FAILURE MECHANISMS IN REPAIRABLE AGRICULTURAL TRACTORS ACROSS ENGINE OPERATING-HOUR CLASSES
/
MECHANIZMY POWSTAWANIA USZKODZEŃ W CIĄGNIKACH ROLNICZYCH W ZALEŻNOŚCI OD CZASU PRACY SILNIKA

Karol DURCZAK*[1]; Tomasz ŻELAZIŃSKI[2]; Adam EKIELSKI[2]

[1] Department of Biosystems Engineering, Faculty of Environmental and Mechanical Engineering, Poznan University of Life Sciences, Poznań / Poland;

[2] Department of Production Engineering, Faculty of Production Engineering, University of Life Sciences in Warsaw, Warsaw / Poland

Tel.: +48 61 846 60 75; E-mail: karol.durczak@up.poznan.pl (corresponding author)

DOI: https://doi.org/10.35633/inmateh-79-92

Keywords: *agricultural tractor, failure mechanism, service record, engine operating hour, reliability, mechanical engineering*

ABSTRACT

Agricultural tractors are repairable mechanical systems whose service records can provide insight into how failure mechanisms evolve over their operating life. This study analysed 200 failure cases recorded for 75 Zetor tractors. Failure causes were classified into six mechanism categories and compared across four engine operating-hour classes. The relationship between operating-hour class and failure mechanism was evaluated using contingency tables, chi-square tests, Cramer's V, odds ratios, and correspondence analysis. Sealing-related failures predominated in the dataset, whereas material/manufacturing and electrical causes were more prevalent during the early stages of operation, and wear-, friction-, and fatigue-related mechanisms became more prominent at higher operating hours. The findings provide a basis for service planning and the assessment of tractor reliability.

STRESZCZENIE

Ciągniki rolnicze są naprawialnymi układami mechanicznymi, a dane serwisowe mogą wskazywać, jak mechanizmy uszkodzeń zmieniają się w trakcie eksploatacji. W pracy przeanalizowano 200 przypadków uszkodzeń zarejestrowanych dla 75 ciągników marki Zetor. Przyczyny uszkodzeń pogrupowano w sześć kategorii mechanizmów i porównano w czterech klasach motogodzin pracy silnika. Zastosowano tabele kontyngencji, statystykę chi-kwadrat, współczynnik V Cramera, ilorazy szans oraz analizę korespondencji. Największy udział w zbiorze danych miały mechanizmy uszczelnieniowe, natomiast wady materiałowo-wykonawcze i elektryczne częściej występowały we wczesnej fazie eksploatacji, a mechanizmy zużyciowo-tarciowe w późniejszych zapisach serwisowych.

INTRODUCTION

Agricultural tractors are complex repairable machines that combine mechanical, hydraulic, pneumatic, electrical and control subsystems. In the discipline of mechanical engineering, they can be treated as mobile technical systems exposed to variable loads, vibration, contamination, thermal cycles, lubricant ageing, environmental effects and operator-dependent usage patterns. Their failure behaviour is important because breakdowns may interrupt agrotechnical operations during short seasonal windows and can increase maintenance costs, downtime and logistic pressure on service networks.

Reliability engineering describes the performance of technical systems using concepts such as failure occurrence, maintainability, availability, lifetime distribution and risk of degradation during operation (*Birolini, 2017; Blischke and Murthy, 2000; O'Connor and Kleyner, 2012; Rausand and Hoyland, 2004*). In many repairable systems, the life cycle is often interpreted through early-life failures, random failures and wear-out failures. However, these phases should not be treated only as statistical intervals. From a mechanical engineering perspective, they should also be linked with loads, material response, contact conditions, lubrication, sealing quality, electrical continuity and structural integrity. This interpretation is consistent with failure-mechanism analysis, which connects observed failure symptoms with the physical processes that caused them (*Tinga, 2013; Zio, 2009*).

A complete lifetime dataset is required to estimate reliability functions, failure intensity or hazard rates with high confidence (*Birolini, 2017; Rausand and Hoyland, 2004*). In agricultural service practice, however, available data are often more limited. Service databases may include only failed cases, incomplete exposure histories, repair descriptions or non-standardised cause descriptions. Such data are not sufficient for estimating absolute failure probability in the whole tractor population, but they can still be useful for analysing the internal structure of recorded failures. This distinction is important because an incomplete service dataset may still indicate which physical mechanisms are more frequent at different stages of recorded operation.

The practical importance of maintenance and diagnostic data in agricultural machinery has been confirmed in several recent studies. Tractor maintenance planning, reliability support systems and replacement strategies have been analysed using field, service and decision-support approaches (*Atli, 2024; Kataev et al., 2024; Kolhe et al., 2024; Mishra and Satapathy, 2023*). Diagnostic and predictive-maintenance methods have also been applied to tractor transmission systems and agricultural machinery components (*da Silva et al., 2019; Jardine et al., 2006; Mobley, 2002; Moubray, 1997*). Other studies have examined failures and reliability models of farm tractors and working parts exposed to abrasive or variable operating conditions (*Durczak and Selech, 2022; Mikolajczak and Napiorkowski, 2016; Napiorkowski and Gonera, 2020; Paman et al., 2024*). These works show that service and field information can support engineering decisions, but they also indicate that the interpretation of failure records depends strongly on the quality and structure of the available data.

