

Acta Technologica Agriculturae 3
Nitra, Slovaca Universitas Agriculturae Nitriae, 2026, pp. 198–203

ENGINE DOWNSIZING AND RIGHTSIZING TRENDS IN MODERN AGRICULTURAL TRACTORS AND THEIR IMPACT ON POWER DEMAND, EFFICIENCY AND EMISSIONS

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The aim of this study was to analyse long-term changes in diesel engines used in agricultural tractors between 2015 and 2030, with particular attention to displacement, cylinder configuration, power output, power density, efficiency and emission compliance. Technical data from tractor catalogues published in 2015 and 2024 were examined for standard agricultural models representing 33 manufacturers and power ratings from 34 kW to 527 kW. Descriptive statistics, comparative analysis and linear trend modelling were used to identify design tendencies and to forecast changes up to 2030. The results showed a systematic increase in average power and torque, accompanied by a moderate reduction in average displacement and the almost complete standardisation of turbocharging. Downsizing, based on smaller displacement and higher specific output, was most evident up to approximately 2020. Later developments indicate a gradual shift towards rightsizing, in which engine size is better matched to sustained agricultural workloads, thermal robustness and durability requirements. This shift is linked to wider implements, higher working speeds, heavier tractors and the integration of emission-control systems required by Stage V regulations. The findings indicate that modern tractor engine development is moving from aggressive displacement reduction towards balanced optimisation of efficiency, torque stability, durability and emission performance.

Keywords: tractors; diesel engines; downsizing; rightsizing; power density; Stage V emission standards

In 2019, the European Stage V emission standards (Regulation 2016/1628 of the European Parliament and of the Council) entered into force, significantly tightening the limits for nitrogen oxides (NO_x), particulate matter (PM), particle number (PN), hydrocarbons (HC), and carbon monoxide (CO) emitted by engines used in non-road mobile machinery (NRMM) (Regulation 2016/1628; Lovarelli and Bacenetti, 2019). These regulations apply, among others, to construction machinery and agricultural tractors and have had a profound impact on the design and operation of modern powertrain systems. Real-operation studies also show that agricultural tractor emissions and load factors may differ substantially from standard test assumptions (Hou et al., 2022; Kim et al., 2024; Lovarelli et al., 2018).

Compliance with Stage V requirements forced manufacturers to implement extensive technological modifications, including advanced exhaust aftertreatment systems such as diesel particulate filters (DPF), selective catalytic reduction (SCR), and exhaust gas recirculation (EGR), higher injection pressures, improved turbocharging solutions, and increasingly sophisticated electronic control units (ECUs). As a result, combustion efficiency and emission performance improved, but at the cost of increased system complexity, higher production costs, and greater service requirements for end users (Ferguson and Kirkpatrick, 2016;

Lovarelli and Bacenetti, 2019; Mollenhauer and Tschöke, 2010). These changes have directly influenced engine architecture and accelerated the search for optimal design strategies. This is consistent with diesel-emission control studies identifying SCR, DPF and EGR as key technologies for reducing NO_x and particulate emissions (Johnson, 2009; Reşitoğlu et al., 2015).

One of the key approaches adopted to meet emission limits was downsizing, a concept originally developed in the automotive sector. Downsizing involves reducing engine displacement or cylinder count while maintaining or increasing power output through turbocharging, charge air cooling, and precise fuel injection control (Bor et al., 2019; Mazanec et al., 2023; Namar et al., 2021). In agricultural tractors, this strategy led to the replacement of traditional 6-cylinder engines with modern 4-cylinder units delivering comparable power and torque levels (Stirnemann and Engelmann, 2017). A representative example is provided by John Deere tractors: the 6630 TLS model from 2010, equipped with a 6-cylinder 6.8 dm³ engine producing 95 kW, compared with the contemporary 6130 M model achieving 105 kW using a 4-cylinder 4.5 dm³ engine. Electrically assisted boosting is also discussed as a route supporting downsizing while maintaining power density (Alshammari et al., 2019).

