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Investigating the Performance Parameters of ITM4120 and ITM399 Tractors Produced by Iran Tractor Manufacturing Company

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ABSTRACT

Considering the rapid advancement of technology worldwide and the emergence of new innovations in agricultural machinery and precision agriculture—especially in recent years—along with the growing emphasis on energy savings and the rising cost of fuel globally, and particularly in Iran, improving the quality of tractors has become essential. As the most important piece of agricultural machinery, tractors play a critical role in modern farming, and enhancing their efficiency and performance is vital for sustainable agricultural development. The purpose of this research is to investigate the effects of installing a turbocharger system on engine fuel consumption, power, slip, and traction parameters in a turbocharged ITM4120 tractor compared to a conventional ITM399 tractor without a turbocharger.

Materials and Methods

The tests were conducted on the second-grade concrete runway at the Tabriz Tractor Manufacturing Company for various tractor evaluations, including traction tests, in accordance with the guidelines provided by the Standards Organization. The air temperature was 23 ± 7 °C, and the air pressure was approximately 96.6 kPa. The weather conditions ranged from partly cloudy to clear, as per OECD standards. To conduct the tests, ITM4120 and ITM399 tractors were used. To measure the traction force between the two tractors, a 5-ton load cell model 5BBP , manufactured by Bongshin Korea, was used. This device has a measurement accuracy of 0.1 kg. A Sigma 5 dynamometer made in England was used to measure PTO power. This dynamometer has a maximum operating speed of 100 km/h, a maximum coupling weight of 100 kg, and a maximum axle weight of 1300 kg, with a power measurement accuracy of 0.1 hp and torque of 0.1 rpm. Additionally, a VDO-EDM1404 fuel gauge

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(manufactured in Germany) with a measurement accuracy of ±1% was employed to measure fuel consumption. A stopwatch with millisecond accuracy was also used for precise timing during the tests. Furthermore, a thermometer was utilized to measure the ambient air temperature and ensure it remained within the OECD standard range, with an accuracy of ±0.1 degrees Celsius.

Preparation of test equipment and devices

According to the recommendations of the standards organization and the manufacturer of the tractor and tires used, prior to the commencement of the tests, eight suitcase-shaped weights, each weighing 34 kg, were permanently installed at the front of the tractor. Additionally, two cast-iron weights, each weighing 50 kg, were permanently installed on each of the rear wheels of the tractors. Ballast, in this study refers to being the tires are filled with water or left empty. Tire ballast was applied to each tractor with an air pressure ranging from 0.8 to 1 bar. To increase tractive force while maintaining the center of gravity and ensuring appropriate weight distribution for four-wheel-drive tractors, the tires were filled with water.

The traction test was conducted on four-wheel-drive tractors in this project. The test was performed in accordance with OECD standards, in light and heavy gears, as well as tortoise and rabbit modes, at varying engine speeds. The tests were repeated three times on the concrete runway of the Tractor Manufacturing Company. During these tests, parameters such as slip percentage, tractive force, power, fuel consumption, specific fuel consumption, and specific power were measured and calculated. These values were also computed with ballast applied at maximum power across different gears (gears one, two, and three in both rabbit and turtle modes, as well as in two modes—light and heavy—using a 12-gear synchronized lever). The tests were carried out under varying loads, corresponding to 25%, 50%, 75%, 85%, and 100% of the pulling force at maximum power, as well as 50% of the pulling force in the first lighter gear, where the engine speed drops in both tractors. The data values were recorded in accordance with the standard table for all three repetitions for each tractor. Subsequently, the necessary analyses were performed on the collected data.

Drawbar tensile test

To conduct the tests, each of the tractors under examination (the turbocharged ITM4120 and the non-turbocharged ITM399) was hitched to the ITM1500 tractor, which was equipped with a throttle to generate drawbar pull as the load tractor. The tested tractors pulled the load tractor in different gears, while a load cell placed between the two tractors recorded the traction force. This data was logged by a data logger installed inside the cabin. These tests were performed for both tractors in three experimental stages. The wheel slip of the driving wheels of the test tractor, forward speed, and data from the load cell and fuel gauge were recorded in two conditions: with and without load, and with and without ballast.

Results and Discussion

In the results, the charts and tables related to the statistical analysis of data from the ITM4120 turbocharged tractor and the ITM399 non-turbocharged tractor's drawbar pull tests with ballast are presented. The effects of the turbocharger system on parameters such as drawbar pull force, fuel consumption, specific fuel consumption, and tractor power have been included. The statistical design employed utilized two-way ANOVA in the SAS software due to the presence of two independent variables (gear effect and tractor type).

1. Introduction

Considering the rapid advancement of technology worldwide and the emergence of new innovations in agricultural machinery and precision agriculture—especially in recent years—along with the growing emphasis on energy savings and the rising cost of fuel globally, and particularly in Iran, improving the quality of tractors has become essential (Lanças et al., 2024). As the most important piece of agricultural machinery, tractors play a critical role in modern farming, and enhancing their efficiency and performance is vital for sustainable agricultural development (de Melo et al., 2022; Hoy & Kocher, 2020; Zhu et al., 2022). In this regard, the Iranian Tractor Manufacturing Company has taken significant steps to manufacture new tractors equipped with turbocharged engines. These efforts aim to enhance the quality of its products and strengthen its competitive position in the global market. Tractor performance is cloud to the work it can perform, with maximum drawbar pull serving as a key metric for comparing and evaluating tractors . However, drawbar pull is significantly affected by soil and field conditions, as well as factors like gear ratios and wheel weighting, which can be optimized by filling tires with water (Lanças et al., 2024; Zoz & Grisso, 2003). Maximum drawbar power is widely regarded as one of the most useful performance metrics for agricultural tractors (Leite et al., 2011). According to the OECD standard, drawbar power refers to the power that can be delivered at the tractor's drawbar over a distance of at least 20 meters. This value is calculated using Equation 1.

$$BDP = \frac{pv}{3\cdot 6} \qquad (1)$$

Where DBP is the drawbar power (kW), P is the traction force (kN), and V is the forward speed (km/h).