Recent developments in agricultural engineering additionally show that tractor operation can be described with increasing detail using mission profiles, CAN-BUS data, GNSS records, working cycles and operational analytics (*Angelucci and Mattetti, 2024; Götz et al., 2025; Mattetti et al., 2021*). These studies are important because they link machine use with real operating conditions. At the same time, many service organisations still rely on ordinary workshop records rather than continuous sensor-based monitoring. Therefore, there is a practical need for simple methods that can extract engineering information from historical service records, even when these records do not contain complete exposure data.

From a mechanical engineering viewpoint, the physical interpretation of the recorded cause is essential. A sealing failure may indicate a different technical problem than a short circuit, a material defect, a seized actuator, a fractured pipe or excessive wear of a transmission component. Therefore, the service cause can be transformed into a mechanism-oriented variable that supports feedback to design, manufacturing quality control, warranty analysis and maintenance planning. This interpretation is also consistent with contemporary agricultural engineering studies, where machine behaviour, material properties, reliability, operational data and environmental aspects are jointly analysed (*Angelucci and Mattetti, 2024; Kim and Kim, 2023; Lovarelli and Bacenetti, 2019; Mattetti et al., 2021; Scolaro et al., 2021; Zelazinski et al., 2023*).

Categorical-data methods are useful when service records are grouped into operating-time classes and mechanism categories. Contingency tables, the Pearson chi-square test, Cramer's V, odds ratios and correspondence analysis allow the researcher to describe associations between two categorical variables without assuming a continuous failure-time distribution (*Agresti, 2019; Friendly and Meyer, 2015; Greenacre, 2017; McHugh, 2013*). In the present context, these methods are not used to build a complete reliability model. They are used to determine whether the structure of recorded failure mechanisms changes across engine operating hour classes.

The research gap addressed in this paper is the limited use of ordinary service records for identifying operating-time-dependent failure mechanisms of agricultural tractors. Previous studies have often focused on failure frequency, maintenance planning, diagnostic methods or general reliability indicators, whereas fewer studies have transformed workshop failure causes into physical mechanism categories and analysed their distribution across operating-time classes. The objective of the study was therefore to analyse how recorded failure causes of Zetor tractors were distributed across engine operating hour classes. The working assumption was that early service records would contain a relatively higher contribution of material, manufacturing, assembly and electrical faults, whereas later records would show a higher contribution of wear-, friction- and fatigue-related mechanisms.

MATERIALS AND METHODS

The empirical material consisted of historical service failure records of Zetor agricultural tractors. The dataset contained 200 diagnostic service cases recorded for 75 unique vehicle identification numbers. Each record included the tractor model, engine operating hours (EOH; the source records used the Polish term motogodziny, abbreviated as “mth”), observed symptom, assembly group, damaged part, failure cause, labour cost, parts cost and total repair cost. The dataset contained recorded failures only; therefore, it was not used to estimate failure probability, reliability function or hazard rate.

The operating time indicator was discretised into four classes: 0-250 EOH, 251-500 EOH, 501-750 EOH and more than 750 EOH. These intervals were used as practical stages of recorded operation: early operation, initial regular operation, intermediate operation and later recorded operation. The descriptive characteristics of the dataset are presented in Table 1.

Table 1

Characteristics of the analysed service failure dataset

Characteristic	Value
Number of service failure cases	200
Number of unique VIN identifiers	75
Minimum [EOH]	2
Maximum [EOH]	1498
Mean [EOH]	414.69
Median [EOH]	390
Number of EOH classes	4
Number of mechanism categories	6

The original service causes were translated from Polish service terminology and grouped into six failure-mechanism categories. The grouping was performed on the basis of the physical interpretation of the cause, not on the basis of the failed subsystem. This distinction is important because the same subsystem may fail through several mechanisms. For example, a pneumatic or hydraulic component may fail because of a sealing fault, material defect, contamination or wear. The taxonomy used in the analysis is shown in Table 2.

Table 2

Failure-cause taxonomy used for mechanism-based analysis

Failure-mechanism category	Original service causes included in the category
Sealing-related	damaged sealing surface; damaged sealing collar; damaged seals; damaged cylinder seal
Material/manufacturing	material defect; defective weld or soldering; inaccurate machining; defective thread; defective battery cell
Electrical	short circuit; burnout; no continuity; broken wire
Wear/friction/fatigue	seizure; excessive wear; excessive clearance; cracking
Assembly/structural	faulty assembly; unriveting; pipe fracture; bending; fracture
Other/contamination/joint	delamination; impurities; clogging; functional fault

Following general recommendations for categorical and count-data analysis (*Agresti, 2019; Friendly and Meyer, 2015*), three statistical measures were used to describe the association between operating-time class and failure-mechanism category. First, the Pearson chi-square statistic was calculated from the contingency table, as shown in Equation (1):

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\frac{(O_{ij}-E_{ij})^2}{E_{ij}} \quad (1)$$

where:

O_{ij} – observed frequency in row i and column j;

E_{ij} – expected frequency in row i and column j under the assumption of independence;

r – number of rows in the contingency table;

c – number of columns in the contingency table.