The literature reports several advantages associated with downsizing, including reduced fuel consumption under comparable operating conditions, lower friction losses, reduced engine mass, improved vehicle manoeuvrability, and compact engine layouts that are advantageous for front-loader applications (Bor et al., 2019; Mazanec et al., 2023; Namar et al., 2021). However, downsizing also introduces important limitations in agricultural applications, where engines frequently operate under high and sustained loads. These drawbacks include increased vibration and noise, higher thermal stress, reduced torque smoothness, greater technical complexity, and potentially reduced durability during long-term heavy-duty operation (Ferguson and Kirkpatrick, 2016; Mollenhauer and Tschöke, 2010).

Due to these limitations, the concept of rightsizing has gained increasing attention in agricultural engineering. Unlike downsizing, rightsizing does not aim to minimise displacement but rather to optimally match engine size to load characteristics, power class, and intended tractor application (Bor et al., 2019). This strategy emphasises stable torque delivery at low engine speeds, thermal robustness, and durability, while facilitating the integration of Stage V emission control systems without excessive stress on engine components (Bor et al., 2019; Stirnimann and Engelmann, 2017). Manufacturers such as Fendt, Valtra, and Massey Ferguson have consistently applied rightsizing by maintaining stable engine displacements over extended production periods and focusing on efficiency improvements rather than aggressive miniaturisation.

At the same time, operational requirements in agriculture have evolved significantly. The widespread adoption of reduced tillage, no-till, and strip-till systems, combined with increasing implement widths, higher working speeds, and growing tractor mass, has led to a rising demand for tractors in the 120–200 kW power range (Jaleta et al., 2019; Mojžiš et al., 2024; Stirnimann and Engelmann, 2017). Under such conditions, engines must deliver stable torque over long operating periods, making overly aggressive downsizing increasingly disadvantageous. Tractor fuel use and transmission studies confirm that energy demand depends strongly on load factor, implement type and transmission concept (Grisso et al., 2004; Howard et al., 2013).

In this context, a systematic assessment of the evolution of diesel engine designs used in agricultural tractors becomes necessary. The aim of this study is to provide a quantitative, market-level analysis of changes in tractor engine power, displacement, and cylinder configuration between 2015 and 2024, and to forecast design trends up to 2030 using linear trend modelling. Particular emphasis is placed on identifying the transition from downsizing towards rightsizing strategies and evaluating their implications for efficiency, durability, and emission compliance in modern agricultural tractors. The rightsizing trend is also relevant to hybrid and electrified agricultural powertrains, where combustion-engine size must be coordinated with electric drive components (Lajunen et al., 2018; Moreda et al., 2016).

Material and Methods

The data sources included tractor model catalogues published by top agrar Polska for the years 2015 and 2024. The 2015 catalogue contained technical specifications, equipment configurations, and prices for 600 tractor models ranging from 28 kW to 462 kW, representing 27 brands. In contrast, the latest 2024 edition covered 1200 models with power outputs from 34 kW to 527 kW, originating from 33 manufacturers.

After preliminary selection, which involved excluding specialist tractors (e.g., orchard tractors, compact municipal machines, and niche designs differing significantly from typical agricultural tractors), the following were qualified for further analysis:

- 385 models from 2015,
- 720 models from 2024.

The analysis focused on standard agricultural tractors intended for field and transport operations, covering general-purpose, medium-power and high-power tractor classes.

This represents an increase of nearly 200% in the number of available tractor models over the past decade, confirming the growing diversity and segmentation of the market. For comparative purposes, the analysed tractors were grouped into predefined power classes (< 75 kW, 75–120 kW, 120–200 kW, > 200 kW), enabling clearer interpretation of trends in engine power, torque and displacement. The need for structured technical data in tractor selection is also consistent with earlier work on decision-support tools for agricultural machinery purchases (Durczak et al., 2020).

The data were compiled in a spreadsheet, where the following analytical operations were performed:

1. Analysis of cylinder configuration structure, including the share of 3-, 4-, 6-cylinder engines and atypical configurations.
2. Descriptive statistics of engine parameters, including:
 - power (mean, median, distribution),
 - displacement,
 - torque,
 - torque-to-displacement ratio ($\text{Nm}\cdot\text{dm}^{-3}$).
3. Comparative analysis of the years 2015 and 2024, taking into account design and technological changes. Linear regression analysis used to identify long-term trends and to support illustrative forecasting of selected engine design parameters.
4. Trend modelling up to 2030 using linear regression, including forecasts of:
 - average engine power,
 - average engine displacement,
 - shares of individual cylinder configurations.
5. Qualitative analysis of market trends based on literature and industry publications (e.g., Bor et al., 2019; Lovarelli and Bacenetti, 2019; Stirnimann and Engelmann, 2017), enabling contextual interpretation of the results.