Brake power is a critical metric used to measure the power output of an engine, crankshaft, or flywheel. It is typically determined using a dynamometer, which measures the torque and rotational speed of the crankshaft or flywheel (Goering, 1992).

$$P_b = \frac{2\pi TN}{60000} \qquad (2)$$

Where P_b is the braking power (kW), T is the torque (N.m) and N is the rotational speed (rpm).

Increasing the weight of a tractor enhances its traction performance, particularly when ballast is added to the drive wheels on sandy loam soils . Adding weight to the tractor tires increases the traction force, which in turn boosts the binding force. However, it is important to note that increasing the ballast also raises the rolling resistance force . Considering these factors, the amount of ballast should be carefully determined to achieve maximum grounding efficiency. Ideally, the slip rate should be maintained between 8% and 15% (ASAE, 1992). The recommended load applied to tires is specified in ASAE Standard S430 (ASAE 1992). Specific fuel consumption (SFC) refers to the mass of fuel consumed to perform a unit of work and is widely used as a metric for comparing the efficiency of tractors. It is defined as the ratio of fuel consumption rate (kg/h or g/s) to the power output (kW) generated by the engine (Goering, 1992). Traction efficiency is function of the dynamic load on the drive wheels. At a constant slip, traction efficiency increases with an increase in dynamic load on compact soils but decreases on loose soils (Karabektas, 2009; Matthes et al., 1988). The Nebraska Tractor Testing

Laboratory (NTTL) was, for many years, the only independent tractor testing institute in the world . With the globalization of tractor manufacturing and sales in the 1980s, the Organisation for Economic Co-operation and Development (OECD) test codes were adopted as the official global test manual for the international market. International standards play a crucial role in evaluating the performance and safety of agricultural equipment, particularly tractors. One of the most significant global standards for tractor testing is the OECD (Organization for Economic Cooperation and Development) standard. This standard serves as an international reference for assessing the performance of agricultural and forestry tractors. The OECD standard includes precise and standardized methods for testing tractor performance. It has been designed to ensure accurate comparisons of the performance of different tractors under identical conditions. Some of the key features of this standard include: measuring the tractor's traction force under various conditions, measuring specific fuel consumption, evaluating engine output power and tractor traction power, and determining environmental conditions such as temperature, humidity, and air pressure to ensure result consistency. This standard enables manufacturers and consumers to reliably compare tractor performance. To conduct OECD-standard tests, appropriate infrastructure is required. A smooth, even concrete or asphalt track without irregularities is necessary. This track should be designed to minimize external influences such as ground slope or unevenness. Measurement equipment includes dynamometers, fuel consumption measurement devices, thermometers, and timers for recording accurate data. Environmental conditions for tractor testing must be carefully controlled. Ambient temperature should be within the range of 20 to 30 degrees Celsius. Relative humidity should be maintained between 40% and 60%, and atmospheric pressure should be within the standard range (typically 101.3 kilopascals). Additionally, tractors must be subjected to specific loading conditions. For this purpose, water or other liquids are used to simulate loading at the front and rear of the tractor, while standard weights are employed to adjust the tractor's weight (Hoy & Kocher, 2020; McFadden, 2022; OECD, 2010). A turbocharger is a highly delicated air pump that increases the amount of air supplied to an engine by harnessing the energy from exhaust gases. Typically, the compressor is located between the air filter and the engine's intake manifold, while its turbine is positioned between the exhaust manifold and the muffler . By compressing the engine's intake air, the turbocharger forces more air into the cylinders, enabling the engine to burn fuel more efficiently and produce greater power . Compared to naturally aspirated or non-turbocharged engines, turbocharged engines offer several advantages: higher torque and power output, reduced fuel consumption, lower emissions, and a more compact and lighter design (Karabektas, 2009; Mehra et al., 2023). Karabektas investigated the effects of turbocharging on the performance of a diesel engine fueled by diesel and biodiesel in terms of brake power, torque, specific fuel consumption, thermal efficiency, and CO and NOx emissions.The evaluation of experimental data showed that the brake thermal efficiency of biodiesel was slightly higher than that of diesel fuel in both naturally aspirated and turbocharged conditions, while biodiesel yielded slightly lower brake power and torque along with higher fuel consumption values. Additionally, use of biodiesel improved the performance parameters and decreased CO emissions of the turbocharged engine compared to diesel fuel.

(Karabektas, 2009). Kumar and Choudhary examined the impact of using a turbocharging system on diesel engine performance and pollutant emissions. Their results demonstrated that incorporating a turbocharger enhances engine efficiency, reduces fuel consumption, and increases power output (Kumar & Choudhary, 2023). In generaly, the combination of biofuels (biodiesel) with a turbocharger can significantly decrease CO_2 and particulate emissions (Chiong et al., 2012). In a study The effect of compression ratio and alternative fuels on performance and exhaust emission in a diesel engine by engine modelling, it was concluded that increasing the compression ratio in a turbocharged engine reduces brake specific fuel consumption and exhaust emissions (Ahmadipour et al., 2019).

