

Article

Relationship Between Power Output, Fuel Consumption and Specific CO₂ Emissions in Agricultural Tractors Using OECD Code 2 Test Reports

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Abstract

In the context of growing attention to environmental sustainability, emission reduction efforts increasingly involve all sectors, including agriculture. European “Stage” regulations (from Stage I in 2002 to Stage V in 2019) have progressively reduced regulated pollutants such as hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and carbon monoxide (CO). However, carbon dioxide (CO₂) emissions from agricultural tractors are not currently subject to specific legislation. This study assesses CO₂ emissions through their direct relationship with fuel consumption. Hourly and specific CO₂ emissions (g/kWh) were estimated using power and fuel consumption data from 877 tractors tested under OECD Code 2 procedures from the 1960s to the present. The same tractors were analyzed under two operating conditions: power take-off (PTO) dynamometer bench tests and drawbar tests, considering maximum power and rated engine speed. The four testing conditions were compared to assess differences in delivered power, fuel consumption, and CO₂ emissions. Fuel consumption was modeled through linear regression using power as the independent variable, while specific fuel consumption and fuel productivity were estimated using a nonlinear regression approach. The comparison between test conditions shows a reduction in delivered power of 21.2% when moving from the PTO dynamometer test at maximum power to the drawbar test at rated engine speed, accompanied by an 18.9% increase in specific CO₂ emissions. These findings indicate that operating conditions significantly influence tractor carbon emissions and suggest that assessments accounting for traction-related losses provide a more realistic estimate of tractor environmental performance than PTO dynamometer tests alone. The proposed approach may support the development of carbon-oriented mitigation strategies and future greenhouse gas reduction policies for agricultural mechanization.

Keywords: OECD Code 2; agricultural tractor; power output; specific fuel consumption; diesel emission factor; fuel productivity



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1. Introduction

Agriculture plays a crucial role in the global effort to mitigate greenhouse gas (GHG) emissions while maintaining food production and economic sustainability. Recent estimates indicate that agrifood systems account for approximately one-third of total anthropogenic GHG emissions worldwide, expressed as CO₂ equivalents [1,2]. Although a substantial proportion of these emissions originates from biological processes such as soil management,

crop production, and livestock systems, the contribution of fossil fuel consumption associated with agricultural mechanisation remains significant, particularly in highly mechanised farming systems.

Within agricultural mechanisation, tractors represent the primary source of direct on-farm energy consumption. As the primary mobile power source in modern agriculture, tractors function as the central energy unit of the farm, supplying the mechanical power required for most field operations and transport activities. Several studies have identified agricultural tractors as the main consumers of fossil energy in mechanised farming systems, accounting for a substantial share of total on-farm energy use and associated greenhouse gas emissions [3,4]. Their exhaust carbon dioxide emissions are directly linked to diesel fuel combustion and therefore closely related to engine performance, drivetrain efficiency, and operational conditions [3,5,6]. For this reason, improving tractor efficiency is widely recognised as an important pathway for reducing the carbon footprint of agricultural production systems. Improvements in machinery management, tractor–implement matching, electrification, and hybridization have been identified as promising strategies to increase on-farm energy efficiency and reduce diesel fuel consumption and related CO₂ emissions [7]. Agricultural machinery represents an important source of fossil energy consumption in mechanised farming systems, and recent studies have shown that its contribution to carbon and air pollutant emissions may become increasingly relevant in future decarbonisation scenarios [8–10]. Hybridization has also been investigated as a strategy to reduce tractor fuel consumption and CO₂ emissions, with recent studies combining simulation approaches and field experiments to compare conventional and hybrid drive systems [11–13].

Over the past decades, international and European regulations have progressively introduced stricter emission standards for diesel engines used in agricultural tractors and other non-road mobile machinery (NRMM). The European “Stage” emission standards, from Stage I to the current Stage V, have primarily focused on regulated pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM), leading to substantial reductions in these emissions [14]. The progressive introduction of Stage IIIB, IV and V standards has required the adoption of advanced exhaust after-treatment systems, including diesel oxidation catalysts (DOC), diesel particulate filters (DPF), selective catalytic reduction (SCR) systems and exhaust gas recirculation (EGR) [15]. Furthermore, while the European Union currently requires new tractors to comply with Stage V emission standards, tractors equipped with Stage IV or earlier engine technologies continue to be commercialized and operated in several countries, highlighting the heterogeneous pace of technological renewal within the global agricultural machinery sector. In contrast, carbon dioxide emissions are not currently subject to specific regulatory limits for agricultural tractors. Consequently, their environmental impact is generally assessed indirectly through fuel consumption measurements, since CO₂ emissions from diesel engines are proportional to the amount of fuel burned [16].

Fuel consumption and exhaust emissions of agricultural tractors have been widely investigated under controlled laboratory conditions using standardised procedures such as OECD Code 2 tests [17]. These procedures allow the determination of engine performance, fuel consumption, and emissions under steady-state conditions and provide reproducible results suitable for comparison among different machines. Nevertheless, laboratory-based tests do not fully represent real operating conditions, where tractors are subjected to variable loads, transient engine regimes, rolling resistance, drivetrain losses, and non-productive operating phases typical of agricultural activities. Previous studies comparing laboratory and field measurements have demonstrated that actual operating conditions can significantly affect fuel consumption and exhaust emissions because of variable loads, soil conditions, and transient engine operation [18,19]. In addition, traction performance is

affected by operational parameters such as ballast distribution and tyre inflation pressure, which influence the power delivered to the ground, machine efficiency, and ultimately fuel consumption during field operations [20].

To overcome these limitations, several studies have focused on real-world measurements of fuel consumption and emissions using Portable Emission Measurement Systems (PEMS) or data acquisition from the tractor electronic control unit (ECU) via CAN bus [19,21,22]. Recent field studies using PEMS and operational data have shown that tractor fuel consumption and CO₂ emissions are strongly affected by engine load, engine speed, gear selection, soil conditions, field geometry, and the type of agricultural operation [19,21,23,24]. These approaches allow the calculation of fuel-based emission factors and CO₂ emissions during actual field operations, providing a more realistic representation of tractor environmental performance. Previous research has shown that fuel consumption and CO₂ emissions can vary significantly depending on the type of operation, soil and terrain conditions, engine load profiles, and working efficiency, highlighting the importance of field-based assessments for sustainable farm management [22]. In parallel with direct measurements, several recent studies have proposed modelling approaches to estimate tractor fuel consumption, specific fuel consumption, and CO₂ emissions from operational or performance data, confirming the usefulness of indirect fuel-based methods [11,12,24,25]. Because PEMS measurements are expensive and difficult to perform under all operating conditions, recent studies have developed tractor operation-based prediction models to estimate exhaust emissions during field operations [26].

Despite the growing body of literature on tractor fuel consumption and emissions, the potential of long-term standardized datasets for analysing historical trends in tractor energy performance has received relatively limited attention. A major source of standardized information on tractor performance and fuel consumption is provided by the OECD tractor testing programme conducted according to OECD Code 2 procedures [10]. These standardized tests provide measurements of engine power, fuel consumption, and traction performance under controlled and reproducible conditions. In particular, OECD Code 2 procedures include measurements of power and fuel consumption at the power take-off (PTO) using brake dynamometers, as well as traction performance tests carried out on test tracks through drawbar tests. Because these tests have been conducted for several decades using harmonised procedures, the OECD tractor test database represents one of the longest continuous datasets available worldwide for analysing the evolution of tractor performance, efficiency, and fuel consumption in agricultural machinery. The consistency and long-term availability of these data provide a unique opportunity to investigate technological developments in agricultural tractors and their implications for energy use and environmental performance. In particular, improvements in transmission systems, drivetrain efficiency, and diesel engine technologies have contributed substantially to the long-term enhancement of tractor performance and fuel efficiency observed over recent decades [27].

In parallel with technological developments in agricultural mechanisation, tractor design has progressively shifted toward four-wheel drive (4WD) configurations, which now dominate medium- and high-power tractor segments. Compared with two-wheel drive machines, 4WD tractors provide improved traction capability, enhanced power transmission to the ground, and greater operational versatility under a wide range of field conditions. As a consequence, focusing on 4WD tractors provides a representative framework for analysing the evolution of tractor performance and fuel-related emissions in modern mechanised agriculture. Although recent studies have investigated tractor fuel consumption and emissions using field measurements, PEMS, simulation models, life-cycle assessment, and alternative powertrain analysis, limited attention has been paid to the

systematic exploitation of long-term standardized OECD tractor test reports for quantifying the relationship between power output, fuel consumption, and specific CO₂ emissions across PTO and drawbar operating conditions. Building upon the long-term OECD Code 2 dataset, this study quantifies fuel consumption and associated CO₂ emissions of 877 four-wheel-drive agricultural tractors tested from 1967 to 2025. The analysis compares PTO and drawbar tests under maximum power and rated engine speed conditions, develops predictive relationships between power output and fuel consumption, and evaluates the resulting specific CO₂ emissions across standardized operating configurations.