The analyses employed SI units: power – kW, torque – Nm, displacement – dm^3 and cm^3 .

The forecasts were developed using a linear approach, assuming the continuation of observed design trends under stable legislative (Stage V) and technological conditions (turbocharging, common rail, SCR/EGR/DPF systems). Regression analysis was used for illustrative trend evaluation rather than for hypothesis testing or statistical significance assessment.

Results and discussion

The analysis of technical parameters of agricultural tractors from 2015 and 2024 revealed clear design changes in terms of engine power, displacement, and overall powertrain characteristics. The average engine power increased from 124.9 kW in 2015 to 131.7 kW in 2024, while the median rose from 88 kW to 105 kW. The power distributions shown in Fig. 1 indicate a shift of the entire tractor population toward higher power classes, meaning that not only the segment of heavy tractors but also the segment of general-purpose machines has experienced a noticeable power increase.

This change is consistent with the observations of Stirnimann and Engelmann (2017), who documented a systematic increase in tractor engine output and torque associated with technological development and stricter emission requirements.

A similar trend was noted with respect to torque. The data presented in Fig. 2 show an increase in the median torque from 564 Nm in 2015 to 648 Nm in 2024, which in practice indicates improved engine flexibility and a greater ability to transmit higher loads at lower rotational speeds.

This is particularly important from the perspective of field operations performed with large tillage and seeding implements, which are characteristic of reduced-tillage and no-till systems.

Despite the increase in power and torque, the average engine displacement decreased from 5533 cm³ to 5097 cm³, while the median remained nearly unchanged. The distributions shown in Fig. 3 indicate that the reduction occurred primarily in the number of models equipped with very large-