Zareei et al. conducted a study to investigate the impact of employing turbochargers and intercoolers on the performance of the MF285 tractor. The findings revealed that the utilization of turbochargers and intercoolers significantly enhanced the engine's power and torque across various operating speeds. Furthermore, the incorporation of an intercooler contributed to a reduction in the temperature of the intake air, thereby improving combustion efficiency. This improvement resulted in a decrease in both exhaust emissions and fuel consumption. The study demonstrated that the combination of a turbocharger and an intercooler can effectively enhance engine performance in agricultural tractors (Zareei et al., 2020). Karabektas investigated the impact of turbochargers on the performance of diesel engines fueled with biodiesel . The results demonstrated that the use of a turbocharger led to an improvement in engine performance and a reduction in emissions. Additionally, the specific fuel consumption decreased in engines equipped with turbochargers, while the output power of the engine increased. These enhancements resulted in significant fuel saving (Karabektas, 2009). Chiong et al. investigated the one-dimensional modeling of a twin-entry turbine in the turbocharger system . The results demonstrated that the turbocharger can effectively increase the engine's output power and reduce the specific fuel consumption in engines equipped with turbochargers, leading to improved engine efficiency and reduced operational costs (Chiong et al., 2012). In a study, the impact of using a turbocharger and intercooler on the performance of an agricultural engine was investigated. The experiments were conducted with six different engine configurations and at ten varying speeds. The results indicated that installing only the turbocharger, without increasing the fuel flow, had no effect on enhancing engine torque or power. Configurations involving "turbocharger + service" and "turbocharger + service + intercooler" reduced specific fuel consumption by up to 10% and increased torque and power by approximately 30% compared to the baseline configuration (natural aspiration). Additionally, the use of the intercooler contributed to improved combustion efficiency and a reduction in emissions (Silveira de Farias et al., 2021). Pashaei Hulasu and et al. investigated the impact of the turbocharger system on engine fuel consumption, power, and traction of tractors ITM475, ITM485, and ITM800. The results showed that tractors equipped with the turbocharger system (ITM485 and ITM800) had significantly higher traction power and force compared to the tractor without a turbocharger (ITM475). This difference was significant at the one percent probability level. Additionally, the specific fuel consumption in tractors with turbochargers (ITM485 and ITM800) was significantly lower than in the tractor without a turbocharger (ITM475), indicating considerable fuel savings (PashaiHulasu et al., 2015).

The purpose of this research is to investigate the effects of installing a turbocharger system on engine fuel consumption, power, slip, and traction parameters in a turbocharged ITM4120 tractor compared to a conventional ITM399 tractor without a turbocharger. The objective of this study is to quantitatively evaluate the impact of using a turbocharging system on the traction performance of nearly equivalent weight tractors. By selecting two tractors with similar operational weights, the effect of weight variation on traction force was eliminated. In this research, performance indicators including Drawbar Pull, Drawbar Power, and Specific Power were measured and compared. The main goal was to investigate the hypothesis that the increase in engine power due to turbocharging, considering physical limitations such as slip and power transmission efficiency, would lead to a corresponding increase in useful drawbar power at the hitch.

2. *Materials and Methods*

The tests were conducted on the second-grade concrete runway at the Tabriz Tractor Manufacturing Company for various tractor evaluations, including traction tests, in accordance with the guidelines provided by the Standards Organization. To conduct the tests, ITM4120 and ITM399 tractors were used (Figure 1).

The specifications of the ITM 399 and ITM 4120 tractors and also test conditions are shown in Table 1.

Fig 1. ITM399 without turbo charger (Left) and ITM 4120 with turbo charger (Right) tractors

Table 1. specifications of ITM 399 and ITM 4120 tractors and also test conditions.

Kind of tractor	ITM399	ITM4120
Maximum engine power in 2200 rpm(hp)	110 hp	120 hp
Number of cylinders	6	6
Engine respiration System	Natural Aspiration	Turbocharger
Engine displacement (liter)	6	6
Weight (kg)	3890	4080
Type of gearbox	Synchronous	Synchronous
air temperature*	23 ± 7 °C	23 ± 7 °C
air pressure*	96.6 kPa	96.6 kPa
weather condition*	partly cloudy to clear	partly cloudy to clear

*as per OECD standards

To measure the traction force between the two tractors, a 5-ton load cell, was used. A Sigma 5 dynamometer was used to measure PTO power. Additionally, a VDO-EDM1404 fuel gauge was employed to measure fuel consumption. A stopwatch was also used for precise timing during the tests. Furthermore, a thermometer was utilized to measure the ambient air temperature and ensure it remained within the OECD standard range. (Table 2 and Figure 2).

Table 2. specifications of all devices used in the research

device	specification	accuracy
Load cell	5-ton load cell model 5BBP (Bongshin Korea)	0.1 kg
Dynamometer	• Sigma 5 (England) • maximum operating speed of 100 km/h • maximum coupling weight of 100 kg • maximum axle weight = 1300 kg	Power measurement of 0.1 hp and torque in 0.1 rpm
VDO-EDM1404 fuel gauge	(Germany)	±1%
Stopwatch		millisecond
Thermometer	3890	±0.1 °C

Fig 2. Load cell, fuel gauge and dynamometer used in the traction test and fuel consumption of tractors

2.1. Preparation of test equipment and devices

According to the recommendations of the standards organization and the manufacturer of the tractor and tires used, prior to the commencement of the tests, eight suitcase-shaped weights, each weighing 34 kg, were permanently installed at the front of the tractor. Additionally, two cast-iron weights, each weighing 50 kg, were permanently installed on each of the rear wheels of the tractors. Ballast, in this study refers to being the tires are filled with water or left empty. Tire ballast was applied to each tractor with an air pressure ranging from 0.8 to 1 bar. To increase tractive force while maintaining the center of gravity and ensuring appropriate weight distribution for four-wheel-drive tractors, the tires were filled with water, as outlined in Table 3.