2. Materials and Methods

2.1. Data Source and Tractor Selection

The dataset used in this study was derived from official tractor test reports published under the OECD Standard Code 2 for the Official Testing of Agricultural and Forestry Tractors [10]. Data collection and cataloguing activities were carried out between 2025 and 2026 through the systematic review of all available OECD Code 2 test reports issued between 1967 and 2025. Earlier reports were available only in hard-copy format, whereas reports published from the early 2000s onward were generally available in digital PDF format. A total of 877 tractor test reports were collected, analysed, and included in the final dataset. These reports provide standardized measurements of tractor performance obtained under controlled testing procedures carried out by accredited testing stations worldwide. OECD Code 2 tests include measurements of engine performance, fuel consumption, and traction performance. In particular, the test reports provide detailed data for:

- Power take-off (PTO) performance tests, performed using brake dynamometers under controlled laboratory conditions;
- Drawbar performance tests, conducted on standardized test tracks to evaluate traction performance and power delivered at the drawbar.

For the purposes of this study, tractors were selected according to the following criteria:

- four-wheel drive (4WD) drivetrain configuration,
- availability of fuel consumption data,
- availability of power measurements at rated engine speed and maximum power conditions,
- availability of both PTO and drawbar performance test results.

2.2. OECD Tractor Test Procedures

OECD Code 2 specifies standardized procedures for evaluating tractor performance under controlled and reproducible conditions. For the purposes of this study, the analysis focused on PTO and drawbar performance tests, which provide complementary information on tractor power output and fuel consumption under different operating conditions:

- rated engine speed conditions,
- maximum power conditions.

The maximum power condition was selected because it identifies the operating point at which the tractor develops its highest PTO power output. Rated engine speed was selected because it corresponds to the nominal engine speed specified by the manufacturer for the delivery of rated power. As a standardized operating condition consistently reported in OECD test reports, it provides a suitable reference point for comparing tractor performance, fuel consumption, and associated CO₂ emissions across different tractor models and technological generations. Consequently, these two operating points provide complementary reference conditions for evaluating tractor performance under both maximum and nominal operating conditions.

2.2.1. PTO Tests

PTO performance tests are conducted using a brake dynamometer connected to the tractor power take-off shaft. During the test, the tractor engine is operated at different load levels while the dynamometer applies a controlled resisting torque.

For each operating condition, the following parameters are typically recorded:

- PTO and engine rotational speed
- Power output
- Fuel consumption

2.2.2. Drawbar Tests

Drawbar tests are conducted on a test track, typically with a controlled surface condition, where the tractor pulls a braking vehicle or load unit through a calibrated drawbar.

During drawbar testing, the following parameters are measured:

- Drawbar pull
- Forward speed
- Drawbar power
- Fuel consumption

Unlike PTO tests, drawbar tests evaluate the effective power transferred to the ground, accounting for drivetrain losses, rolling resistance, and tyre–soil interaction effects. Therefore, they provide a more representative assessment of tractor operating performance under field-like conditions.

2.3. Fuel Consumption Data

Fuel consumption values reported in the OECD tractor test reports were used as the basis for estimating tractor-related specific CO₂ emissions.

In OECD reports, fuel consumption is typically expressed as:

- hourly fuel consumption (kg h^{−1} or L h^{−1}), or
- specific fuel consumption (g kWh^{−1}).

When necessary, values expressed in volumetric units were converted to mass units using the diesel fuel density declared in each individual test report. Therefore, no average density value was adopted; instead, the conversion from litres to kilograms was performed using the specific density value reported for each test by the OECD test station that carried out the test. The resulting dataset allowed the analysis of both fuel consumption rates and specific fuel consumption values under standardized operating conditions.

2.4. CO₂ Emissions Estimation Method

Carbon dioxide emissions associated with tractor operation were estimated using a fuel-based emission factor approach, which assumes that CO₂ emissions from diesel engines are proportional to the amount of fuel consumed.

According to the IPCC Guidelines for National Greenhouse Gas Inventories [16], the combustion of diesel fuel produces approximately:

$$3.16 \text{ kg CO}_2 \text{ per kg of diesel fuel burned} \quad (1)$$

Based on this relationship, CO₂ emissions were estimated using the following equation:

$$\text{CO}_2 = \text{FC} \cdot \text{EF} \quad (2)$$

where CO₂ represents carbon dioxide emissions (kg CO₂ h^{−1}), FC represents fuel consumption (kg h^{−1}), and EF represents the emission factor for diesel fuel (3.16 kg CO₂ kg^{−1} fuel).

When specific fuel consumption values (g kWh^{-1}) were available, specific CO_2 emissions ($\text{g CO}_2 \text{ kWh}^{-1}$) were calculated accordingly.

2.5. Performance and Emission Comparison

The dataset used in the study was analyzed to compare performance and emission data. The main characteristics of the dataset are summarized in Table 1.

Table 1. Main characteristics of the dataset used in the study derived from OECD Code 2 tractor test reports.

Parameter	Description
Data source	OECD Code 2 tractor test reports
Period considered	1960s—present
Tractor configuration	Four-wheel drive (4WD)
Test types considered	PTO test and drawbar test
Operating conditions	Rated engine speed, maximum power
Main variables extracted	Power output, fuel consumption, specific fuel consumption, fuel productivity
Derived variables	Specific CO_2 emission, CO_2 productivity

Four test conditions were analyzed and compared:

1. Performance under maximum power conditions during the PTO test
2. Performance at rated engine speed during the PTO test
3. Performance under maximum power conditions during the drawbar test
4. Performance at rated engine speed during the drawbar test

To quantify the differences between laboratory and real operating conditions, comparisons between the main variables (Table 2) measured during drawbar tests and PTO tests were calculated for each tractor. Differences in fuel consumption and resulting CO_2 emissions between PTO and drawbar tests were evaluated on both hourly and specific bases. Fuel productivity (kWh kg^{-1} fuel) was defined as the amount of useful mechanical energy produced per unit mass of fuel consumed. Similarly, CO_2 productivity ($\text{kWh kg}^{-1} \text{CO}_2$) was defined as the amount of useful mechanical energy produced per unit mass of CO_2 emitted.

Table 2. Main variables extracted and calculated from OECD Code 2 tractor test reports.

Variable	Symbol	Unit	Description
Power output	P	kW	Power measured at PTO or drawbar
Fuel consumption	FC	kg h^{-1}	Hourly diesel fuel consumption
Specific fuel consumption	SFC	g kWh^{-1}	Ratio between fuel consumption and power
Fuel productivity	FPR	kWh kg^{-1}	Ratio between power and fuel consumption
Specific CO_2 emissions	SE_{CO_2}	$\text{g CO}_2 \text{ kWh}^{-1}$	Estimated using diesel emission factor
CO_2 productivity	PR_{CO_2}	$\text{kWh kg}^{-1} \text{CO}_2$	Estimated using diesel emission factor

2.6. Data Analysis

The collected dataset was analysed as a function of the year of testing in order to investigate long-term trends in tractor fuel consumption and power over time. This approach made it possible to evaluate the evolution of tractor energy performance across different decades of technological development.

For each selected tractor, data from both PTO and drawbar tests, corresponding to maximum power and rated engine speed operating conditions, were extracted from the OECD test reports. For each test configuration, the following parameters were considered:

- Power output
- Fuel consumption
- Specific fuel consumption
- Fuel productivity

In addition to the descriptive analysis of tractor performance, the relationship between fuel consumption and power output was investigated. For both PTO and drawbar test conditions, fuel consumption values were compared with the corresponding power values reported in the OECD test reports. A linear regression analysis was performed in order to evaluate the relationship between fuel consumption and power output. The analysis showed that fuel consumption increased approximately linearly with increasing power, which is consistent with the typical operating behaviour of diesel engines under steady-state conditions. The resulting linear relationship was used to describe the dependence of fuel consumption on power and to support the estimation of CO₂ emissions associated with tractor operation. The relationships between specific fuel consumption, fuel productivity, and power were investigated using nonlinear regression models, with power considered as the independent variable. This approach enabled the characterization of how specific fuel consumption and fuel productivity varied across the range of operating conditions represented in the dataset. Regression analyses were conducted separately for different test conditions. In particular, separate analyses were performed for PTO and drawbar tests, and within each test type, the regressions were further conducted considering both rated engine speed and maximum power conditions (Table 3).