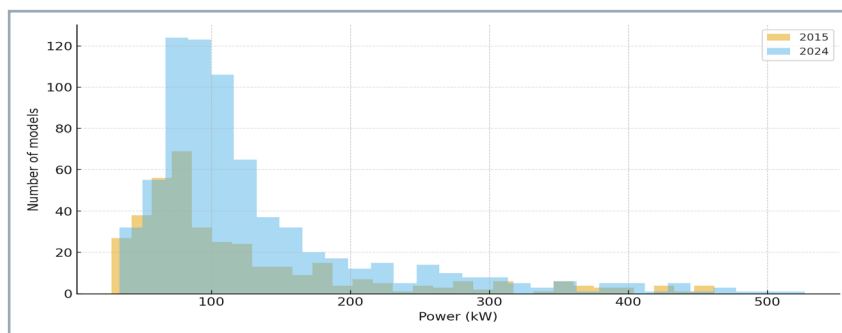


Fig. 1 Power distribution (kW) – 2015 vs 2024

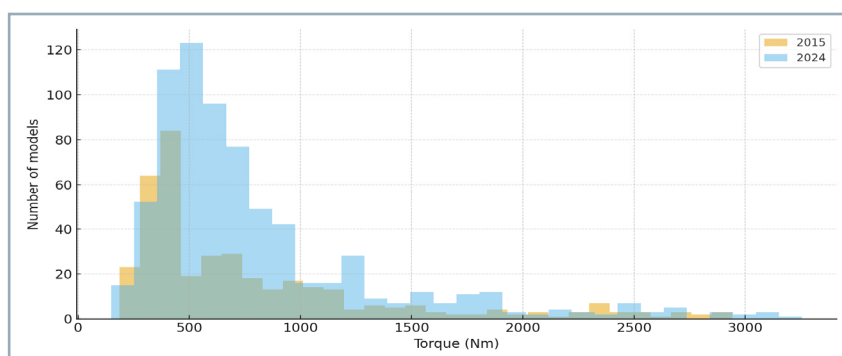


Fig. 2 Torque distribution (Nm) – 2015 vs 2024

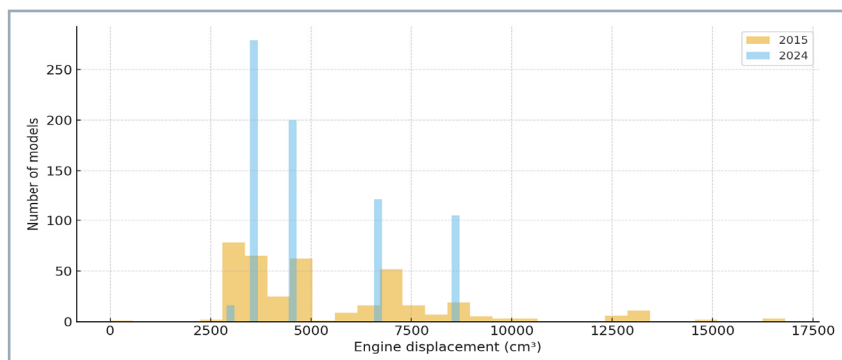


Fig. 3 Engine displacement distribution (cm³) – 2015 vs 2024

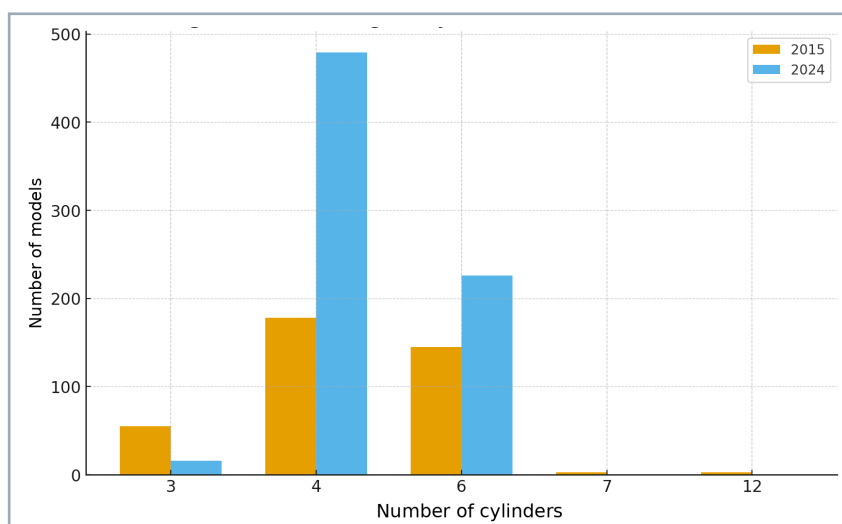


Fig. 4 Changes in tractor engine cylinder structure (2015 vs 2024)

Table 1 Engine downsizing trends by brand

Brand	Example series	Characteristics
John Deere	6M, 6R, 5E	transition from 6.8 L to 4.5 L engines while maintaining the same power output; stronger turbochargers and exhaust gas recirculation (EGR) plus selective catalytic reduction (SCR) systems
New Holland	T5, T6	reduction of engine displacement (e.g., from 6.7 L to 4.5 L) through the use of Common Rail and intercooler technologies
Case IH	Farmall, Maxxum	in many models, 4-cylinder Fiat Powertrain Technologies (FPT) 4.5 L engines replaced the previous 6-cylinder 6.7 L units – a classic example of downsizing
Deutz-Fahr	Series 5 and 6	transition from 6-cylinder Deutz Turbocharged Common-rail Diesel (TCD) 6.1 L engines to 4-cylinder 4.1 L units in models with the same power output
Claas	Arion 400-500	Fiat Powertrain Technologies (FPT) and John Deere Power Systems (DPS) engines with smaller displacement – but equipped with higher injection pressure and variable-geometry turbochargers