The strength of association was expressed using Cramer's V, as given in Equation (2):

$$V = \sqrt{\frac{\chi^2}{n \cdot min(r-1,\ c-1)}} \quad (2)$$

where: n – total number of observations included in the contingency table;

$min(r-1, c-1)$ – the smaller dimensional correction factor used to normalise the chi-square statistic.

For early-life comparison, the odds ratio for each failure-mechanism category was calculated using the 0-250 EOH class versus all later records, as shown in Equation (3):

$$OR = \frac{(a+0.5)(d+0.5)}{(b+0.5)(c+0.5)} \quad (3)$$

where:

OR – odds ratio for the occurrence of a given failure mechanism in early-life service cases compared with later service cases;

a – number of early-life cases with the analysed failure mechanism;

b – number of early-life cases without the analysed failure mechanism;

c – number of later service cases with the analysed failure mechanism;

d – number of later service cases without the analysed failure mechanism;

0.5 – Haldane–Anscombe continuity correction added to each cell to stabilise the odds-ratio estimate when sparse cells occur.

Finally, correspondence analysis was used as an exploratory graphical method to visualise associations between EOH classes and failure-mechanism categories. The map was not treated as a predictive model; it was used to support interpretation of the contingency structure.

RESULTS

The overall distribution of failure-mechanism categories is shown in Figure 1. The largest category was sealing-related failures, which included 90 service cases and represented 45.0% of the dataset. Material/manufacturing mechanisms accounted for 37 cases, electrical mechanisms for 32 cases and wear/friction/fatigue mechanisms for 23 cases. Assembly/structural and other/contamination/joint mechanisms were less frequent.

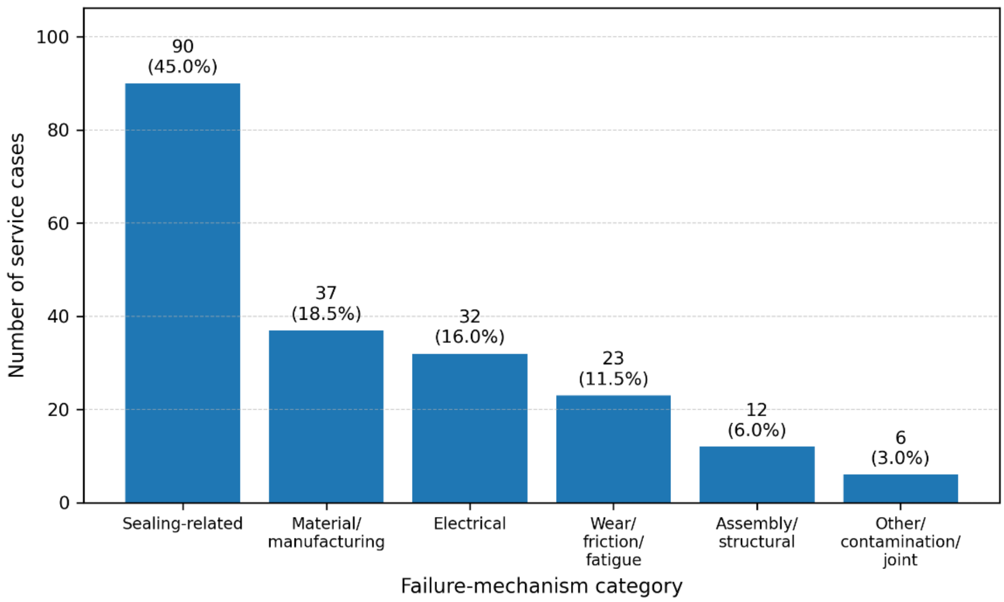

Fig. 1 - Distribution of failure-mechanism categories in the analysed service records

The predominance of sealing-related causes is mechanically meaningful. Many tractor assemblies operate with hydraulic oil, lubricants, compressed air or coolant, and their functional reliability depends on the integrity of seals, collars, sealing surfaces and joints. A sealing fault may therefore appear in different subsystems, but it represents one common physical mechanism that can be targeted by improved material selection, assembly control and early leakage inspection.

The cross-classification of EOH classes and failure-mechanism categories is presented in Table 3.

Table 3

Contingency table of engine operating hour class and failure-mechanism category

EOH class	Sealing-related	Material/ manufacturing	Electrical	Wear/ friction/ fatigue	Assembly/ structural	Other/ contamination/ joint	Total
0-250	18	14	11	2	3	4	52
251-500	38	16	8	10	4	2	78
501-750	29	7	10	5	4	0	55
>750	5	0	3	6	1	0	15
Total	90	37	32	23	12	6	200

The chi-square statistic calculated according to Equation (1) was 31.25, with 15 degrees of freedom and p = 0.008. Cramer's V calculated according to Equation (2) was 0.228. This indicates a weak-to-moderate but interpretable association between operating-time class and failure-mechanism category.