Table 3. Regression models used to analyse the relationship among power output, fuel consumption, specific fuel consumption and fuel productivity.

Model	Equation ¹	Purpose
Linear regression	$FC = a + b \cdot P$	Relationship between fuel consumption and power
Nonlinear regression	$SFC = c + \frac{d}{P}$	Relationship between specific fuel consumption and power
Nonlinear regression	$FPR = \frac{P}{e + f \cdot P}$	Relationship between fuel productivity and power

¹ *a*, *b*, *c*, *d*, *e* and *f* are regression coefficients.

This resulted in four distinct regression analyses, allowing the relationship among power, fuel consumption, specific fuel consumption and fuel productivity to be evaluated under different standardized operating conditions (Table 4). The goodness of fit of the regression models was evaluated using the coefficient of determination (*R*²). All statistical analyses and regression procedures were performed using MATLAB (vR2025b) (MathWorks, Natick, MA, USA).

Table 4. Different test conditions for regression analyses.

Test Type	Operating Condition	Regression Type
PTO	Rated engine speed	Linear/Nonlinear
PTO	Maximum power	Linear/Nonlinear
Drawbar	Rated engine speed	Linear/Nonlinear
Drawbar	Maximum power	Linear/Nonlinear

3. Results

3.1. OECD Reports Data Source Analysis

The power and fuel consumption data were analysed according to the year of OECD report approval and are presented in Figure 1. The tractors included in the dataset covered a wide range of power ratings, with maximum engine power varying from 10 kW to 403 kW and fuel consumption varying from 3.28 kg h⁻¹ to 96.87 kg h⁻¹. An increase in both power and fuel consumption over time can be observed. The data were classified into four configurations: black symbols represent PTO test values, while red symbols represent drawbar test values. Cross symbols indicate tests conducted at rated engine speed, whereas circle symbols indicate tests performed at maximum power. Using this representation, the data points overlap considerably, making the figure difficult to interpret. Nevertheless, one finding is clear: the results indicate an expansion of the available tractor power range over time (Figure 2).

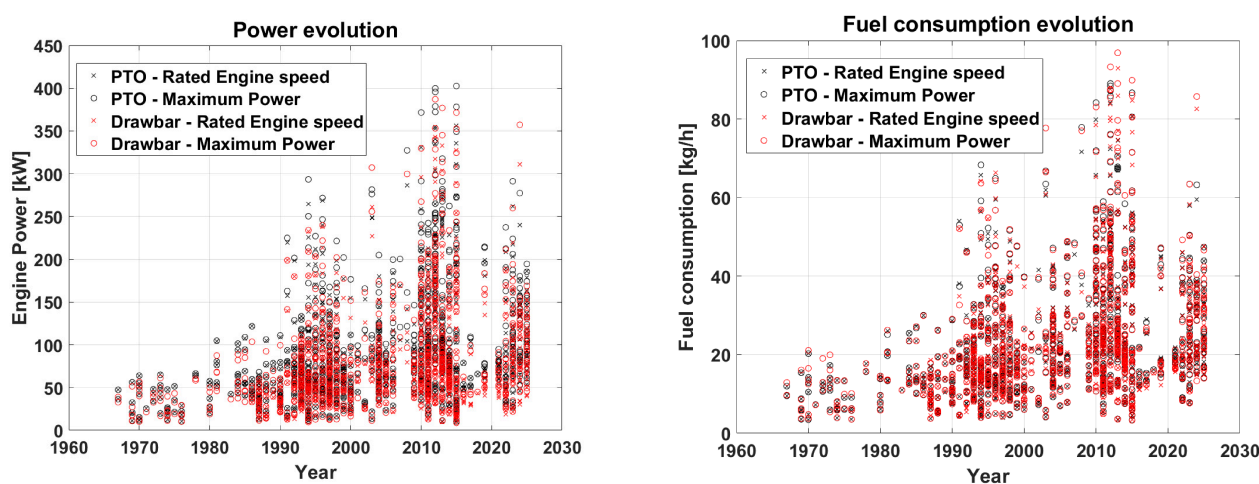


Figure 1. PTO power and fuel consumption as a function of the year of report approval.

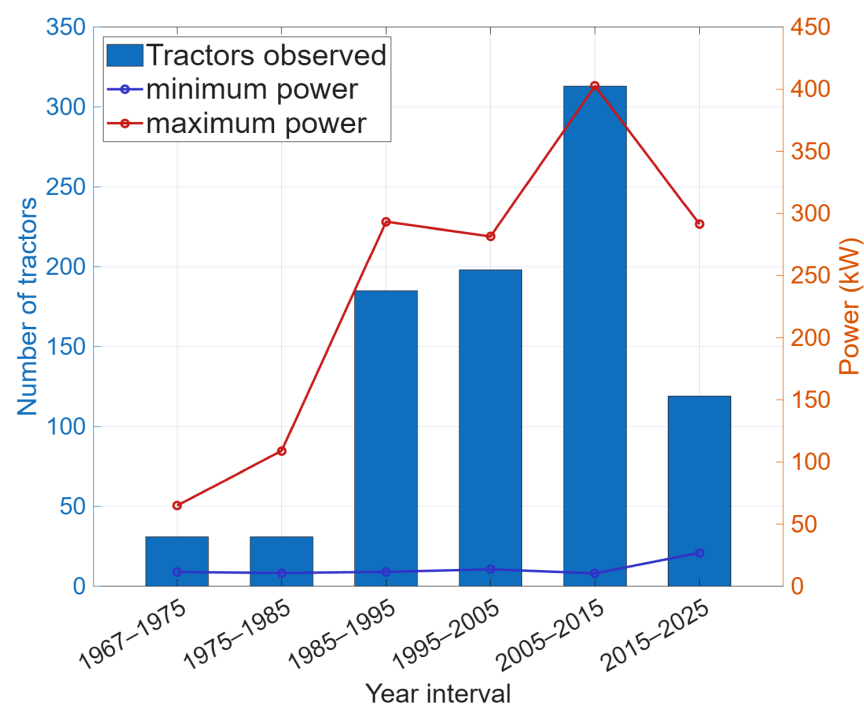


Figure 2. Distribution of tractors included in the dataset across decades, together with the associated power ranges.

A better understanding of the data can be achieved by excluding the time variable. A comparison between the PTO and drawbar test results shows a linear relationship between power output and fuel consumption. The comparison highlights a reduction in power between the PTO and drawbar measurements (Figure 3a), whereas the variation in fuel consumption remains negligible (Figure 3b). The 1:1 reference line included in both plots represents the theoretical condition of equal values between PTO and drawbar measurements. While most observations fall below this line in the power comparison, indicating reduced power under drawbar conditions, fuel consumption values remain much closer to the line, suggesting only minor differences between the two test configurations.

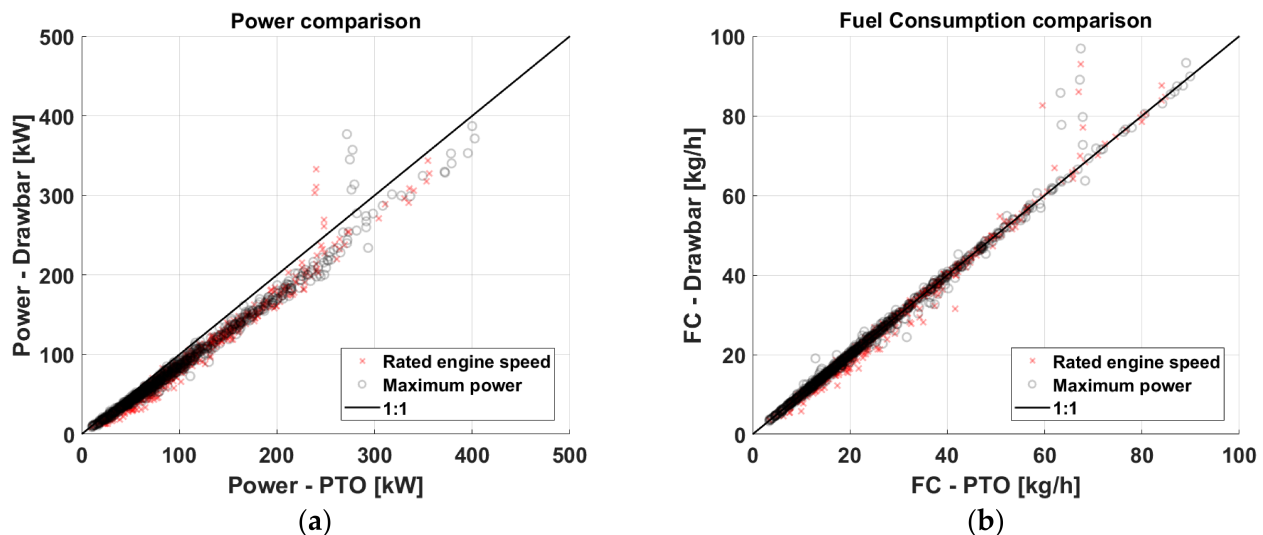


Figure 3. Comparison between PTO and drawbar tests: comparison of power outputs (a) and fuel consumption (b).

