

Table 5. Weight transfer for each treatment.

Treatment	Mass (kg)	Pressure (kPa)	Weight Transfer (kgf)	Weight Transfer Limit (kgf)
1	1150	151.685	560.98	364
2	1150	165.474	560.98	383.2
3	1150	179.264	560.98	373.6
4	1150	193.053	560.98	384
5	850	151.685	414.63	547.2
6	850	165.474	414.63	552.8
7	850	179.264	414.63	528.8
8	850	193.053	414.63	545.6
9	550	151.685	268.29	699.2
10	550	165.474	268.29	694.4
11	550	179.264	268.29	689.6
12	550	193.053	268.29	690.4

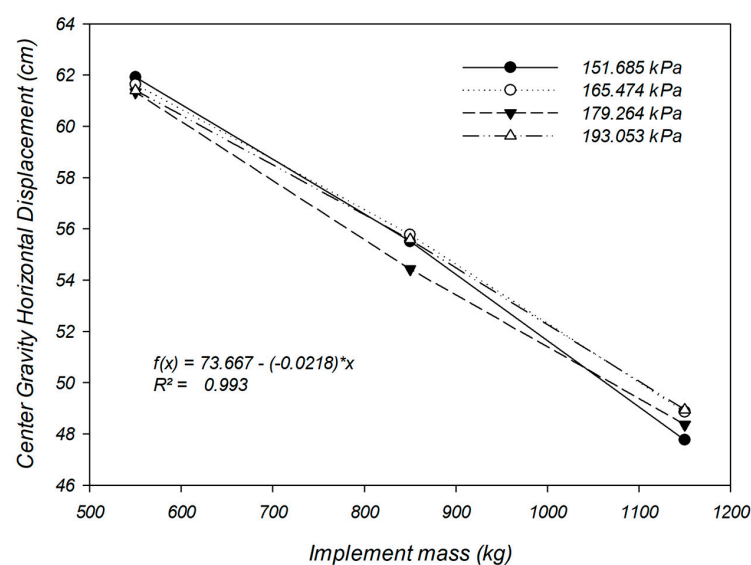
The data in Table 6 indicate a direct relationship between the sprayer mass increase and elevated weight transfer rate. For treatments where the sprayer was fully loaded (1150 kg), the total system mass varied from 4357 to 4363 kg according to the tire pressure. In this condition, the weight transfer was 560.98 kgf at all pressure levels, resulting in very close percentage rates, oscillating between 12.86% and 12.88% of the total mass. The tire inflation pressure variation presented a marginal effect on the transfer rate, reflecting only small oscillations attributed to variations in tire deformation and dynamic load distribution, without significantly altering the absolute mass transfer.

Table 6. Tractor weight transfer rate for each treatment.

Treatment	Sprayer Mass (kg)	Pressure (kPa)	Total Mass (kg)	Weight Transfer (kgf)	Weight Transfer Rate (%)
1	1150	151.685	4360	560.98	12.8664
2	1150	165.474	4363	560.98	12.8576
3	1150	179.264	4357	560.98	12.8753
4	1150	193.053	4360	560.98	12.8664
5	850	151.685	4057	414.63	10.2202
6	850	165.474	4064	414.63	10.2026
7	850	179.264	4051	414.63	10.2354
8	850	193.053	4045	414.63	10.2505
9	550	151.685	3782	268.29	7.09394
10	550	165.474	3779	268.29	7.09957
11	550	179.264	3778	268.29	7.10145
12	550	193.053	3777	268.29	7.10333

In the intermediate treatments (850 kg), the total system mass was between 4045 and 4064 kg, with a weight transfer of 414.63 kgf. The transfer rates in this range varied from 10.20% to 10.25%, also without relevant differences due to tire pressure. For the treatments with the sprayer in the minimum configuration (550 kg), the total mass was approximately 45% lower than the values for the treatments at 1150 kg condition, following the same implement mass reduction ratio. The percentage rate, in turn, varied slightly with the total system mass.