Table 2 Brands applying rightsizing

Brand	Example series	Characteristics
Fendt	500, 700, 900 Vario	does not radically reduce engine displacement – instead applies rightsizing: 4.04 L and 7.8 L MAN engines optimised for working loads
Valtra	N Series, T Series, Q Series	AGCO Power engines of 4.4 L and 7.4 L – very stable displacements maintained for many years. Focus on durability and consistent torque delivery
Massey Ferguson	5S, 6S, 7S	the same 4.4 L and 6.6 L engine blocks, but with different electronic control unit (ECU) maps – classic rightsizing with emphasis on flexibility
Zetor	Forterra, Proxima	traditional approach – large displacements (4.2 L) without significant reduction, with emphasis on simplicity and durability
Landini/McCormick	Series 6, 7	optimisation without radical displacement downsizing; focus on matching torque characteristics to transmission demands

displacement engines, whereas the typical tractor is still fitted with an engine of approximately 4.5 dm³.

Such a combination of parameters – rising engine power alongside decreasing displacement – constitutes a classic example of the implementation of a downsizing strategy, widely described in the literature (Bor et al., 2019; Mazanec et al., 2023; Namar et al., 2021; Stirnimann and Engelmann, 2017).

The cylinder configuration structure illustrated in Fig. 4 confirms the dominance of 4-cylinder engines and a stable, though smaller, share of 6-cylinder units.

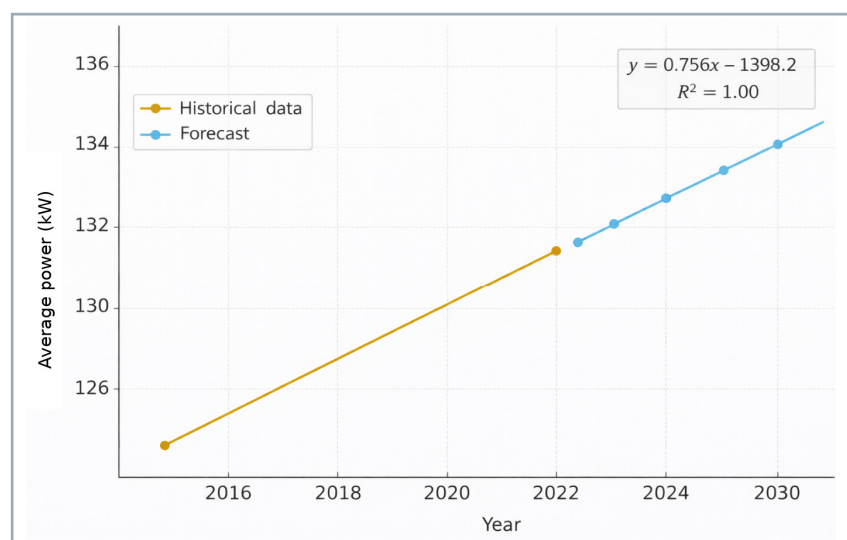
The average number of cylinders in the analysed population was 4.70 in 2015 and 4.60 in 2024, with the mode and median consistently equal to 4. The share of 3-cylinder models decreased markedly, and atypical configurations virtually disappeared. At the same time, the share of turbocharged engines increased from 96.4% to 100%, indicating complete standardisation of turbocharging in agricultural tractors and confirming the findings of Lovarelli and Bacenetti (2019) and Stirnimann and Engelmann (2017).

The results also made it possible to identify differences in the design strategies of individual manufacturers. Table 1 presents the brands employing the downsizing concept, which involves replacing 6.7–6.8 dm³ engines with 4-cylinder units of 4.1–4.5 dm³ while maintaining comparable power and torque levels.

A different approach is taken by manufacturers such as Fendt, Valtra,

Massey Ferguson, Zetor, and Landini, whose characteristics are presented in Table 2.

In their case, the rightsizing strategy consists of maintaining stable engine displacements over longer production periods and optimising the torque characteristics (Bor et al., 2019; Stirnimann and Engelmann, 2017).

**Fig. 5** Forecast of average tractor engine power (2015–2030); linear regression trend and coefficient of determination (R^2) are shown

The obtained results confirm that downsizing dominated between 2015 and 2020, whereas after 2020 a clear shift toward rightsizing can be observed, particularly in the premium brand segment.

The forecasts of design trends up to 2030 are presented in Figs 5–7. The presented forecasts are based on linear regression trend modelling of catalogue data from 2015 and 2024 and should be interpreted as indicative trends rather than precise predictions. The coefficients of determination (R^2) shown in Figs 5–7 illustrate the consistency of the observed design tendencies within the analysed period.