Additional data were obtained from the comparison among the four test configurations. The analysed parameters were specific fuel consumption (*SFC*) and fuel productivity (*FPR*). The qualitative results are presented in Figure 4: specific fuel consumption increases in the drawbar test conditions, whereas fuel productivity increased in the PTO test conditions.

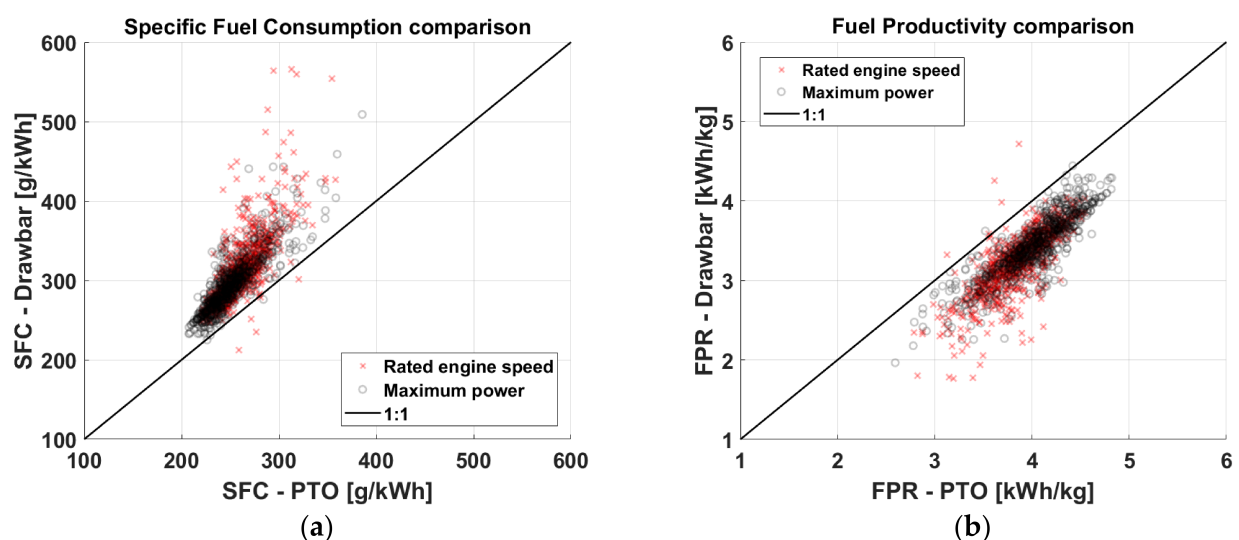


Figure 4. Qualitative comparison of specific fuel consumption (a) and fuel productivity (b) under PTO and drawbar test conditions.

A preliminary comparison showed that fuel consumption increased approximately linearly with power output (Figure 5); this relationship is analysed in detail in Section 3.2.

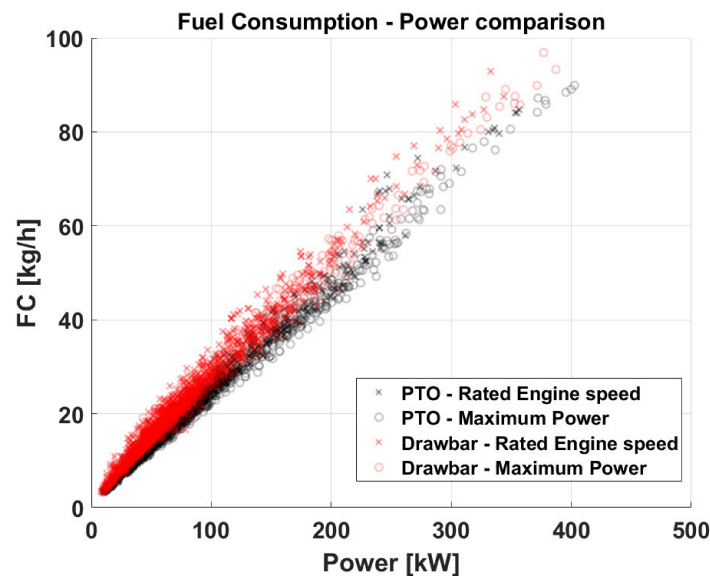


Figure 5. Fuel consumption vs. power comparison.

3.2. Relationship Between Fuel Consumption and Power

A linear regression analysis was performed using the fuel consumption values reported in the OECD test reports and the corresponding power measurements. The relationship between fuel consumption and power can be expressed as:

$$FC = a + b \cdot P \quad (3)$$

where FC is the fuel consumption (kg h^{-1}), P is the power output (kW), and a and b are regression coefficients determined from the dataset. Equation (3) provides a useful basis for estimating tractor fuel consumption from power data obtained during standardized performance tests. The coefficient a (y-intercept value) represents the amount of fuel required to keep the engine running, whereas the coefficient b (slope coefficient, i.e., the gradient of the line) represents the rate at which fuel consumption increases with power output.

The linear behaviour observed in the analysis is consistent with the operating characteristics of diesel engines working under steady-state conditions, where fuel injection increases proportionally with the engine load in order to produce higher mechanical power. Figure 6 shows the relationship between tractor fuel consumption and power output obtained from the OECD Code 2 test dataset under the four different test conditions (see Table 4). The results highlight a strong linear correlation between the two variables, confirming that fuel consumption increases proportionally with the mechanical power delivered by the tractor engine. The number of tractor observations included in each regression model (n), the estimated coefficients a and b , the p -value of the model, the coefficient of determination (R^2), and the Root Mean Square Error (RMSE) are reported in Table 5. The regression models showed excellent goodness of fit, with coefficients of determination (R^2) ranging from 0.980 to 0.992 and RMSE values ranging from 1.39 to 2.13 kg h^{-1} . Together with the highly significant regression coefficients ($p < 0.001$), these results indicate a close agreement between observed and predicted fuel consumption values and confirm the existence of a very strong linear relationship between tractor power output and fuel consumption across all operating conditions considered.

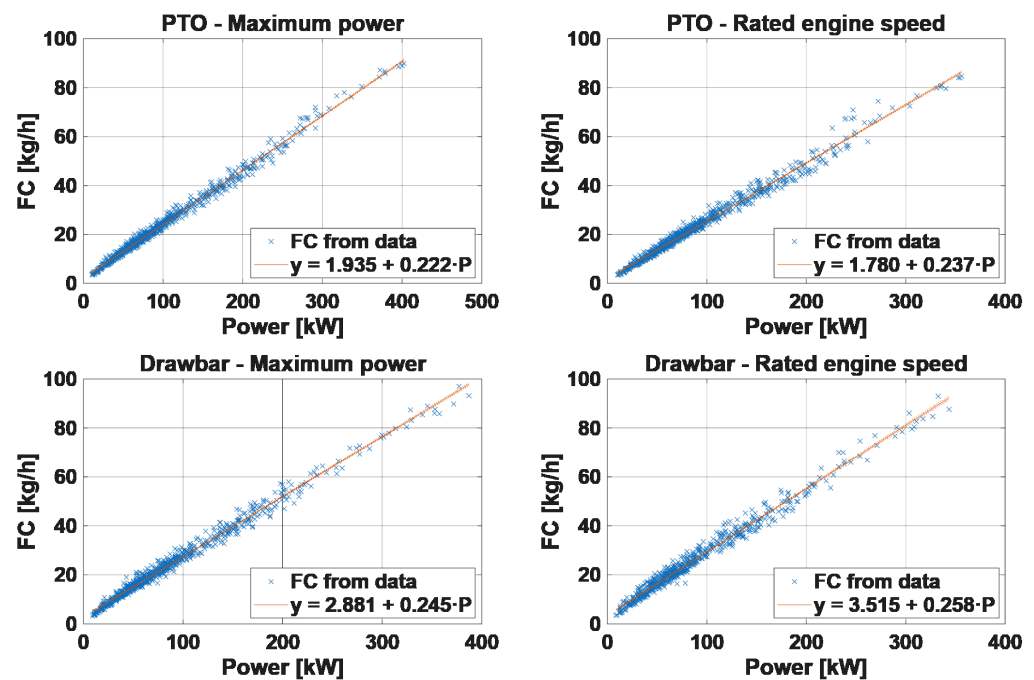


Figure 6. Linear regression between power output (kW) and fuel consumption (kg h^{-1}). Actual data and fitted model according to Equation (3).