The horizontal center of gravity (CG) displacement of the tractor–sprayer system (Figure 7) presented linear, increasing, and monotonic behavior in response to coupled sprayer mass increase. The analysis of the data in Table 3 showed that the CG moved rearward, displaced from an average position of 61.57 cm with the implement at 550 kg to 48.49 cm at a maximum mass condition of 1150 kg, caused by mounted implement (sprayer) coupling, which altered the mechanical system configuration. Linear regression demonstrated approximately 0.0218 cm rearward movement for each kilogram added, with high correlation ($R^2 \approx 0.99$), indicating that the mass increment in the hydraulic system results in systematic CG displacement toward the rear axle. Although implement mass was identified as the main factor, tire pressure and the mass $\times$ pressure interaction also had a statistically significant effect on horizontal CG displacement. In the evaluated interval, total CG rearward movement was approximately 21%, bringing the center of gravity closer to the rear axle and consequently negatively influencing the operational safety of the system.

**Figure 7.** Center of gravity (CG) displacement of tractor–sprayer system as a function of implement mass.

3.3. Tire Pressure Impacts

Figure 8 presents the front tire contact area values as a function of sprayer mass and tire inflation pressures. Under the lowest coupled mass (550 kg) and the lowest tire pressure (151.685 kPa), the results indicated that the contact area reached approximately 1.18 cm². As sprayer mass increased, this area underwent a progressive reduction, reaching approximately 0.35 cm² under the maximum load condition (1150 kg) and the highest tire pressure (193.053 kPa). The area decrease was systematic at all pressure levels, with the smallest areas always recorded with the combination of highest implement weight and elevated front tire pressure.

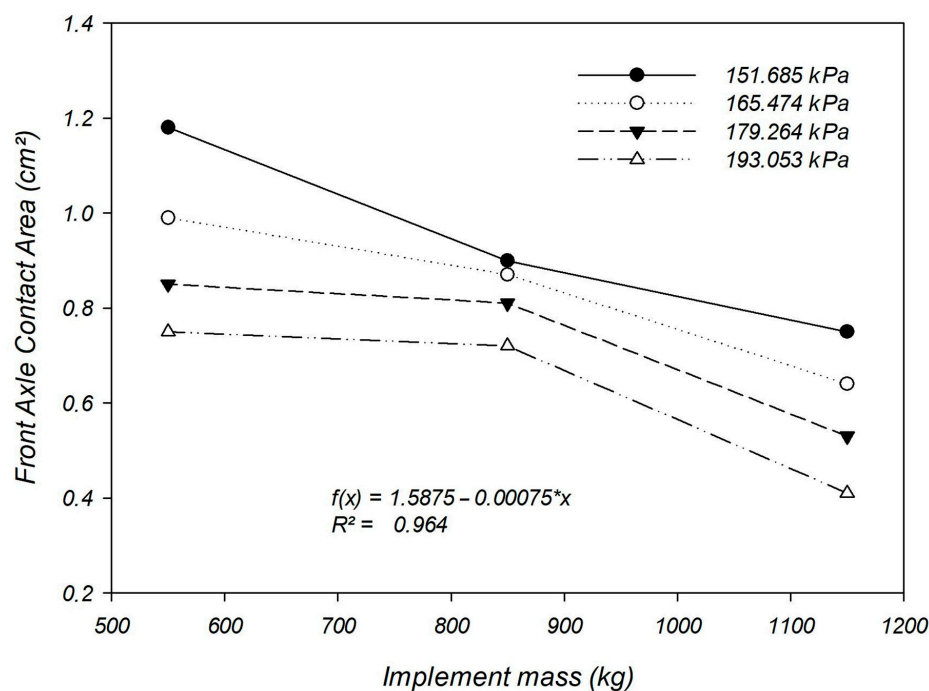


Figure 8. Front tire contact area as a function of sprayer mass and tire pressure.

Figure 9 presents rear tire contact area variation as a function of implement mass and tire inflation pressure. At the lowest inflation pressure (151.685 kPa), the tire contact area increased from approximately 5.8 cm² to 7.1 cm² as sprayer mass was elevated from 550 kg to 1150 kg. Under this condition, the largest contact area was verified, favoring load dissipation to the soil; however, greater sensitivity to load loss was also evidenced, as indicated by the more pronounced slope of the characteristic curve. For other pressures (165.474; 179.264; and 193.053 kPa), the contact area presents smaller variations, maintaining between approximately 4.3 cm² and 5.6 cm² throughout the evaluated mass range. This occurs due to the contact area being smaller and less sensitive to load variation, demonstrating reduced deformability of more rigid tires.