The traction test was conducted on four-wheel-drive tractors in this project. The test was performed in accordance with OECD standards, in light and heavy gears, as well as tortoise and rabbit modes, at varying engine speeds. The tests were repeated three times on the concrete runway of the Tractor Manufacturing Company. During these tests, parameters such as slip percentage, tractive force, power, fuel consumption, specific fuel consumption, and specific power were measured and calculated. These values were also computed with ballast applied at maximum power across different gears (gears one, two, and three in both rabbit and turtle modes, as well as in two modes—light and heavy—using a 12-gear synchronized lever). The tests were carried out under varying loads, corresponding to 25%, 50%, 75%, 85%, and 100% of the pulling force at maximum power, as well as 50% of the pulling force in the first lighter gear, where the engine speed drops in both tractors. The data values were recorded in accordance with the standard table for all three repetitions for each tractor. Subsequently, the necessary analyses were performed on the collected data.

Table 3. The weight of tested tractors and ballast weight

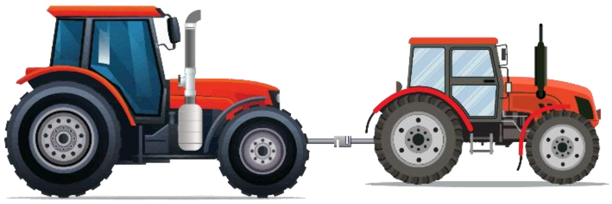
Ballast weight	ITM4120(kg)	ITM399(kg)
Front ballast weight (big weight and water)	474	442
Rear ballast weight (big weight and water)	600	650
Tractor weight on front axle	1610	1510
Tractor weight on rear axle	1970	1900

2.2. Drawbar pulling test

To conduct the tests, each of the tractors under examination (the turbocharged ITM4120 and the non-turbocharged ITM399) was hitched to the ITM1500 tractor, which was equipped with a throttle to generate drawbar pull as the load tractor. The tested tractors pulled the load tractor in different gears, while a load cell placed between the two tractors recorded the pulling force. This data was logged by a data logger installed inside the cabin (Figure 3a). These tests were performed for both tractors in three experimental stages. The wheel slip of the driving wheels of the test tractor, forward speed, and data from the load cell and fuel gauge were recorded in two conditions: with and without load, and with and without ballast.

When the load tractor is placed in the desired gear and pulled by the test tractor, the movement transfers from the wheels of the load tractor to the differential and gearbox. Eventually, this causes the flywheel to rotate, which in turn moves the crankshaft and pistons. The fuel supply system of the load tractor is disabled and taken out of the circuit. If, for any reason, the exhaust air flow is restricted during the exhaust stroke, considering that the compression ratio of the ITM1500 tractor engine (16:1) generates significant pressure, the accumulated compressed air will exert pressure on the pistons. This pressure prevents the crankshaft from rotating, causing the wheels to lock up and thereby applying drawbar pull force to the pulling tractor.To create such conditions, the exhaust pipe connected to the exhaust manifold of the load tractor is removed, and a new exhaust pipe is installed. This exhaust pipe is made from a 3-inch cylindrical profile (tube), with a 2-inch valve incorporated into its path, which is accessible to the driver. (Figure 3b) As the degree to which the valve is closed increases, the resistance to the release of pressurized air from the cylinder combustion chamber rises. This leads to an increase in accumulated pressure on the piston, which prevents the crankshaft from rotating. It is clear that the heavier the gear selected for the load tractor, the more resistance it will create against movement. The reason for this is the larger gear ratio of the power transmission system in the heavier gear, which results in an increase in the forces acting on the tractor's wheels. This explanation highlights the relationship between gear selection and the mechanical resistance generated, which is directly linked to the gear ratio and its impact on wheel force.

a



b

Fig 3. The drawbar traction force tests with ballast (a) and schematic of connected exhaust pipe to the exhaust manifold of the load tractor (b)

Based on the required load for the test tractor, which is equivalent to the draft resistance of a three-share plow at a depth of 30 to 35 centimeters, the gear and the degree of closure of the exhaust valve of the load tractor were adjusted to create the desired resistive load. To measure the amount of draft force between the two tractors, a 5-ton load cell manufactured by Bongshin5BBP was used. The data related to the draft force between the two tractors were read and recorded through a data logger connected to the load cell, which recorded 10 data points per second. To measure the fuel consumption of tractors in the experiments of this study, a fuel gauge of the type VDO-EDM1404 manufactured in Germany was used. This device calculates the flow rate of fuel from the tank to the engine and the return flow from the engine back to the tank, displaying the average fuel consumption digitally in liters per hour. In the drawbar pull tests, over a distance corresponding to 10 rotations of the tractor's rear wheels (between 46 and 50 meters), the amount and time of fuel consumption were measured. Using these parameters, the fuel consumption rate was calculated in terms of liters per hour (Lit h^{-1}) and kilograms per hour (kg h^{-1}). According to the OECD standard, for measuring the required values in the project, the traction performance was measured at speeds ranging from 1.93 to 17.54 kilometers per hour across different gears.