The percentage structure by EOH class is illustrated in Figure 2.

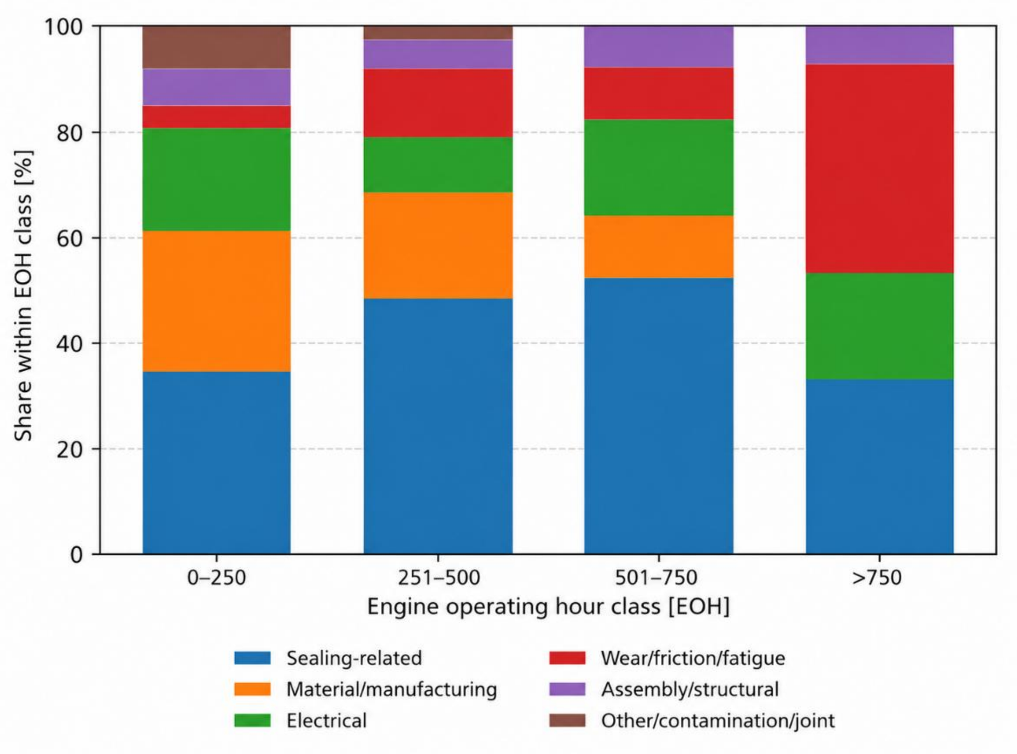

Fig. 2 - Failure-mechanism structure across engine operating hour classes

In the 0-250 EOH class, material/manufacturing and electrical mechanisms together accounted for 48.1% of records, while wear/friction/fatigue accounted for only 3.8%. In the >750 EOH class, wear/friction/fatigue represented 40.0% of recorded cases. Sealing-related mechanisms remained important in all classes, but they were particularly visible in the 251-500 and 501-750 EOH classes.

The early-life odds ratios calculated according to Equation (3) are presented in Table 4.

Table 4

Early-life odds ratios for failure-mechanism categories

Failure-mechanism category	0-250 EOH	>250 EOH	OR	95% CI
Sealing-related	18	72	0.57	0.30-1.08
Material/manufacturing	14	23	2.01	0.95-4.25
Electrical	11	21	1.64	0.74-3.65
Wear/friction/fatigue	2	21	0.29	0.08-1.13
Assembly/structural	3	9	1.04	0.29-3.69
Other/contamination/joint	4	2	5.44	1.12-26.39

Values above 1.0 indicate that the category was relatively more frequent in the 0-250 EOH group than in later records. Material/manufacturing mechanisms had an odds ratio of 2.01, while electrical mechanisms had an odds ratio of 1.64. Wear/friction/fatigue mechanisms had an odds ratio of 0.29, confirming their lower occurrence in early records and higher occurrence after 250 EOH.

The correspondence analysis map is presented in Figure 3.