Table 5. Linear regression model describing fuel consumption with estimated coefficients, number of observations, p -value, R^2 and RMSE.

FC	n	a [kg h^{-1}]	b [kg kWh^{-1}]	p -Value	R^2	RMSE [kg h^{-1}]
PTO—Maximum power	877	1.935	0.222	<0.001	0.992	1.39
PTO—Rated engine speed	877	1.780	0.237	<0.001	0.985	1.74
Drawbar—Maximum power	875	2.881	0.245	<0.001	0.988	1.68
Drawbar—Rated engine speed	685	3.515	0.258	<0.001	0.980	2.13

By dividing fuel consumption by power, it is possible to derive a relationship for specific fuel consumption from the regression in Equation (3). Using this approach, the coefficient b represents the asymptotic value of specific fuel consumption as the power output P approaches infinity, since the second term ($\frac{a}{P}$) tends to zero. Following this approach, its reciprocal corresponds to fuel productivity, and therefore, the results shown in Table 6 can be obtained.

Table 6. Specific fuel consumption and fuel productivity under the four test conditions, derived from fuel consumption regression.

Parameter	PTO—Maximum Power	PTO—Rated Engine Speed	Drawbar—Maximum Power	Drawbar—Rated Engine Speed
Specific fuel consumption (g kWh^{-1})	222	237	245	258
Fuel productivity (kWh kg^{-1})	4.50	4.22	4.08	3.88

3.3. Relationship Between Specific Fuel Consumption and Power

In addition to the analysis of fuel consumption, specific fuel consumption (SFC) was evaluated in order to compare the fuel consumption of tractors operating at different power

levels. Since specific fuel consumption is defined as the ratio between fuel consumption and power output, its relationship with power is inherently nonlinear.

For this reason, specific fuel consumption was estimated using a nonlinear regression model, where power was considered as the independent variable. The relationship between specific fuel consumption and power was described using the following equation:

$$SFC = c + \frac{d}{P} \quad (4)$$

where SFC is specific fuel consumption (g kWh^{-1}), P is the power output (kW), and c and d are regression coefficients.

This formulation reflects the typical behavior of diesel engines; similar approaches have been used in previous studies to describe the relationship between tractor power output and fuel consumption characteristics [28,29]. The regression curve and the experimental data are presented in Figure 7. The coefficient c in Equation (4) represents the asymptotic value of the specific fuel consumption as the power output P approaches infinity, since the second term ($\frac{d}{P}$) tends to zero. The number of tractor observations included in each regression model (n), the estimated coefficients c and d , the p -value of the model, the coefficient of determination (R^2), and the Root Mean Square Error (RMSE) are reported in Table 7. By setting c equal to the specific fuel consumption and its reciprocal equal to the fuel productivity, the results shown in Table 8 can be obtained.

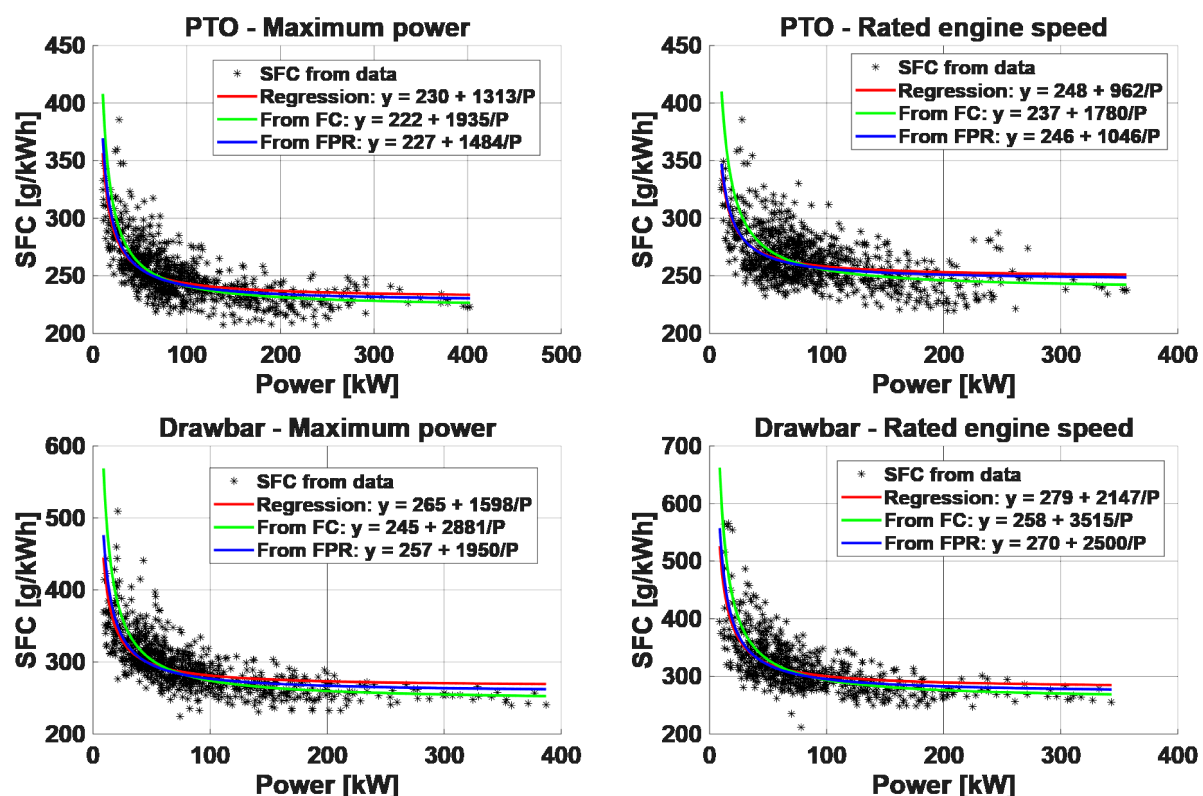


Figure 7. Nonlinear regression between power output and specific fuel consumption. Actual data and fitted model according to Equation (4) and derived models from FC Equation (3), and FPR Equation (5).

Table 7. Nonlinear regression model describing specific fuel consumption with estimated coefficients, number of observations, p -value, R^2 and RMSE.

SFC	n	c [g kWh ⁻¹]	d [g h ⁻¹]	p -Value	R^2	RMSE [g kWh ⁻¹]
PTO—Maximum power	877	230	1313	<0.001	0.518	16.8
PTO—Rated engine speed	877	248	962	<0.001	0.306	19.1
Drawbar—Maximum power	875	265	1598	<0.001	0.492	25.7
Drawbar—Rated engine speed	685	279	2147	<0.001	0.428	34.6

Table 8. Specific fuel consumption and fuel productivity under the four test conditions, derived from specific fuel consumption regression.

Parameter	PTO—Maximum Power	PTO—Rated Engine Speed	Drawbar—Maximum Power	Drawbar—Rated Engine Speed
Specific fuel consumption (g kWh ⁻¹)	230	248	265	278
Fuel productivity (kWh kg ⁻¹)	4.35	4.03	3.77	3.60

3.4. Relationship Between Fuel Productivity and Power

A nonlinear regression analysis was performed using the fuel productivity data. The relationship between power (kW) and fuel productivity (kWh kg⁻¹) was described using the following nonlinear regression model:

$$FPR = \frac{P}{e + f \cdot P} \quad (5)$$

where FPR is the fuel productivity (kWh kg⁻¹), P is the power output (kW), and e and f are regression coefficients.