3. *Results and Discussion*

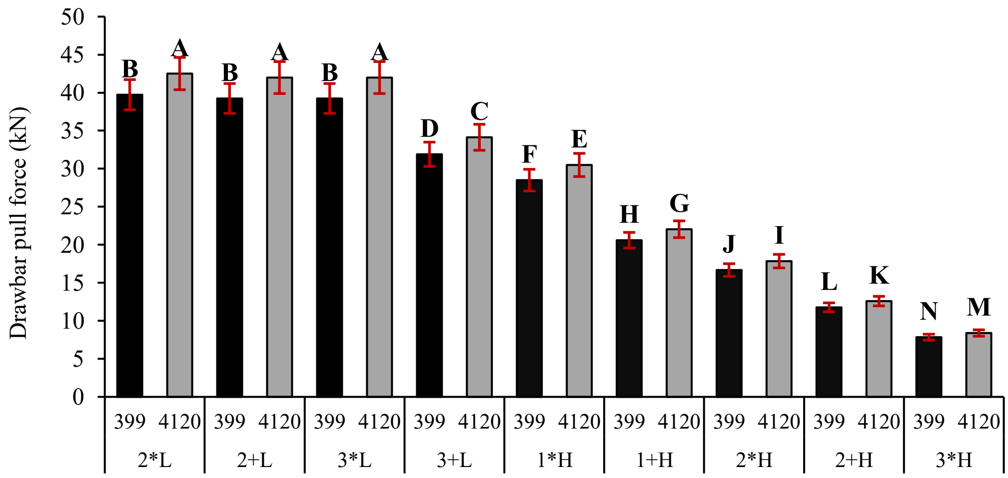
In the results, the charts and tables related to the statistical analysis of data from the ITM4120 turbocharged tractor and the ITM399 non-turbocharged tractor's drawbar pull tests with ballast are presented. The effects of the turbocharger system on parameters such as drawbar pull force, fuel consumption, specific fuel consumption, and tractor power have been included. The statistical design employed utilized two-way ANOVA in the SAS software due to the presence of two independent variables (gear effect and tractor type).

3.1. Comparison of drawbar pull force in turbocharged ITM4120 and non-turbocharged ITM399 tractors at different gears during ballasted drawbar pull tests

For this comparison, a two-way ANOVA was utilized (Table 4). The results of the variance analysis indicate that the effect of the tractor type is significant at the 1% probability level. This means that there is a notable difference in drawbar pull force between the turbocharged ITM4120 tractor and the non-turbocharged ITM399 tractor at the 1% significance level. The findings reveal that the drawbar pull force of the turbocharged ITM4120 tractor is significantly higher than that of the non-turbocharged ITM399 tractor. Additionally, the effect of gear selection is also significant, meaning that the drawbar pull force varies significantly across different gears at the 1% probability level. The results demonstrate that the highest drawbar pull force values are observed in gears L+2, L*2, L*3 , and L , while the lowest values occur in gears H+2 and H*3 (Figure 4). Which L, H, +, * and the number represent low, high, rabbit, turtle and gear number respectively.

Table 4. Two way ANOVA of drawbar pull force data at drawbar pull test with ballast

Source	DF	Sume of square	Mean of square	F value
Model	17	7871.310565	463.018269	12849.7**
Kind of tractor	1	42.435869	42.435869	1177.68**
Gear	8	7821.059148	977.632394	27131.3**
Kind of tractor * Gear	8	7.815548	0.976944	27.11**
Error	36	1.297200	0.036033	
Corrected Total	53	7872.607765		



(Letters that are not similar in each column indicate a significant difference based on Duncan's multiple range test at the 1% probability level)

Fig 4. The effect of tractor type and gear on drawbar pull force

The observation that drawbar pull decreases with increasing gear number, both in the LOW and HIGH ranges, points towards specific engine and transmission characteristics that limit the available tractive force at higher speeds. This is different from the power trend and relates directly to the torque available at the wheels and the gearing.

The observed continuous decrease in drawbar pull force with increasing gear number, across both the LOW and HIGH ranges, is fundamentally governed by the transmission's gear ratios and the engine's torque characteristics at the operating speeds corresponding to those gears.

Drawbar pull is a manifestation of the torque delivered to the drive wheels multiplied by the effective rolling radius of the wheels, reduced by drivetrain losses.

By analysing Across Gear Ranges:

1. **LOW Gear Range:** As the gear number increases within the LOW range, the total gear ratio (G_{total}) decreases. While the engine torque (T_{engine}) might be increasing or operating within a favorable band, the significant reduction in G_{total} dominates the equation. This gearing down means less torque is ultimately multiplied to the wheels. Consequently, even if engine RPM increases, the resultant torque at the wheels decreases, leading to a reduction in drawbar pull.
2. **HIGH Gear Range:** Shifting into the HIGH range further reduces the overall gear ratios (G_{total}) compared to the LOW range. As the gear number continues to increase within the HIGH range, G_{total} decreases even more substantially. This pronounced reduction in the multiplication of torque results in a lower torque at the drive wheels. Coupled with potentially reaching the engine's maximum power output, the diminishing gear ratio becomes the primary factor causing a continued decrease in drawbar pull.

While the primary driver is the gear ratio, the engine's torque curve also plays a role. If the engine's peak torque occurs at lower RPMs, and the higher gears force the engine to operate at RPMs where torque is lower, this exacerbates the reduction in tractive force. Turbocharged engines, which can offer broader torque bands, might mitigate this effect to some extent within their optimal operating range, but the overwhelming effect of the decreasing gear ratios at higher speeds will still lead to a net decrease in drawbar pull.