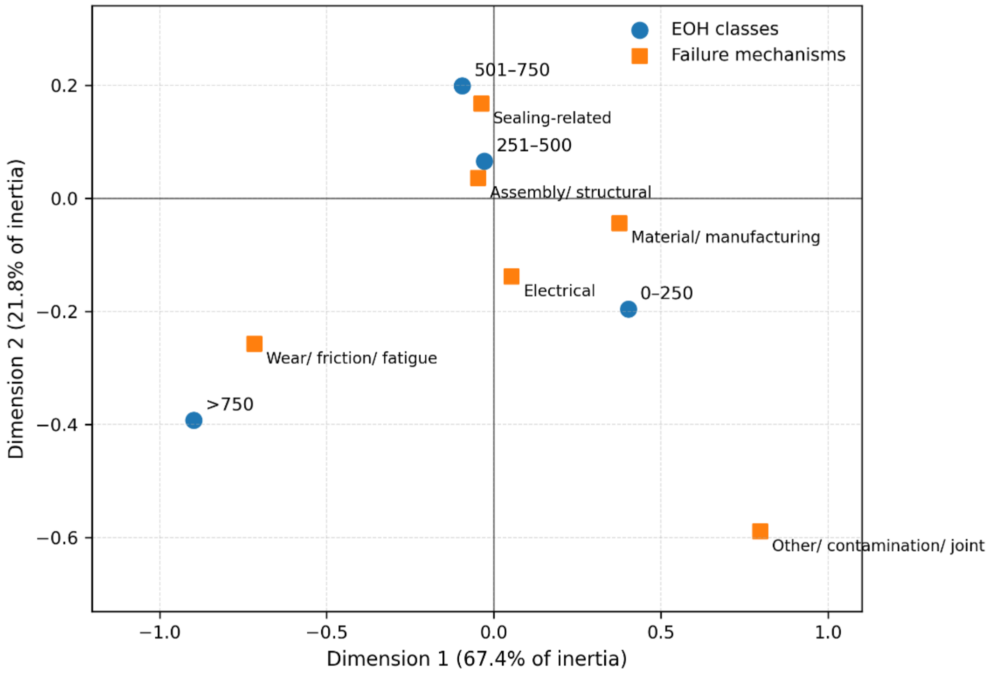

Fig. 3 - Correspondence analysis map of EOH classes and failure-mechanism categories

The first two dimensions explained 89.2% of the total inertia. The 0-250 EOH class was located closer to material/manufacturing, electrical and other/contamination/joint categories. The >750 EOH class was located closest to wear/friction/fatigue mechanisms. The 251-500 and 501-750 EOH classes were positioned nearer to sealing-related mechanisms, which reflects the high contribution of sealing faults in these operating ranges.

To connect the mechanism-oriented view with the mechanical structure of the tractor, the failure mechanisms were also compared across aggregated subsystem classes. The percentage structure is presented in Figure 4. Cabin/control failures were dominated by sealing-related causes associated mainly with gas springs, locks and cabin fittings. Electrical/starting failures were mostly electrical or material/manufacturing in nature. Engine/cooling and pneumatic/braking classes showed mixed mechanisms, which confirms that subsystem names alone do not fully explain the physical origin of the failure.

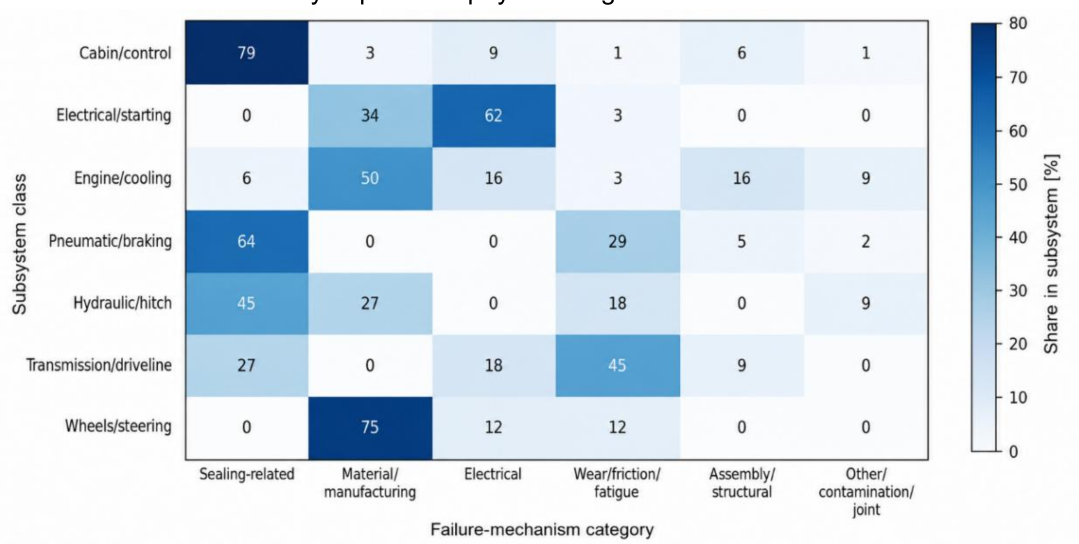

Fig. 4 - Failure-mechanism share within aggregated tractor subsystem classes

Values inside the cells represent shares of mechanism categories within a given subsystem class, [%].

Table 5 confirms that the mechanism-oriented approach adds information that is not visible in a subsystem-only classification.

Table 5

Dominant failure mechanism in each aggregated subsystem class

Subsystem class	Dominant mechanism	Share [%]	Secondary mechanism
Cabin/control	Sealing-related	79.1	Electrical
Electrical/starting	Electrical	62.1	Material/manufacturing
Engine/cooling	Material/manufacturing	50.0	Electrical
Pneumatic/braking	Sealing-related	64.3	Wear/friction/fatigue
Hydraulic/hitch	Sealing-related	45.5	Material/manufacturing
Transmission/driveline	Wear/friction/fatigue	45.5	Sealing-related
Wheels/steering	Material/manufacturing	75.0	Electrical

Cabin/control and pneumatic/braking were dominated by sealing-related mechanisms, whereas electrical/starting was dominated by electrical mechanisms. Hydraulic/hitch and transmission/driveline had more mixed patterns, which suggests that their maintenance cannot be reduced to a single inspection action. For these assemblies, a technician should consider leakage, wear, material condition and adjustment simultaneously.