In this case, the relationship was derived from the reciprocal of the model used to represent the specific fuel consumption, since fuel productivity is defined as the reciprocal of specific fuel consumption. The regression curve and the experimental data are presented in Figure 8. The number of tractor observations included in each regression model (n), the estimated coefficients e and f , the model p -value, the coefficient of determination (R^2), and the Root Mean Square Error (RMSE) are reported in Table 9. Using the same approach as before, by letting P tend to infinity, the fuel productivity approaches the reciprocal of the coefficient f , whereas the specific fuel consumption approaches the coefficient f itself (Table 10).

Table 9. Nonlinear regression model describing fuel productivity with estimated coefficients, number of observations, p -value, R^2 and RMSE.

FPR	n	e [kg h ⁻¹]	f [kg kWh ⁻¹]	p -Value	R^2	RMSE [kg kWh ⁻¹]
PTO—Maximum power	877	1.484	0.227	<0.001	0.536	0.242
PTO—Rated engine speed	877	1.046	0.246	<0.001	0.308	0.260
Drawbar—Maximum power	875	1.950	0.257	<0.001	0.542	0.260
Drawbar—Rated engine speed	685	2.500	0.270	<0.001	0.467	0.295

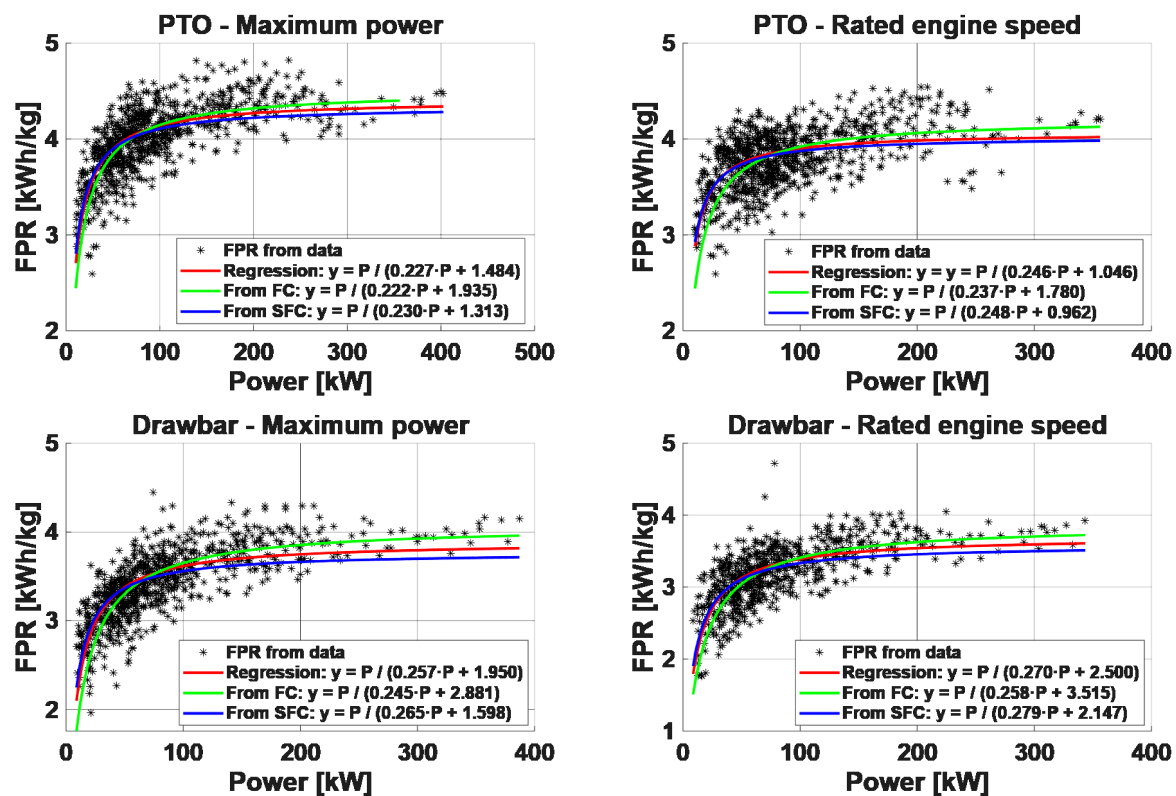


Figure 8. Nonlinear regression between power output and fuel productivity. Actual data and fitted model according to Equation (5) and derived models from FC Equation (3), and SFC Equation (4).

Table 10. Specific fuel consumption and fuel productivity under the four test conditions, derived from fuel productivity regression.

Parameter	PTO—Maximum Power	PTO—Rated Engine Speed	Drawbar—Maximum Power	Drawbar—Rated Engine Speed
Specific fuel consumption (g kWh^{-1})	227	246	257	270
Fuel productivity (kWh kg^{-1})	4.41	4.07	3.89	3.70

3.5. Comparison Between the Relationships

A summary of the results for specific fuel consumption and fuel productivity, including actual data and the fitted models according to the three different relationships, is presented, respectively, in Figures 7 and 8. For each configuration, the actual data values were compared with the corresponding regression. In addition, the functions were calculated using the values obtained from the other computed regressions. In the case of specific consumption, the consumption regression was divided by the power, and the reciprocal of the fuel productivity regression was also calculated. Similarly, in the case of fuel productivity, the consumption regression was divided by the power and its reciprocal was calculated, while the reciprocal of the specific consumption regression was also determined. The result is three alternative mathematical formulations for each configuration.

All nonlinear regression models were statistically significant ($p < 0.001$). However, the coefficients of determination were lower than those obtained for the fuel consumption models. For specific fuel consumption, R^2 values ranged from 0.306 to 0.518, whereas for fuel productivity, they ranged from 0.308 to 0.536. The lower R^2 values obtained for specific fuel consumption and fuel productivity indicate that these variables are influenced not

only by power output, but also by technological and operational factors such as engine efficiency, transmission design, and tractor generation.

Most of the dispersion was observed in the lower power range, whereas higher-power tractors showed more homogeneous efficiency levels.

It is possible to observe that specific fuel consumption decreases with increasing engine load until reaching a minimum value near the region of maximum fuel productivity. The model shows an asymptotic behavior, where fuel productivity increases with power and approaches a limiting value as P increases. This behavior suggests that increases in power lead to progressively smaller gains in fuel productivity, indicating a saturation effect in the energy–power relationship. Based on the calculated parameters b , c and f , the asymptotic limits of the functions were calculated (Tables 6, 8 and 10). The obtained results differ only slightly from one another, indicating good consistency among the three mathematical formulations. Since fuel consumption, specific fuel consumption, and fuel productivity are algebraically related, the three regression approaches should not be interpreted as statistically independent models. Rather, they represent three alternative mathematical formulations of the same fuel–power relationship. Therefore, the arithmetic mean of the three asymptotic values was used as a representative comparison value for the four test configurations, rather than as a combination of statistically independent estimates. The resulting averaged values are reported in Table 11. Specific fuel consumption increases progressively from the PTO maximum power condition to the PTO rated engine speed condition, then to the drawbar maximum power condition, and finally to the drawbar rated engine speed condition. Conversely, fuel productivity follows the opposite trend.

Table 11. Specific fuel consumption and fuel productivity under the four test conditions, mean values.

Parameter	PTO—Maximum Power	PTO—Rated Engine Speed	Drawbar—Maximum Power	Drawbar—Rated Engine Speed
Specific fuel consumption (g kWh ^{−1})	226	244	256	269
Fuel productivity (kWh kg ^{−1})	4.42	4.10	3.91	3.72

The best performance in terms of fuel productivity is therefore achieved under the PTO maximum power test condition (4.42 kWh kg^{−1}), whereas the lowest fuel productivity is observed under the drawbar rated engine speed test condition (3.72 kWh kg^{−1}).

3.6. PTO and Drawbar Performance

The comparison between PTO tests and drawbar tests highlights the differences between engine output power and the power effectively transmitted to the ground.

The analysis of the four test conditions allowed the variations in power and fuel consumption to be quantified. Table 12 summarizes the variations in power and fuel consumption between PTO and drawbar tests under maximum power and rated engine speed conditions. As expected, drawbar power was lower than PTO power because of traction-related losses (Figure 9a). The largest reduction was observed between the PTO maximum power condition and the drawbar rated engine speed condition, with a decrease of 21.2%.

Table 12. Relative variations between PTO and drawbar test conditions.