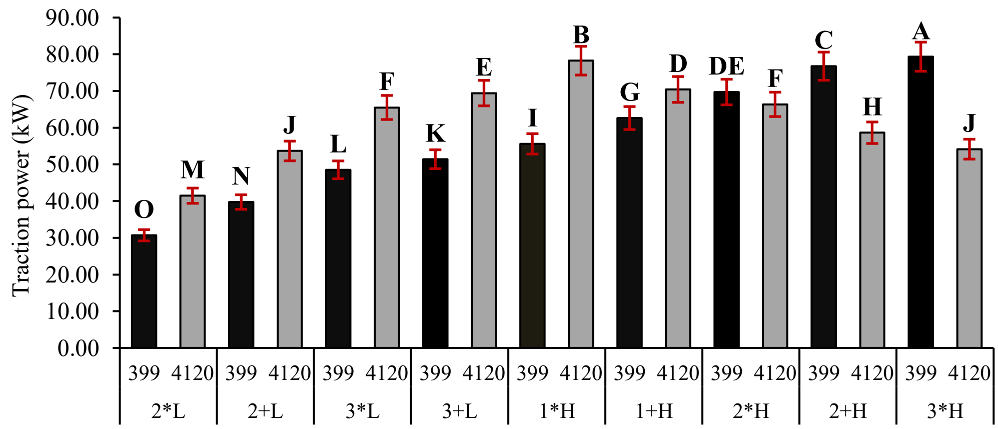
The consistent decline in drawbar pull with increasing gear numbers in both LOW and HIGH ranges is predominantly a consequence of the diminishing total gear ratio (Gtotal). This reduction in gear multiplication leads to lower torque at the drive wheels, thereby decreasing the available tractive force, irrespective of the engine's torque output within its operating RPM band.

3.2. Comparison of traction power in turbocharged ITM4120 and non-turbocharged ITM399 tractors at different gears in drawbar pull tests with ballast

For this comparison, a two-way ANOVA was employed (Table 5). The results of the ANOVA indicate that the effect of the tractor type on traction power is significant at the 1% probability level. This means that there is a notable difference in traction power between the turbocharged ITM4120 tractor and the non-turbocharged ITM399 tractor. Specifically, when the gear is held constant, the traction power of the turbocharged ITM4120 tractor is significantly higher than that of the non-turbocharged ITM399 tractor. The effect of the gear selection is also significant, meaning that traction power varies significantly across different gears at the 1% probability level. In light gears, the tractive effort of a turbocharged tractor is typically reduced. This can be attributed to the fact that turbochargers require sufficient exhaust gas flow to generate effective boost pressure, which is generally achieved at higher engine speeds (RPM). In light gears, the engine operates at a lower speed, where the turbocharger may not provide adequate boost, leading to a decrease in torque and power output. Furthermore, in light gears, the transmission ratio results in higher tractor speed but lower torque at the wheels. Since tractive effort is directly proportional to engine torque, this reduction in torque leads to diminished pulling force. Additionally, turbocharged tractors are typically designed to operate most efficiently within the engine speed range that produces maximum torque (1500–2000 RPM). When operating in light gears, the engine may function outside this optimal range, thereby reducing overall efficiency. The findings suggest that the highest traction power values are observed in gears H*3, H+2, H*1, and L+3, while the lowest values occur in gears L+2 and L*2 (*turtle" mode and + "rabbit" mode) (Figure 5). These results are consistent with those of Pashaei Holasu, Silveira de Farias, and Zareei(PashaiHulasu et al., 2015; Silveira de Farias et al., 2021; Zareei et al., 2020).

Table 5. Two way ANOVA of traction power data at drawbar pull test with ballast

Source	DF	Sume of square	Mean of square	F value
Model	17	9801.062370	576.533081	8965.01**
Kind of tractor	1	315.085067	315.085067	4899.53**
Gear	8	6094.275504	761.784438	11845.6**
Kind of tractor * Gear	8	3391.701800	423.962725	6592.56**
Error	36	2.315133	0.064309	
Corrected Total	53	9803.377504		



(Letters that are not similar in each column indicate a significant difference based on Duncan's multiple range test at the 1% probability level)

Fig 5. The effect of tractor type and gear on traction power

The distinct trends in drawbar power output between naturally aspirated (NA) and turbocharged tractors across gear ranges are primarily attributable to their differing engine torque curves and volumetric efficiency characteristics.

In NA tractors, drawbar power exhibits a continuous increase as gear number increases, both within the LOW and HIGH ranges. This is because NA engines typically produce maximum torque at lower RPMs and their torque output generally rises with RPM until reaching a peak, after which it may plateau or slightly decline at very high speeds. As the gear number increases, forward speed rises, and the engine is pushed into higher RPMs. Consequently, the engine operates within an increasingly favorable portion of its torque curve, leading to a steady increase in power output (Power = Torque × Angular Velocity). The air intake is solely dependent on atmospheric pressure and engine displacement, limiting the peak power achievable at higher speeds.

Turbocharged tractors demonstrate a more complex power delivery profile. Within the LOW gear range, drawbar power increases with gear number, mirroring the NA tractor. This is because, in lower gears, the engine operates at speeds where the turbocharger is effectively spooling up and boosting cylinder filling, thus enhancing torque and power output. However, as the tractor shifts into the HIGH gear range and the gear number increases, drawbar power output begins to decrease. This phenomenon occurs because, at higher forward speeds and consequently higher engine RPMs in the HIGH gears, the engine may reach its maximum power capacity. Beyond this point, further increases in engine speed do not translate into proportional increases in torque due to limitations in turbocharger efficiency at very high RPMs, intercooler capacity, or simply the engine's inherent design limits. In some cases, excessive exhaust backpressure at high speeds can also limit the turbocharger's effectiveness or even lead to a slight reduction in volumetric efficiency. Consequently, while angular velocity continues to rise, the torque may plateau or slightly decrease, causing the overall power output to stabilize or decline.