Figure 5 indicates a linear trend and a moderate increase in average tractor power, reaching approximately 136–137 kW by 2030.

In turn, the forecast of average engine displacement (Fig. 6) suggests a further decrease to approximately 4800 cm³.

Changes in the cylinder configuration structure (Fig. 7) indicate a projected increase in the share of 4-cylinder engines to approximately 79–80%, accompanied by a corresponding decrease in the share of 6-cylinder engines and the marginalisation of 3-cylinder units.

The obtained results confirm that in the period 2015–2030 the design of tractor engines undergoes a systematic evolution. An increase in power combined with a moderate reduction in engine displacement is clearly visible, along with the full standardisation of turbocharging and a shift from aggressive downsizing toward more balanced rightsizing. These trends are consistent with global legislative conditions and the growing power demand in agricultural operations.

Conclusion

The analysis of technical parameters of agricultural tractors from 2015 to 2024, together with forecasts up to 2030, demonstrates that the design of diesel engines used in agricultural machinery is undergoing systematic yet evolutionary modernisation. This study provides a rare market-scale, quantitative comparison of tractor engine design trends across two reference years and multiple manufacturers, offering empirical

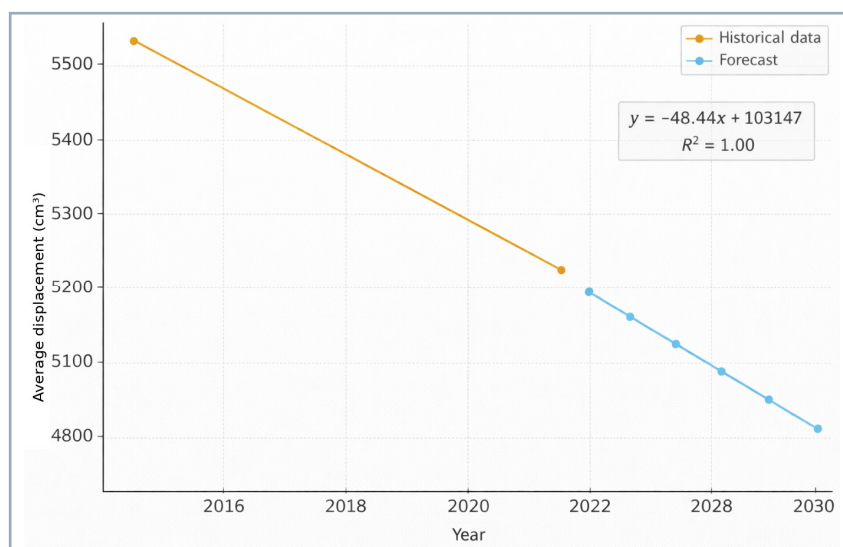


Fig. 6 Forecast of average engine displacement in agricultural tractors (2015–2030) based on linear regression trend analysis; the coefficient of determination (R^2) is indicated