The highest contact area values were always recorded under the lowest pressure and highest mass, while the smallest areas occurred at elevated pressures, even with the load increase. There is a general tendency for a contact area increase with the implement mass increment, compatible with the growing load transferred to the rear axle. The curve with the lowest pressure presents the largest contact area throughout the implement mass range, with more pronounced growth. For higher pressures, the area increase is more discrete, with almost constant behavior. This behavior is typical of non-linear tire response: above a certain load level, high-pressure tires do not proportionally increase their contact area due to greater carcass rigidity.

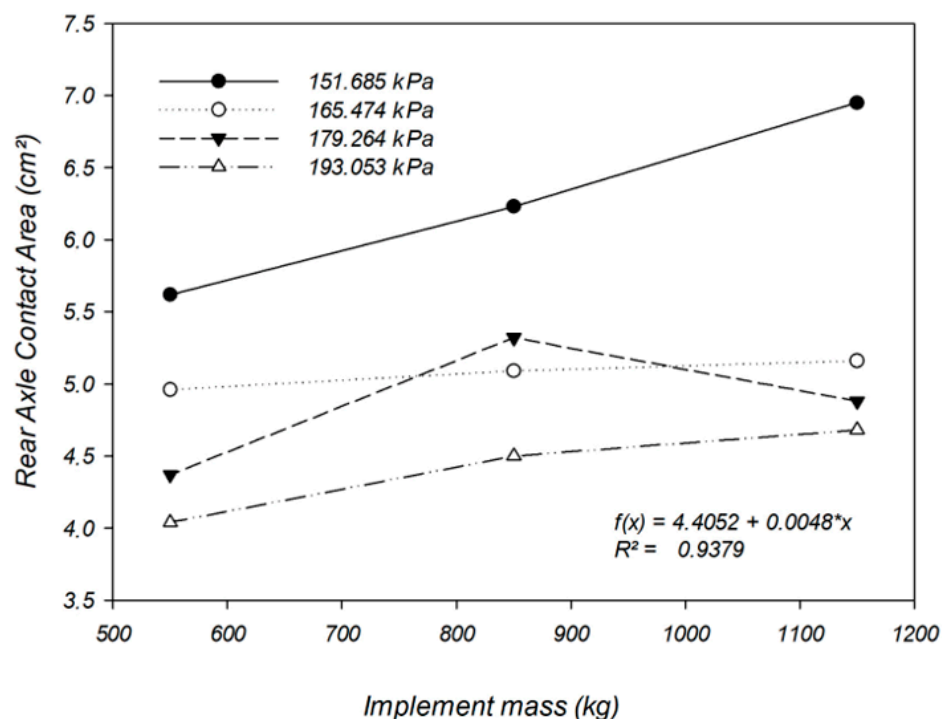


Figure 9. Rear tire contact area as a function of sprayer mass and tire pressure.

3.4. Lead Ratio

Figure 10 presents the relationship between the implement mass and tractor lead ratio. The results revealed a linear increase in the lead ratio (%) as the implement mass increased, as described by the equation $f(x) = 0.0048x + 1.7496$. The equation suggests that for every 100 kg added, the lead ratio increased by approximately 0.48 percentage points, which is technically significant. The lowest lead ratio value was recorded with the empty sprayer, around 1.7%, while under the highest mass condition (1150 kg), the lead ratio reached values close to 7.5% to 8%. Point dispersion indicates that the main variable influencing the lead ratio was coupled mass, with the tire pressure effect being secondary in the tested interval, a fact confirmed by the analysis of variance (Table 3).