Table 6 summarises the mechanical interpretation of the identified failure-mechanism categories and indicates their practical implications for tractor servicing, inspection planning and maintenance decision-making.

Table 6

Mechanical interpretation and practical service implications of failure-mechanism categories

Failure mechanism	Mechanical interpretation	Service implication
Sealing-related	Loss of tightness, damaged sealing surface, collar or elastomer element	Leakage inspection, cleanliness control, seal material and surface check
Material/manufacturing	Defect originating from material quality, machining, weld, thread or component manufacture	Quality feedback, incoming component control, warranty monitoring
Electrical	Short circuit, burnout, interrupted continuity or wiring defect	Connector, wiring, switch and protection-system inspection
Wear/friction/fatigue	Seizure, excessive wear, excessive clearance or cracking during operation	Lubrication, adjustment, clearance, load and friction-pair control
Assembly/structural	Faulty assembly, bending, fracture or loss of mechanical connection	Assembly procedure verification and structural inspection
Other/contamination/joint	Impurities, clogging, functional fault or joint degradation	Filtration, cleaning, fluid quality and functional testing

The mechanism-oriented interpretation presented in Table 6 expands the meaning of the numerical results. The high share of sealing-related failures indicates that tightness should be treated as one of the central reliability problems in the analysed tractor records. This category included failures of sealing surfaces, collars and seals, and it appeared in several subsystem classes. Therefore, the result should not be interpreted only as a problem of one assembly group. It rather indicates a cross-system mechanism associated with leakage, contact surface condition, elastomer quality, installation accuracy, contamination and pressure or temperature variation during operation.

The operating-time distribution of mechanisms also has a clear engineering meaning. In the 0-250 EOH class, material/manufacturing and electrical mechanisms were more visible than wear/friction/fatigue mechanisms. This pattern is consistent with the interpretation of early service records as a period in which hidden defects of manufacturing, assembly, component quality, wiring, connectors or protection systems may become visible. In this stage, inspection activities should therefore include targeted checks of sealing surfaces, threaded joints, welded or soldered parts, wiring continuity, connectors and hydraulic or pneumatic tightness. The early-life odds ratios support this interpretation because material/manufacturing and electrical categories had values above 1.0, whereas wear/friction/fatigue had a value below 1.0.

For later operation, especially above 750 EOH, the increasing contribution of wear/friction/fatigue mechanisms suggests a different service logic. In these cases, maintenance should pay more attention to lubrication quality, friction pairs, clearances, seizure risk, fatigue cracking and components exposed to cyclic loads.

This transition from quality-related and electrical mechanisms toward wear-related mechanisms is consistent with the general mechanical interpretation of repairable systems. However, the present dataset does not include non-failed tractors or complete exposure histories, so it cannot be used to estimate the absolute probability of failure or to construct a complete bathtub curve.

The subsystem-mechanism comparison confirms that a parts-based classification is not sufficient for engineering interpretation. Cabin/control and pneumatic/braking failures were dominated by sealing-related mechanisms, electrical/starting failures were mostly electrical or material/manufacturing in nature, whereas hydraulic/hitch and transmission/driveline groups showed more mixed patterns. This means that the same subsystem may require different corrective actions depending on the underlying physical mechanism. For example, a hydraulic failure may require leakage inspection, material-quality feedback, contamination control or wear assessment, depending on the coded cause.

From a service-management perspective, the results show that ordinary workshop records can support more than spare-parts logistics and can contribute to maintenance support systems and strategic maintenance management (*Kataev et al., 2024; Tsang, 2002*). If a record is coded only as a replacement of a component, it mainly supports inventory planning and repair-cost accounting. If the same record is additionally coded as sealing-related, electrical, material/manufacturing, assembly-related or wear-related, it becomes useful for design feedback, warranty monitoring and maintenance planning. This distinction is important in mechanical engineering because the same external symptom may result from different degradation processes and may require different preventive actions.

The obtained association between EOH class and failure-mechanism category was statistically significant but not strong. Cramer's V indicated a weak-to-moderate association, which is reasonable for field service data affected by variable tractor use, operator behaviour, maintenance history, environmental exposure and recording practices. Therefore, the results should be interpreted as evidence of an interpretable structure in the recorded service cases, not as a deterministic rule for all tractors. The value of the approach lies in its ability to organise incomplete service data into mechanically meaningful categories and to identify where targeted inspections may be most useful.