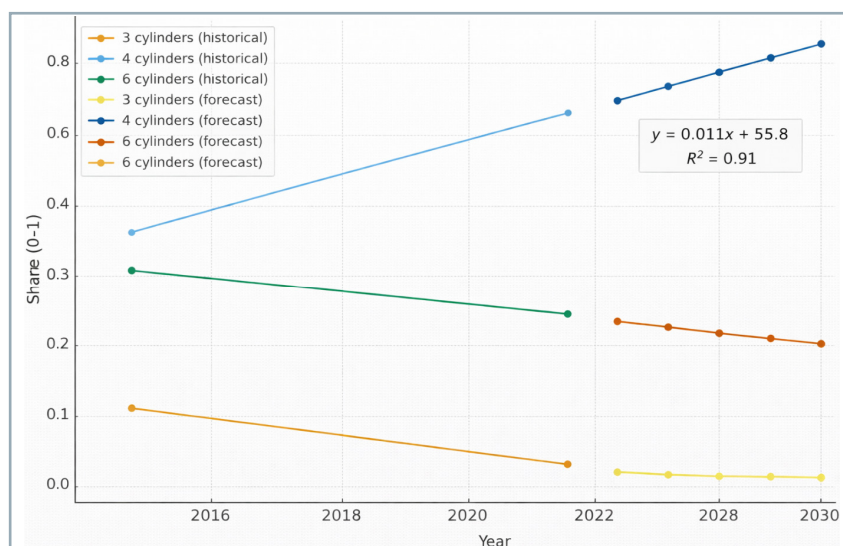


Fig. 7 Historical and forecasted shares of 3-, 4-, and 6-cylinder engines in agricultural tractors (2015–2030), with linear regression trend and R^2 indicated for the dominant 4-cylinder group

evidence of the transition from downsizing to rightsizing in agricultural powertrain development. Over the examined period, engine power and torque increased, while average displacement decreased moderately, confirming continuous improvements in efficiency, combustion control, and the widespread use of turbocharging technologies.

Based on an in-depth analysis of catalogue data and practical experience, the following conclusions can be drawn:

1. Cylinder configuration structure has stabilised, with 4-cylinder engines becoming the dominant

solution across most tractor classes. They increasingly replace both 3-cylinder designs and part of the 6-cylinder segment, especially in medium power ranges. Nevertheless, 6-cylinder engines remain essential for tractors intended for intensive field operations and large-scale cultivation systems, where sustained high loads require robust torque delivery.

2. The period 2015–2020 was dominated by downsizing, characterised by reductions in engine displacement and cylinder count while maintaining similar

power output. After 2020, manufacturers increasingly transitioned toward rightsizing, focusing on selecting displacement adequate for expected loads rather than minimising it. Rightsizing supports stable torque at low speeds, high durability, and smoother engine operation – features that are critical for farms employing intensive cultivation technologies and wide implements.

3. Forecasts up to 2030 indicate a continued moderate increase in average tractor power, accompanied by a gradual further reduction in average displacement and the sustained dominance of 4-cylinder units. Achieving an optimal balance between emission requirements, fuel consumption, torque characteristics, and structural durability will remain the principal direction of modern powertrain development.

In summary, the prominence of downsizing has visibly diminished over the last decade. Today, both manufacturers and users increasingly emphasise rightsizing, aiming for durability, operating flexibility, and efficiency rather than minimising displacement “at all costs” to meet Stage V emission limits. Downsizing still offers benefits in light or transport-oriented applications, but rightsizing provides a more balanced approach for multifunctional tractors operating under variable and demanding field conditions.

The results of this study confirm that the development of agricultural tractor engines is driven not by radical conceptual changes but by gradual technological optimisation and adaptation to evolving user expectations and regulatory constraints. This evolutionary path leads to powertrain systems that are more efficient, more versatile, and better suited to the specific operating requirements of modern agriculture.