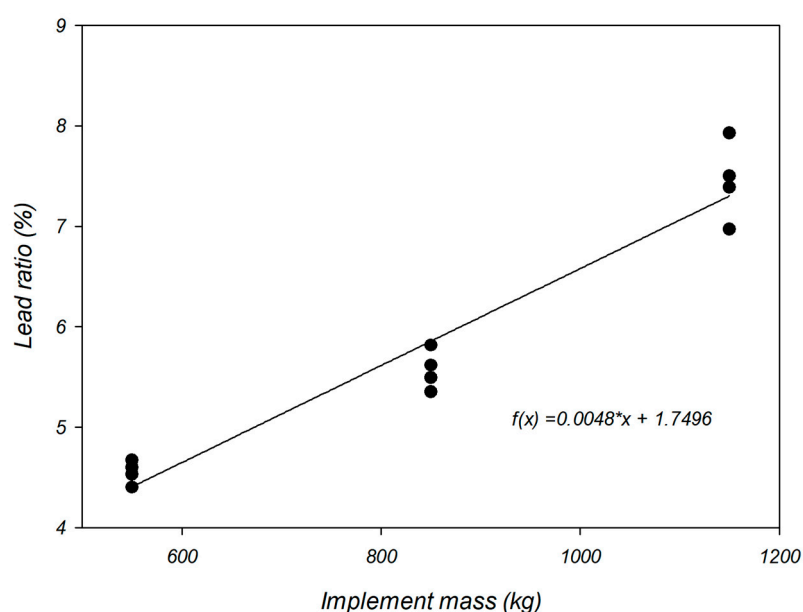


Figure 10. Lead ratio as a function of sprayer mass.

4. Discussion

The results obtained demonstrated predictable and linear mechanical behavior of load transfer in agricultural tractors equipped with rear implements, evidenced by determination coefficients exceeding 0.99. Additional weight force applied to the hitch by the suspended implement acts behind the tractor's center of gravity, generating a torque moment that displaces the load to the rear axle, which acts as a lever fulcrum point.

This pattern indicates a highly mass-increment-sensitive system, reinforcing the importance of careful adjustment of operational variables such as ballasting, tire pressure, and weight distribution to ensure stability, traction, and operational safety. Mechanical behavior predictability allows operators and designers to anticipate operational risks and adopt preventive strategies that optimize tractor–implement system performance.

A substantial front axle load drop from more than 850 kg to less than 500 kg is a direct indicator of directional capacity and stability loss, particularly in maneuvers and braking. This load relief compromises front tire adhesion to soil and significantly increases the risk of the condition known as “rearing”, characterized by directional control loss. This phenomenon occurs because the torque transmission capacity from the wheel to soil is limited by the load over the wheel and the soil support capacity, observable in Equation (6):

$$m = FT/W \quad (6)$$

where

m: adhesion coefficient;

FT: horizontal force transmitted;

W: weight over wheel.

Since the traffic surface was not altered and mass reduction occurred, an adhesion decrease resulted, observable in increased front-wheel rotation relative to the rear (lead ratio).

Such effects reinforce the technical recommendation to maintain at least 20% of the total tractor mass over the front axle, as a fundamental requirement to ensure safe drivability and operational stability under load transfer conditions [10]. The R^2 equation coefficients for axle masses (approximately -0.66 and $+1.63$, front and rear, respectively) show that the implement load increase significantly alters tractor balance, reinforcing the need for counterbalancing through front masses. The coefficient difference indicates that not all the load lost by the front axle is directly received by the rear, as part is transferred integrally via the hitch and part is redistributed via the center of mass.

This situation demands technical countermeasures, such as applying front ballasts or implement redistribution, to restore system balance. Figure 11 illustrates the sprayer–tractor unit operating conditions analyzed in this study.

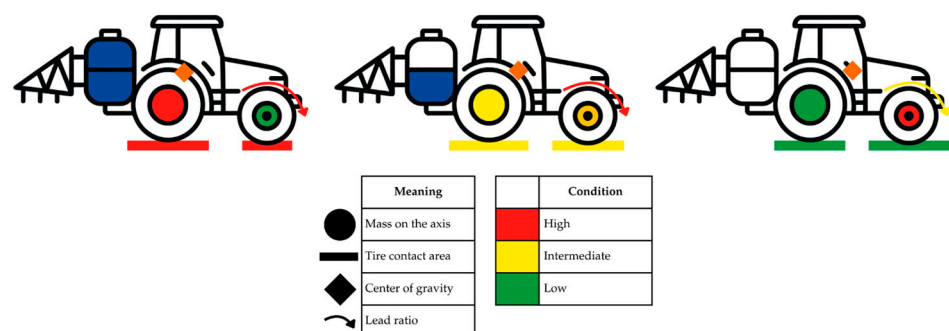


Figure 11. Sprayer–tractor operating conditions.

Previous studies demonstrate that the load distribution between tractor axles directly influences traction performance. Various approaches have been proposed to alter this distri-

bution, such as automatic ballasting systems with liquid transfer between reservoirs [11] or dynamic systems applied to conventional tractors [12]. However, not all presented effective field results or operational efficiency gains [13].