Parameter	Variation from PTO to Drawbar at Maximum Power (%)	Variation from PTO to Drawbar at Rated Engine Speed (%)
Power (kW)	−11.7	−13.1
Fuel consumption (kg h ^{−1})	−0.7	+0.1

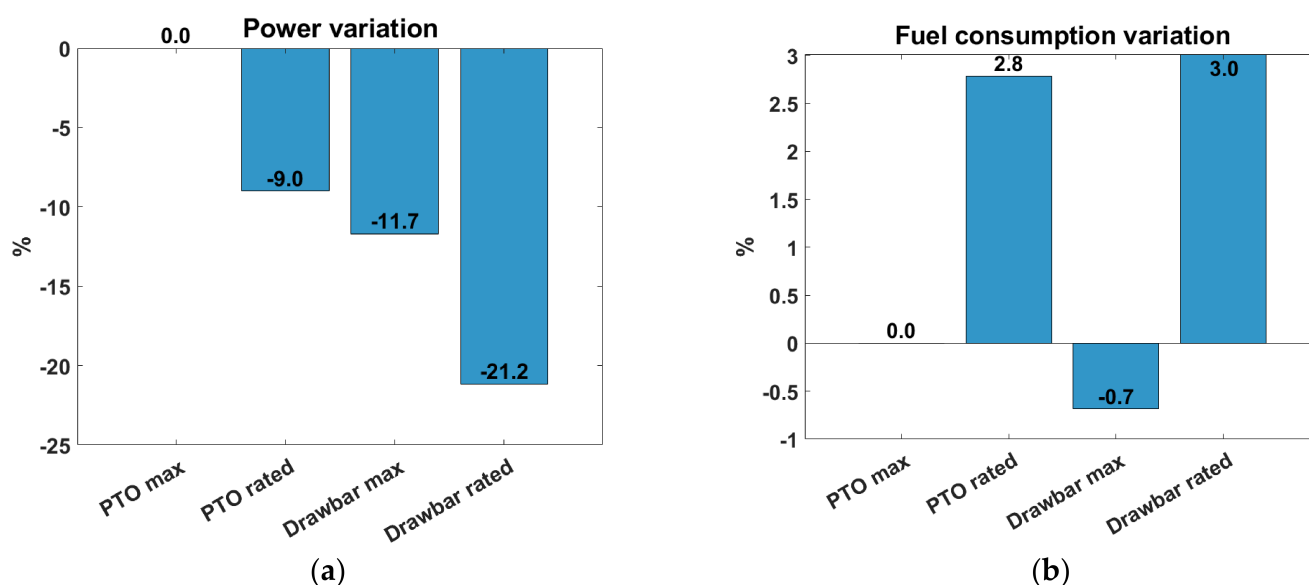
**Figure 9.** Comparison of variations in power (a) and fuel consumption (b) calculated from PTO—maximum power.

Figure 9b shows that fuel consumption varied only slightly among the four test configurations, indicating that it was more strongly influenced by engine operating conditions than by the delivered power alone. The greatest variation was observed between the PTO maximum power reference test and the drawbar rated engine speed test condition, with a percentage difference of 3%. Table 13 reports the specific fuel consumption and fuel productivity values, calculated by comparing the mean values obtained from the previously identified regressions. As can be observed, differences in power directly affect the specific fuel consumption proportionally, while fuel productivity is affected inversely.

Table 13. Percentage variation relative to the PTO—maximum power condition.

Parameter	PTO—Rated Engine Speed (%)	Drawbar—Maximum Power (%)	Drawbar—Rated Engine Speed (%)
Specific fuel consumption (g kWh ^{−1})	+7.7	+13.1	+18.9
Fuel productivity (kWh kg ^{−1})	−7.2	−11.5	−15.9

3.7. Estimation of CO₂ Emissions

Using the fuel consumption values reported in the OECD tractor test reports, CO₂ emissions were estimated according to Equation (2).

Because CO₂ emissions were estimated using a fuel-based emission factor, the fuel consumption–power relationship directly translated into a corresponding CO₂ emission trend. Consequently, higher power levels are associated with higher hourly CO₂ emissions. However, when expressed on a specific basis (g CO₂ kWh^{−1}), emissions provide an indicator of the carbon intensity of tractor operation and, indirectly, of its energy efficiency.

Specific CO₂ emissions are closely related to specific fuel consumption; therefore, improvements in tractor efficiency contribute to reducing the carbon intensity of mechanical power generation. The estimated values of specific CO₂ emissions increased from 716 g kWh⁻¹ under the PTO maximum power test condition to 851 g kWh⁻¹ under the drawbar rated engine speed test condition. Conversely, CO₂ productivity showed a decreasing trend, declining from 1.40 kWh kg⁻¹ under the PTO maximum power test condition to 1.18 kWh kg⁻¹ under the drawbar rated engine speed condition. Overall, the maximum increase in specific CO₂ emissions was estimated at 18.9% between the PTO maximum power and drawbar rated engine speed conditions, corresponding to a 15.9% reduction in CO₂ productivity. These results further highlight the influence of operating conditions on tractor carbon performance and confirm that configurations associated with lower fuel productivity are characterized by higher specific CO₂ emissions. The increase observed under drawbar conditions reflects the combined effect of drivetrain losses, tyre slip, rolling resistance, aerodynamic resistance, and other traction-related factors that reduce the efficiency of power transfer from the engine to the ground. The results are reported in Figure 10 and Table 14.

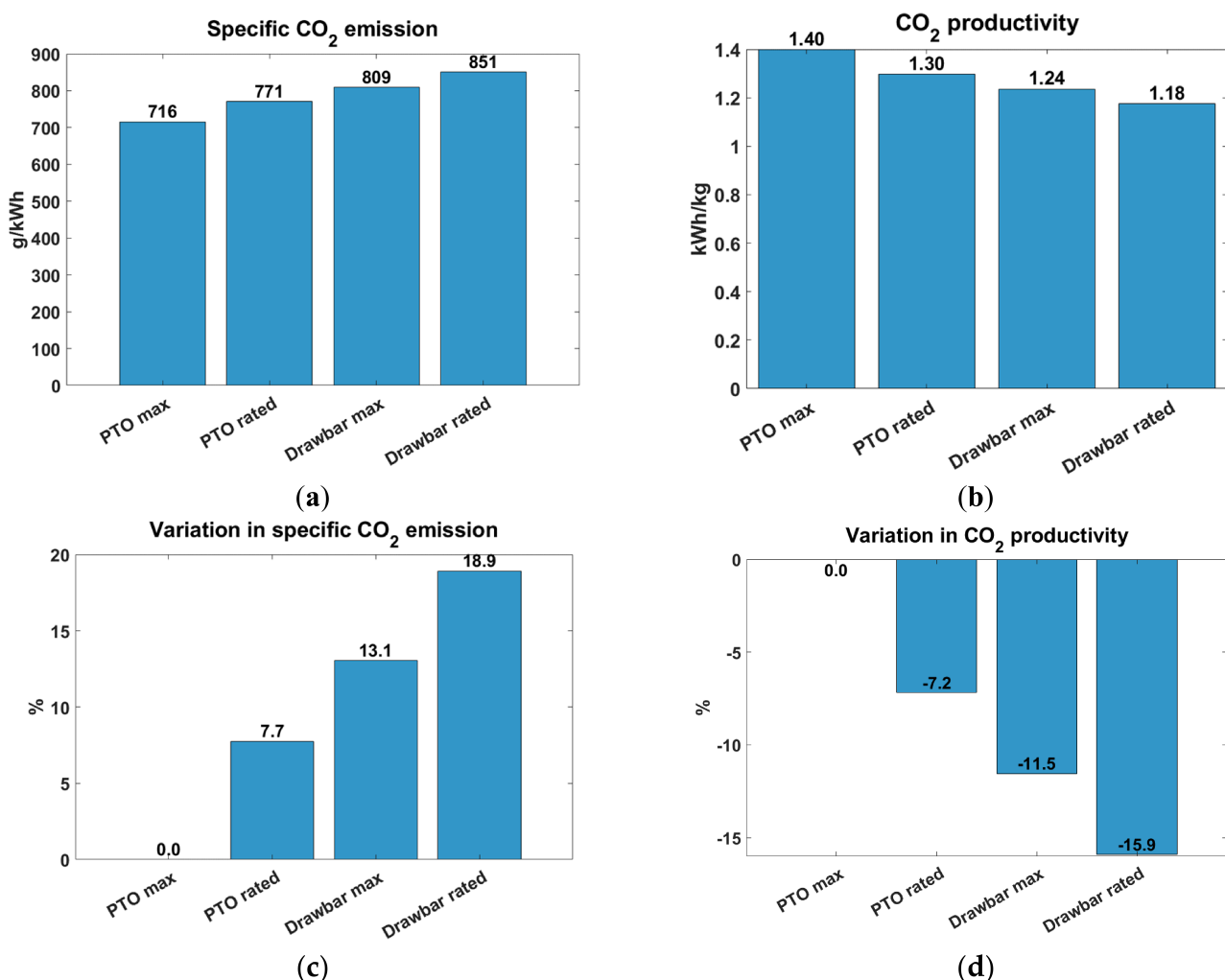


Figure 10. Comparison of specific CO₂ emission (a) and CO₂ productivity (b) calculated from PTO and drawbar tests. Comparison of variations in power (c) and fuel consumption (d) calculated from PTO—maximum power.