The continuous rise in drawbar power in NA tractors with increasing gear number is a function of operating along a steadily increasing torque curve. In contrast, the eventual decrease in drawbar power in turbocharged tractors at higher gears signifies reaching the engine's maximum power threshold and potential limitations in volumetric efficiency or turbocharger performance at very high engine speeds. This highlights the engine's specific torque characteristics and boost management as critical factors influencing drawbar power delivery across different transmission ratios.

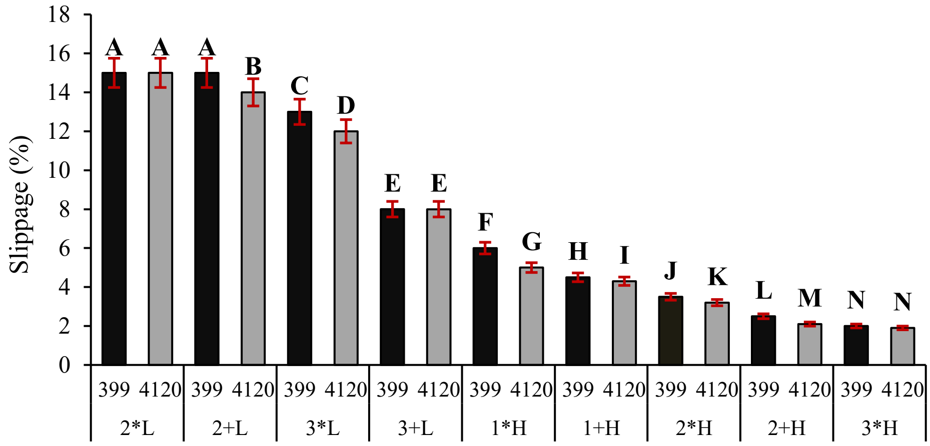
3.3. Comparison of slippage in turbocharged ITM4120 and non-turbocharged ITM399 tractors at different gears in drawbar pull tests with ballast

For this comparison, a two-way ANOVA was utilized. The results of the ANOVA analysis indicated that the tractor effect on slippage is significant. This means that the slippage levels in the turbocharged tractor ITM4120 and non-turbocharged tractor ITM399 show a significant difference at the one percent probability level (Table 6).

The findings suggest that the slippage rate in the turbocharged tractor ITM4120 is lwoer than in the non-turbocharged tractor ITM399. Additionally, the gear effect is also significant, meaning that the slippage rate differs significantly across various gears at the one percent probability level. The highest slippage rates are observed in gears 2*L and 2+L, while the lowest rates occur in gears 2+H and 3*H (Figure 6). These results are consistent with those of Pashaei and Zareei (PashaiHulasu et al., 2015; Zareei et al., 2020).

Table 6. Two way ANOVA of slippage data at drawbar pull test with ballast

Source	DF	Sume of square	Mean of square	F value
Model	17	1297.333	76.313	Infty**
Kind of tractor	1	6.000000	6.00	Infty**
Gear	8	1288.333	161.041	Infty**
Kind of tractor * Gear	8	3.00	0.375	Infty**
Error	36	0.00	0.00	
Corrected Total	53	1297.333		



(Letters that are not similar in each column indicate a significant difference based on Duncan's multiple range test at the 1% probability level)

Fig 6. The effect of tractor type and gear on slippage

The observed reduction in wheel slip with increasing gear number, both within the LOW range and after shifting into the HIGH range, can be attributed to the combined effects of increased forward velocity, reduced torque amplification, and the corresponding shift in the traction–load balance at the tire–soil interface. At lower gears, the high transmission ratio produces elevated torque at the drive wheels, resulting in high shear stress on the soil and consequently greater slip. As the gear number increases in the LOW range, the transmission ratio decreases and the torque delivered to the wheels is reduced. Although drawbar load remains relatively constant due to ballast and controlled test conditions, the reduction in wheel torque limits soil shear failure, causing slip to decline.

Upon shifting into the HIGH range, the transmission ratio becomes even smaller, and the tractor operates at higher forward speeds with substantially lower torque at the wheels. Under these conditions, the available traction force approaches the soil's sustainable shear capacity without exceeding it, thereby minimizing slip. Furthermore, the increase in travel speed enhances the dynamic stiffness of the tire–soil contact zone, reducing the extent of soil deformation per unit of tractive effort. This dynamic effect further contributes to lowering wheel slip as gear number increases in the HIGH range.