In agricultural operations requiring sprayers with large-capacity tanks, a feasible alternative involves the installation of an auxiliary front-mounted reservoir on the tractor, allowing for a reduction in the volume of the rear-mounted tank. Additionally, embedded monitoring and dynamic adjustment technologies, such as load sensors and attitude compensation systems, have proven effective in proactively mitigating lateral instabilities in tractors operating under challenging field conditions [14].

Nevertheless, this overload condition may elevate the risk of soil compaction and exceed the structural limits of axle components or the tires themselves. Furthermore, the increase in overall mass contributes to higher power losses associated with rolling resistance, exacerbated by the reduction in the tire dynamic radius during operation. According to [15], elevated axle loads, combined with inappropriate tire configurations, intensify soil bulk density, degrade the soil physical structure, and restrict root development.

The statistical analysis conducted in this study demonstrated that while implement mass was the dominant factor influencing load transfer between axles, tire inflation pressure and, importantly, the interaction between both variables also exerted a statistically significant effect on the load distribution over the front and rear axles, as well as on the displacement of the center of gravity. This finding underscores that tire inflation pressure is not merely a factor for adjusting the contact area but also a critical tool with a proven impact on load distribution and, consequently, on surface compaction control.

The analysis of tire contact area further confirmed this influence, showing that reduced load on front tires, combined with elevated internal pressures, decreased tire deformation and soil traction capacity. Conversely, rear tires exhibited a substantial increase in contact area under higher loads and lower inflation pressures, favoring tractive performance. This behavior is consistent with the findings of [16,17], who emphasized the importance of radial tire use and appropriate inflation pressure settings to enhance the net tractive force, expand the contact area, and reduce soil contact pressures.

Another noteworthy result was the rearward displacement of the tractor–implement system's center of gravity (CG), which exhibited a linear shift of approximately 0.022 cm per kilogram of added mass, accumulating more than 11 cm under the full-tank condition.

Moreover, an increase in the lead ratio was observed as implement mass increased, remaining within acceptable operational limits (<5%) only when the sprayer tank was empty. Lead ratios exceeding this threshold compromised traction efficiency and resulted in increased fuel consumption and accelerated wear of transmission components. These effects are attributable to the elevated lead ratio induced by rear axle overload and load redistribution, as demonstrated by [18], who highlighted the importance of load balancing and proper tire–soil interaction to maintain tractor energy efficiency under high-draft conditions. As a direct consequence of increased lead, the relative rotational speed of the front wheels rose, given their reduced load and lower deformation, which maintained or even increased their rotational speed and, consequently, the lead ratio.

In a study by [19], the combination of moderate tire inflation pressures with well-distributed ballast yielded significant improvements in traction efficiency without increasing energy consumption, even under controlled track conditions. Therefore, excessive tire slip resulting from improper inflation pressure settings negatively affects directional stability and reduces the tractor's tractive capacity, particularly when operating on highly deformable soils [20].

5. Conclusions

The mounted implement mass was identified as the primary factor responsible for load redistribution between the tractor axles, promoting a rearward shift of the system's center of gravity. This effect compromised operational stability, exceeding regulatory safety limits under maximum load conditions. The observed behavior exhibited a linear trend, with high coefficients of determination ($R^2 > 0.99$), highlighting the strong predictability of the phenomenon and reinforcing the reliability of the collected data. Therefore, the tractor's structural response to implement mass is more significantly influenced by the global center of mass position and the coupling geometry than by tire stiffness.

The load transfer from the front to the rear axle altered the tire deformation patterns, consequently affecting the contact areas. The magnitude of these variations depended on the tire inflation pressure, with more pronounced changes observed at lower inflation levels.

The lead ratio was directly influenced by the increase in mass, raising the traction demand on the drive wheels. Although tire pressure did not present a statistically significant effect on the lead ratio, it proved to be a critical factor in load distribution and in determining the center of gravity position.

It can be concluded that the coupling of mounted implements affects both the static and kinematic dynamics of the tractor–implement system in a coordinated manner. The adoption of management strategies, such as proper tire pressure adjustment, additional front axle ballast optimization, and continuous lead ratio monitoring, is essential for ensuring operational efficiency, reducing energy consumption, and preserving soil physical conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

MF	front axle mass
MR	rear axle mass
AF	front axle tire contact area
AR	rear axle tire contact area
CG	center of gravity displacement

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