Table 14. Specific CO₂ emission and CO₂ productivity under the four test conditions, mean values.

Parameter	PTO—Maximum Power	PTO—Rated Engine Speed	Drawbar—Maximum Power	Drawbar—Rated Engine Speed
Specific CO ₂ emission (g kWh ^{−1})	716	771	809	851
CO ₂ productivity (kWh kg ^{−1})	1.40	1.30	1.24	1.18

4. Discussion

A correct interpretation of the results requires consideration of the mathematical relationships among the analysed variables. The OECD tractor test reports provide direct measurements of power output and fuel consumption, whereas specific fuel consumption and fuel productivity are derived quantities. Specifically, specific fuel consumption is obtained as the ratio between fuel consumption and power output, while fuel productivity is proportional to the ratio between power output and fuel consumption. Consequently, once power output and fuel consumption are known, both specific fuel consumption and fuel productivity can be calculated directly.

The strong linear relationship observed between power output and fuel consumption suggests that tractor energy performance can be largely described through the interaction of these two variables. Therefore, once the fuel consumption–power relationship has been established for a given operating condition, it becomes possible to estimate not only fuel consumption but also the corresponding specific fuel consumption and fuel productivity values over the entire power range.

However, the proportionality between fuel consumption and power output is not perfectly constant because the regression functions include a non-zero intercept. As a consequence, specific fuel consumption and fuel productivity vary with power, particularly in the lower power range, where the influence of the intercept becomes more pronounced. This behaviour explains why the assumption of constant specific fuel consumption or constant fuel productivity, often adopted in simplified approaches, does not accurately describe tractor performance over the full operating range.

Because the proportionality factor between fuel consumption and power changes according to the operating condition, four different test configurations were analysed. Separate regressions were developed for fuel consumption, specific fuel consumption, and fuel productivity. Since these variables are algebraically related through power output and fuel consumption, the three regression approaches should not be interpreted as statistically independent models. Rather, they represent three alternative mathematical formulations of the same fuel–power relationship.

The consistency among the asymptotic values derived from the three regression approaches supports the use of averaged estimates as representative comparison values for the four test configurations.

All nonlinear regression models were highly significant ($p < 0.001$). For specific fuel consumption, the coefficients of determination ranged from 0.306 to 0.518, whereas for fuel productivity they ranged from 0.308 to 0.536. Although these values are lower than those obtained for the fuel consumption models ($R^2 = 0.980–0.992$), they still indicate a meaningful relationship between power output and the corresponding response variables.

A closer inspection of the data revealed that most of the variability was concentrated in the lower power range (<100 kW), where both specific fuel consumption and fuel productivity exhibited a wide dispersion of observations. This behaviour suggests substantial differences in performance among tractors with similar nominal power. Such variability is likely associated with differences in engine technology, fuel injection systems, transmission

design, and overall machine efficiency, particularly considering that the dataset includes tractors manufactured over nearly six decades.

In contrast, tractors in higher power classes showed more homogeneous behaviour, resulting in lower dispersion and more consistent efficiency levels. This finding may reflect the progressive standardisation and technological convergence that has occurred in modern high-power tractors, where improvements in engine management systems, power transmission, and overall machine design have contributed to reducing performance variability.

An additional aspect that should be considered when interpreting the results is the breadth and heterogeneity of the dataset. The OECD database made it possible to include a large number of tractors covering a wide range of power classes, technological generations, and design solutions. As a consequence, the regression models developed in this study can be considered broadly representative of the agricultural tractor fleet operating worldwide. Although the diversity of the dataset contributes to the moderate R^2 values obtained for specific fuel consumption and fuel productivity, it also increases the general applicability of the results.

The analysis highlights those parameters, such as specific fuel consumption and fuel productivity, which are often treated as constant values in simplified approaches, actually vary as a function of power output and operating condition, particularly in the lower power range. A similar behaviour was observed across the four test configurations investigated. Differences in the estimated values emerged both between maximum power and rated engine speed conditions and between PTO and drawbar tests, indicating that tractor energy performance is strongly influenced by the operating conditions under which it is assessed. These findings suggest that the use of fixed reference values may oversimplify the assessment of tractor fuel consumption, fuel productivity, and associated CO₂ emissions.

5. Conclusions

The following conclusions were drawn from the study:

The analysis of 877 OECD tractor test reports confirmed the existence of a strong linear relationship between fuel consumption and power output under all operating conditions considered. The regression models showed excellent goodness of fit, confirming that fuel consumption can be reliably estimated from tractor power output and providing a robust basis for the indirect estimation of CO₂ emissions.

Specific fuel consumption and fuel productivity were successfully described using non-linear regression models. Although the coefficients of determination were lower than those obtained for fuel consumption, all models were highly significant. The greater variability observed reflects the influence of additional technological and operational factors affecting tractor energy performance, particularly among tractors in the lower power classes.

The comparison of the four test configurations demonstrated that both engine operating condition and test type influence tractor carbon performance. While fuel consumption was primarily affected by the transition from maximum power to rated engine speed conditions, specific CO₂ emissions were also influenced by the testing configuration. In particular, the drawbar test at rated engine speed represented the least favourable condition, whereas the PTO test at maximum power exhibited the highest CO₂ productivity and the lowest specific CO₂ emissions. The comparison between PTO and drawbar tests highlighted the importance of considering traction-related losses when evaluating tractor environmental performance. Relative to the PTO maximum power condition, drawbar operation at rated engine speed resulted in lower delivered power and higher specific CO₂ emissions, suggesting that assessments based only on PTO tests may underestimate the carbon intensity of tractor operation under traction conditions.

The results demonstrate the potential of OECD tractor test databases as a valuable resource for analysing long-term developments in tractor energy performance and associated greenhouse gas emissions. By exploiting standardized test data collected over several decades, it is possible to investigate how technological progress in agricultural machinery has influenced fuel consumption and the carbon intensity of tractor operation.

The results also provide practical information for farmers, machinery managers, and tractor manufacturers. The proposed methodology makes it possible to estimate tractor CO₂ emissions from standardized performance data without the need for direct emission measurements. This approach can support the selection of more energy-efficient tractors, the optimization of operating conditions, and the development of strategies aimed at reducing fuel consumption and the carbon footprint of agricultural operations. Furthermore, the identification of operating conditions associated with higher specific CO₂ emissions may contribute to improved tractor management practices and support future carbon-oriented policies in agricultural mechanization.

Future research will focus on two complementary aspects. First, the OECD database will be further analysed by dividing the tractor population into temporal groups in order to investigate the evolution of fuel consumption, specific fuel consumption, and fuel productivity over successive technological generations. The linear and nonlinear models developed in the present study provide the methodological framework required for these analyses, enabling consistent comparisons among tractors tested in different decades. This approach will provide a quantitative assessment of the effects of improvements in engine technology, transmission systems, and overall tractor design on energy performance over the last six decades.

Second, direct measurements of CO₂ emissions will be carried out on modern agricultural tractors using Portable Emission Measurement Systems (PEMS) during field operations. Particular attention will be devoted to evaluating the relationship between fuel consumption and CO₂ emissions under different engine speed and load conditions. This approach will make it possible to validate the methodology proposed in the present study through a direct comparison between measured CO₂ emissions and those estimated from fuel consumption data. Furthermore, it will enable the assessment of whether the theoretical fuel-to-CO₂ conversion relationship adopted in this study remains constant under the different engine speeds, loads, and operating conditions encountered during actual field operations.

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