The practical recommendation is that warranty-period servicing should not be limited to routine replacement or adjustment. Early inspections should include quality-control-oriented checks of sealing elements, electrical connections, threads, welds, machined surfaces and hydraulic or pneumatic tightness. In contrast, later inspections should increasingly focus on lubrication, friction pairs, clearances, fatigue-sensitive elements and components exposed to cyclic or abrasive loading. Such a distinction can help service organisations adapt inspection priorities to the operating-time class of the tractor.

The study also has several limitations that should be considered when applying the findings to other service networks. The dataset covers a single tractor brand and a single historical set of service records. Information on non-failed tractors, the exact population at risk, and complete maintenance histories was unavailable. Therefore, the results characterize the distribution of recorded failure mechanisms rather than the failure probability of the entire tractor population in service. Future research should integrate failure-mechanism classification with cost data, downtime, warranty status, operating conditions, and complete exposure histories to develop more robust reliability and maintenance decision-support models.

CONCLUSIONS

1. The analysed service dataset contained enough information to distinguish six practical failure-mechanism categories of agricultural tractors: sealing-related, material/manufacturing, electrical, wear/friction/fatigue, assembly/structural and other/contamination/joint mechanisms.
2. The strongest group of recorded mechanisms was sealing-related failure, which represented 45.0% of all service cases. This confirms that sealing elements are a critical reliability area in repairable tractor systems.
3. The association between EOH class and failure-mechanism category was statistically visible. The chi-square test gave $p = 0.008$ and Cramer's V was 0.228, indicating a weak-to-moderate but interpretable structure in the service records.
4. Material/manufacturing and electrical mechanisms were relatively more visible in the 0-250 EOH class, whereas wear/friction/fatigue mechanisms were more visible in later records, especially above 750 EOH.
5. The same tractor subsystem may be affected by different physical mechanisms. Therefore, maintenance decisions should combine subsystem information with mechanism-oriented interpretation of the service cause.

6. For maintenance practice, early service inspections should emphasise sealing, electrical and quality-control-related defects, while later inspections should increasingly focus on wear, friction, fatigue, lubrication and clearance-related mechanisms.
7. The method supports mechanical reliability assessment from incomplete service records, but it should not be treated as a replacement for full lifetime reliability modelling based on complete exposure data and non-failed observations.

ACKNOWLEDGEMENT

This research received no external funding. The authors acknowledge that the analysis was based on historical service records of agricultural tractors. AI-assisted tools were used only to support language editing, formatting and checking of the manuscript; the authors verified all calculations, interpretations and references.

REFERENCES

[1] Agresti A., (2019). An Introduction to Categorical Data Analysis, 3rd ed., Wiley, Hoboken/USA. DOI: https://doi.org/10.1002/9781119405269
[2] Angelucci L., Mattetti M., (2024). The development of reference working cycles for agricultural tractors, *Biosystems Engineering*, vol.242, pp.29-37, London/United Kingdom. DOI: https://doi.org/10.1016/j.biosystemseng.2024.04.004
[3] Atli H.F., (2024). Safety of agricultural machinery and tractor maintenance planning with fuzzy logic and MCDM for agricultural productivity, *International Journal of Agriculture Environment and Food Sciences*, vol.8, no.1, pp.25-43, Turkey. DOI: https://doi.org/10.31015/jaefs.2024.1.4
[4] Birolini A., (2017). Reliability Engineering: *Theory and Practice*, 8th ed., Springer, Berlin/Germany. DOI: https://doi.org/10.1007/978-3-662-54209-5
[5] Blischke W.R., Murthy D.N.P., (2000). Reliability: Modeling, Prediction, and Optimization, Wiley, New York/USA. DOI: https://doi.org/10.1002/9781118150481
[6] da Silva C.A.G., Rodrigues de Sá J.L., Menegatti R., (2019). Diagnostic of failure in transmission system of agriculture tractors using predictive maintenance based software, *AgriEngineering*, vol.1, no.1, pp.132-144, Basel/Switzerland. DOI: https://doi.org/10.3390/agriengineering1010010
[7] Durczak K., Selech J., (2022). The quantification of operational reliability of agricultural tractors with the competing risks method, *Technical Gazette*, vol.29, no.2, pp.628-633, Croatia. DOI: https://doi.org/10.17559/TV-20201118115902
[8] Friendly M., Meyer D., (2015). Discrete Data Analysis with R: Visualization and Modeling Techniques for Categorical and Count Data, CRC Press, Boca Raton/USA. DOI: https://doi.org/10.1201/b19022
[9] Greenacre M., (2017). Correspondence Analysis in Practice, 3rd ed., CRC Press, Boca Raton/USA. DOI: https://doi.org/10.1201/9781315369983
[10] Götz K., Kusuma A., Dörfler A., Lienkamp M., (2025). Agricultural load cycles: tractor mission profiles from recorded GNSS and CAN bus data, *Data in Brief*, vol.60, article 111494, Amsterdam/Netherlands. DOI: https://doi.org/10.1016/j.dib.2025.111494
[11] Jardine A.K.S., Lin D., Banjevic D., (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance, *Mechanical Systems and Signal Processing*, vol.20, no.7, pp.1483-1510, London/United Kingdom. DOI: https://doi.org/10.1016/j.ymssp.2005.09.012
[12] Kataev Y., Malykha E., Gradov E., (2024). Maintaining the reliability of agricultural machinery in the complex of developing an engineering and technical system, BIO Web of Conferences, vol.141, article 04059, Les Ulis/France. DOI: https://doi.org/10.1051/bioconf/202414104059
[13] Kolhe K.P., Lemi D.G., Busse S.K., (2024). Studies of tractor maintenance and replacement strategies of Wonji Shoa Factory, Ethiopia, *Journal of Agricultural Engineering*, vol.55, no.1, article 1552, Pavia/Italy. DOI: https://doi.org/10.4081/jae.2024.1552
[14] Kim M.H., Kim S.M., (2023). Estimation of air pollutant emissions by tractor utilization in Korea, *Agriculture*, vol.13, no.9, article 1811, Basel/Switzerland. DOI: https://doi.org/10.3390/agriculture13091811
[15] Lovarelli D., Bacenetti J., (2019). Exhaust gases emissions from agricultural tractors: state of the art and future perspectives for machinery operators, *Biosystems Engineering*, vol.186, pp.204-213, London/United Kingdom. DOI: https://doi.org/10.1016/j.biosystemseng.2019.07.011