References

- Alshammari, M., Alshammari, F., Pesyridis, A., 2019. Electric boosting and energy recovery systems for engine downsizing. *Energies* 12(24), 4636. <https://doi.org/10.3390/en12244636>
- Bor, M., Idzior, M., Karpiuk, W., Smolec, R., 2019. Possibilities of development of internal combustion engines, including downsizing and rightsizing strategy. *Autobusy – Technika, Eksploatacja, Systemy Transportowe* 24(6), 155–160. <https://doi.org/10.24136/atest.2019.143>
- Durczak, K., Ekielski, A., Kozłowski, R., Żelaziński, T., Pilarski, K., 2020. A computer system supporting agricultural machinery and farm tractor purchase decisions. *Heliyon* 6(10), e05039. <https://doi.org/10.1016/j.heliyon.2020.e05039>
- Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013 and amending and repealing Directive 97/68/EC. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R1628>
- Ferguson, C.R., Kirkpatrick, A.T., 2016. *Internal Combustion Engines: Applied Thermosciences*. 3rd ed. John Wiley & Sons, Chichester, United Kingdom. ISBN 978-1-118-53331-4.
- Grisso, R.D., Kocher, M.F., Vaughan, D.H., 2004. Predicting tractor fuel consumption. *Applied Engineering in Agriculture* 20(5), 553–561. <https://doi.org/10.13031/2013.17455>
- Hou, X., Xu, C., Li, J., Liu, S., Zhang, X., 2022. Evaluating agricultural tractors emissions using remote monitoring and emission tests in Beijing, China. *Biosystems Engineering* 213, 105–118. <https://doi.org/10.1016/j.biosystemseng.2021.11.017>
- Howard, C.N., Kocher, M.F., Hoy, R.M., Blankenship, E.E., 2013. Testing the fuel efficiency of tractors with continuously variable and standard geared transmissions. *Transactions of the ASABE* 56(3), 869–879. <https://doi.org/10.13031/trans.56.10222>
- Jaleta, M., Baudron, F., Krivokapic-Skoko, B., Erenstein, O., 2019. Agricultural mechanization and reduced tillage: Antagonism or synergy? *International Journal of Agricultural Sustainability* 17(3), 219–230. <https://doi.org/10.1080/14735903.2019.1613742>
- Johnson, T.V., 2009. Review of diesel emissions and control. *International Journal of Engine Research* 10(5), 275–285. <https://doi.org/10.1243/14680874JER04009>
- Kim, W.-S., Baek, S.-M., Baek, S.-Y., Jeon, H.-H., Siddique, M.A.A., Kim, T.-J., Lim, R.-G., Kim, Y.-J., 2024. Evaluation of exhaust emissions of agricultural tractors using portable emissions measurement system in Korean paddy field. *Scientific Reports* 14, 3491. <https://doi.org/10.1038/s41598-024-53995-0>
- Lajunen, A., Sainio, P., Laurila, L., Pippuri-Mäkeläinen, J., Tammi, K., 2018. Overview of powertrain electrification and future scenarios for non-road mobile machinery. *Energies* 11(5), 1184. <https://doi.org/10.3390/en11051184>
- Lovarelli, D., Bacenetti, J., 2019. Exhaust gases emissions from agricultural tractors: State of the art and future perspectives for machinery operators. *Biosystems Engineering* 186, 204–213. <https://doi.org/10.1016/j.biosystemseng.2019.07.011>
- Lovarelli, D., Fiala, M., Larsson, G., 2018. Fuel consumption and exhaust emissions during on-field tractor activity: A possible improving strategy for the environmental load of agricultural mechanisation. *Computers and Electronics in Agriculture* 151, 238–248. <https://doi.org/10.1016/j.compag.2018.06.018>
- Mazanec, J.M., Vang, N.S., Kokjohn, S.L., 2023. Enabling off-highway diesel engine downsizing and performance improvement using electrically assisted turbocharging. *International Journal of Engine Research* 24(9), 4104–4126. <https://doi.org/10.1177/14680874231181002>
- Mojžiš, M., Jobbágy, J., Rataj, V., Zsembeli, J., 2024. Impact of machinery passages on soil compaction in field conditions. *Acta Technologica Agriculturae* 27(2), 116–124. <https://doi.org/10.2478/ata-2024-0016>
- Mollenhauer, K., Tschöke, H., 2010. *Handbook of Diesel Engines*. 1st ed. Springer, Berlin, Heidelberg, Germany. ISBN 978-3-540-89082-9. <https://doi.org/10.1007/978-3-540-89083-6>
- Moreda, G.P., Muñoz-García, M.A., Barreiro, P., 2016. High voltage electrification of tractor and agricultural machinery – A review. *Energy Conversion and Management* 115, 117–131. <https://doi.org/10.1016/j.enconman.2016.02.018>
- Namar, M.M., Jahanian, O., Shafaghat, R., Nikzadfar, K., 2021. Engine downsizing; global approach to reduce emissions: A world-wide review. *HighTech and Innovation Journal* 2(4), 384–399. <https://doi.org/10.28991/HIJ-2021-02-04-010>
- Reşitoğlu, İ.A., Altinişik, K., Keskin, A., 2015. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. *Clean Technologies and Environmental Policy* 17, 15–27. <https://doi.org/10.1007/s10098-014-0793-9>
- Stirnemann, R., Engelmann, D., 2017. Development of tractor engines in the past twenty years. *ATZ offhighway worldwide* 10(4), 70–77. <https://doi.org/10.1007/s41321-017-0051-2>