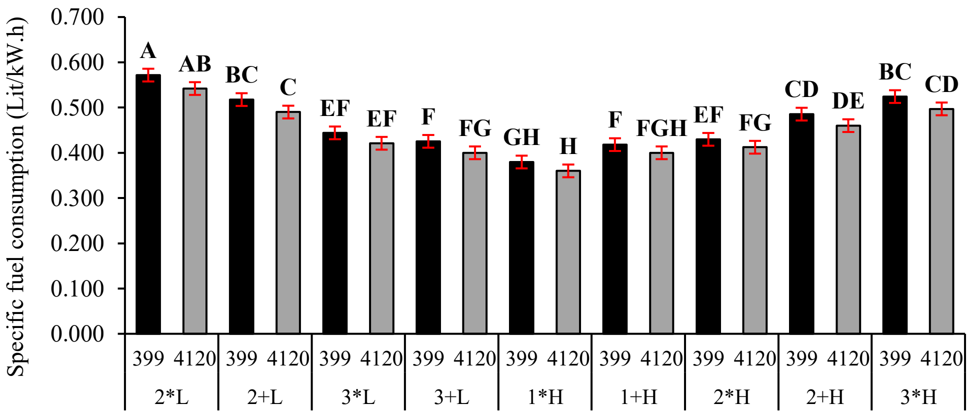
Overall, the continuous reduction in wheel slip across both gear ranges is a direct consequence of decreasing torque demand at the wheels, improved traction efficiency at higher speeds, and the stabilization of soil shear stresses below the failure threshold as the transmission ratio decreases with higher gear numbers.

3.4. Comparison of Specific Fuel Consumption (SFC) in the Turbocharged ITM4120 Tractor and the Non-Turbocharged ITM399 Tractor at Different Gears During Ballasted Drawbar Pull Tests

The results of the variance analysis indicate that the effect of the tractor type on the specific fuel consumption in the turbocharged ITM4120 tractor and the non-turbocharged ITM399 tractor is significantly different at the 1% probability level (Table 7). The specific fuel consumption in the turbocharged ITM4120 tractor is significantly lower than that of the non-turbocharged ITM399 tractor. The effect of gear selection is also significant, meaning that the specific fuel consumption varies significantly across different gears at the 1% probability level. The test results demonstrate that the highest specific fuel consumption values are observed in gears 3*H, 2+L, and 2*L, while the lowest values occur in gears 1*H and 1+H (Figure 7). The results of this study are consistent with the results of other researchers (Kumar & Choudhary, 2023; PashaiHulasu et al., 2015; Silveira de Farias et al., 2021).

Table 7. Two way ANOVA of Specific fuel consumption data at drawbar pull test with ballast

Source	DF	Sume of square	Mean of square	F value
Model	17	0.17737987	0.01043411	21.90**
Kind of tractor	1	0.03655602	0.03655602	76.74**
Gear	8	0.13986637	0.01748330	36.70**
Kind of tractor * Gear	8	0.00095748	0.00011969	0.25^{ns}
Error	36	0.01714867	0.00047635	
Corrected Total	53	0.19452854		



(Letters that are not similar in each column indicate a significant difference based on Duncan's multiple range test at the 1% probability level)

Fig 7. The effect of tractor type and gear on specific fuel consumption

The lower SFC of the turbocharged ITM4120 tractor compared to the non-turbocharged ITM399 across different gears in ballasted drawbar pull tests is primarily due to the enhanced air–fuel mixing, higher torque availability at lower engine speeds, improved performance under load, and higher brake thermal efficiency provided by turbocharging. These advantages enable the turbocharged engine to produce greater drawbar power while consuming less fuel per unit of work.

Analysis of the drawbar performance data shows that the specific fuel consumption (SFC) exhibits two distinct trends across the LOW and HIGH gear ranges. In the LOW range, SFC decreases with increasing gear number, whereas in the HIGH range SFC increases as the gear number rises. This contrasting behavior is governed by variations in engine loading and the corresponding shift in the engine's operating point relative to its brake-specific fuel consumption (BSFC) map.

In the LOW gears, the high transmission ratios impose substantial load on the engine, enabling operation within the region of relatively high brake thermal efficiency. At the lowest gears, the engine experiences lugging conditions and functions below its optimal speed–load region. As the gear number increases, forward speed rises and the engine transitions toward a more favorable combination of torque demand and rotational speed. This shift moves the operating point closer to the minimum BSFC zone, thereby reducing SFC across successive LOW gears.

Conversely, in the HIGH gear range the reduced transmission ratio significantly lowers the torque demand at the engine crankshaft. As the gear number increases, the engine becomes progressively under-loaded and operates in a partial-load regime characterized by reduced combustion temperature, lower volumetric efficiency, and diminished thermal efficiency. Since the fuel injection system continues to deliver a near-constant baseline fuel quantity, the decrease in effective power output causes SFC to rise. This behavior aligns with the well-established characteristic of diesel engines, wherein partial-load operation results in inherently higher SFC compared with moderate–high load conditions.

Thus, the observed SFC patterns across the two gear ranges are a direct consequence of the interplay between gear ratio, engine load, and the engine's position on its BSFC map.

4. Conclusion

The test results indicated that, considering the gear types, the power and traction force of the turbocharged ITM4120 tractor were higher than those of the non-turbocharged ITM399 tractor. These differences were statistically significant at the 1% confidence level. Additionally, in terms of specific fuel consumption and slippage the turbocharged ITM4120 tractor demonstrated lower fuel consumption and improved slippage performance compared to the non-turbocharged ITM399 tractor. These differences were also statistically significant at the 1% confidence level from all aspects. Based on the analysis of the tractive force, the specific fuel consumption and the specific fuel consumption of the different gears, it was found that the L+3 and H*1 gears offered the highest power-to-fuel and traction-to-fuel ratios with 48.5 and 20.6 kN tractive force and 322 g/kWh specific fuel consumption, respectively. These gears also showed slip values within acceptable limits, although they were below the recommended range of 8 to 15 percent. Further studies are recommended to evaluate these gears under field conditions to confirm their efficiency.

Nomenclature

BDP	Drawbar power (kW)	T	Torque (N.m)
N	Rotational speed (rpm)	v	Speed (km h^{-1})
p	Traction force (kN)	π	Pi number
P_b	Braking power (kW)		

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