[16] Mattetti M., Maraldi M., Lenzini N., Fiorati S., Sereni E., Molari G., (2021). Outlining the mission profile of agricultural tractors through CAN-BUS data analytics, *Computers and Electronics in Agriculture*, vol.184, article 106078, Amsterdam/Netherlands. DOI: https://doi.org/10.1016/j.compag.2021.106078

[17] McHugh M.L., (2013). The chi-square test of independence, *Biochemia Medica*, vol.23, no.2, pp.143-149, Croatia. DOI: https://doi.org/10.11613/BM.2013.018

[18] Mikolajczak P., Napiorkowski J., (2016). Analysing the reliability of working parts operating in abrasive soil pulp taking into consideration confounding factors, *Eksploatacja i Niezawodnosc - Maintenance and Reliability*, vol.18, no.4, pp.544-551, Warsaw/Poland. DOI: https://doi.org/10.17531/ein.2016.4.9

[19] Mishra D., Satapathy S., (2023). Reliability and maintenance of agricultural machinery by MCDM approach, International Journal of System Assurance Engineering and Management, vol.14, no.1, pp.135-146, Singapore. DOI: https://doi.org/10.1007/s13198-021-01256-y

[20] Mobley R.K., (2002). An Introduction to Predictive Maintenance, 2nd ed., Butterworth-Heinemann, Oxford/United Kingdom.

[21] Moubray J., (1997). Reliability-Centered Maintenance, 2nd ed., Industrial Press, New York/USA.

[22] Napiorkowski J., Gonera J., (2020). Analysis of failures and reliability model of farm tractors, *Agricultural Engineering*, vol.24, no.2, pp.89-101, Krakow/Poland. DOI: https://doi.org/10.1515/agriceng-2020-0020

[23] O'Connor P.D.T., Kleyner A., (2012). Practical Reliability Engineering, 5th ed., Wiley, Chichester/United Kingdom. DOI: https://doi.org/10.1002/9781119961260

[24] Paman U., Khairizal, Sutriana S., (2024). Field investigation of component failures for selected farm machinery used in small rice farming operations, *Open Agriculture*, vol.9, no.1, article 20220292, Berlin/Germany. DOI: https://doi.org/10.1515/opag-2022-0292

[25] Rausand M., Hoyland A., (2004). System Reliability Theory: Models, Statistical Methods, and Applications, 2nd ed., Wiley, Hoboken/USA. DOI: https://doi.org/10.1002/9780470316900

[26] Scolaro E., Beligoj M., Estevez M.P., Alberti L., Renzi M., Mattetti M., (2021). Electrification of agricultural machinery: a review, *IEEE Access*, vol.9, pp.164520-164541, USA. DOI: https://doi.org/10.1109/ACCESS.2021.3135037

[27] Tinga T., (2013). Principles of Loads and Failure Mechanisms: Applications in Maintenance, *Reliability and Design*, Springer, London/United Kingdom. DOI: https://doi.org/10.1007/978-1-4471-4917-0

[28] Tsang A.H.C., (2002). Strategic dimensions of maintenance management, *Journal of Quality in Maintenance Engineering*, vol.8, no.1, pp.7-39, Bradford/United Kingdom. DOI: https://doi.org/10.1108/13552510210420577

[29] Zelazinski T., Ekielski A., Durczak K., Morawska M., (2023). Study on biodegradable materials from thermoplastic starch with the addition of nuts shell, *INMATEH - Agricultural Engineering*, vol.70, no.2, pp.201-210, Bucharest/Romania. DOI: https://doi.org/10.35633/inmateh-70-20

[30] Zio E., (2009). Reliability engineering: old problems and new challenges, *Reliability Engineering & System Safety*, vol.94, no.2, pp.125-141, Amsterdam/Netherlands. DOI: https://doi.org/10.1016/j.ress.2008.06.002