

## PREDICTION OF C9 ENGINE PERFORMANCE ON A D6R DOZER BASED ON WEAR OF PISTON RINGS, MAIN JOURNALS, CRANKPINS, AND CYLINDER LINERS

Thai Ha Phi<sup>1,a</sup>, Bui Thanh Danh<sup>2,\*</sup>, Ngo Dang Binh<sup>3,b</sup> (Caterpillar)

<sup>1</sup>University of Transport Technology (UTT).

<sup>2</sup>University of Transport and Communications (UTC).

<sup>3</sup>Phu Thai CAT Corporation.

Article Received on 01/09/2026

Article Revised on 21/09/2026

Article Accepted on 01/10/2026

### \*Corresponding Author

**Bui Thanh Danh**

University of Transport and  
Communications (UTC).

<https://doi.org/10.5281/zenodo.23038452>



**How to cite this Article:** Thai Ha Phi<sup>1,a</sup>, Bui Thanh Danh<sup>2,\*</sup>, Ngo Dang Binh<sup>3,b</sup> (Caterpillar) (2026). Prediction Of C9 Engine Performance On A D6r Dozer Based On Wear Of Piston Rings, Main Journals, Crankpins, And Cylinder Liners. World Journal of Engineering Research and Technology, 12(10), 181–193.

This work is licensed under Creative Commons Attribution 4.0 International license.

### ABSTRACT

This study develops a technical-life prediction model for the Cat C9 engine installed on a D6R dozer using teardown inspection data. The dataset comprised 20 inspection sheets; after duplicate checking, 18 independent engines remained, with 10,651-20,991 operating hours. The analyzed variables included the end gaps of three piston-ring types, main-journal diameter, crankpin diameter, and cylinder-liner diameter. Damage was normalized against the technical limits stated in the inspection records, and Taguchi signal-to-noise ratios under the “smaller-is-better” criterion were calculated across repeated measurement locations. Linear regression between mean dimensions and operating hours was used to determine threshold-crossing times. The predicted threshold lives of piston rings 1, 2, and 3 and the

cylinder liner were 9,896, 10,005, 9,926, and 10,254 h, respectively, substantially shorter than those of the main journals (20,393 h) and crankpins (24,722 h). The cylinder liner (-3.084 dB) and piston rings (-0.996 dB) had the lowest mean S/N values, confirming that these two component groups govern the overhaul interval. Under the weakest-link principle, system life was estimated at approximately 9,900 h; a proactive inspection window of 9,500-10,000 h is recommended for operating conditions similar to those represented by the sample. The method provides a quantitative basis for maintenance planning while explicitly treating

the Taguchi S/N metric as a retrospective application rather than a substitute for a controlled orthogonal-array experiment.

**KEYWORDS:** C9 engine; D6R dozer; wear; service life; piston rings; crankshaft; cylinder liner; Taguchi; Minitab.

## 1. INTRODUCTION

The D6R dozer operates under widely varying loads, dust, vibration, and severe thermal conditions. The C9 engine is its primary power source; degradation of the piston-cylinder assembly and crankshaft increases oil consumption, reduces compression pressure, increases blow-by, and may cause unplanned downtime. Caterpillar specifies the CAT C9 engine for the D6R2, with net power of approximately 148 kW depending on configuration.<sup>[2]</sup> Given the high costs of downtime and overhaul, shifting from breakdown maintenance to predictive maintenance offers clear techno-economic benefits.

Internal-combustion engine wear is a multi-mechanism tribological problem governed simultaneously by thermomechanical loading, sliding velocity, oil viscosity and contamination, surface roughness, and lubrication regime. Taylor<sup>[9]</sup>, Priest and Taylor<sup>[11]</sup>, and Tung and McMillan<sup>[13]</sup> classified three major engine friction groups: the piston assembly, valve train, and crankshaft journal bearings. They showed that trends toward higher specific loads and temperatures and lower oil viscosity impose increasingly stringent wear-resistance requirements. Priest, Dowson, and Taylor<sup>[10]</sup> developed an interactive model of diesel-engine piston-ring dynamics, lubrication, and wear, showing that wear is strongly concentrated near top dead center under high gas loading and thin oil-film conditions.

For the piston-ring-cylinder-liner pair, Andersson, Tamminen, and Sandström<sup>[12]</sup> reviewed more than 150 studies on thermomechanical loading, contact pressure, blow-by, lubrication, wear, and surface technology. Delprete and Razavykia<sup>[15]</sup> further showed that ring geometry, ring dynamics, oil rheology, and surface topography govern oil-film thickness, friction loss, and durability. Using reciprocating bench tests, Truhan, Qu, and Blau<sup>[14]</sup> demonstrated that lubricant condition, soot, and oxidation products significantly affect piston-ring and liner-material wear. These findings explain why piston-ring end gap and liner diameter are direct indicators of degradation in the piston-cylinder group.

For main journals and crankpins, damage depends on hydrodynamic oil-film formation, shaft-bearing deformation, assembly misalignment, cyclic loading, and start-stop events. The review by Santos, Roso, and Faria<sup>[16]</sup> showed that engine journal bearings face a high wear risk before a complete oil film is established; accumulated wear increases clearance, reduces oil pressure, and may result in scuffing or seizure. Main-journal and crankpin diameters are therefore suitable variables for describing the remaining life of the crankshaft assembly.

Regarding life prediction, Koszałka<sup>[17]</sup> proposed determining the durability of the piston-ring-cylinder assembly from wear data and a sealing model; the conventional method of extrapolating a wear law until the technical limit is reached is structurally similar to the approach adopted here. Chmielewski<sup>[18]</sup> used changes in the physicochemical properties of engine oil to predict liner wear and obtained a service life close to the technical standard. More generally, Jardine, Lin, and Banjevic<sup>[19]</sup> and Si et al.<sup>[20]</sup> identified remaining useful life as the central quantity in condition-based maintenance, estimated from degradation trends and condition-monitoring information.

Relatively few academic publications address the C9 specifically. Recently, Vikky, Aisyah, Sugiyanto, and Prihadianto<sup>[21]</sup> analyzed Caterpillar C9 engine failures in a hydraulic drilling unit using Scheduled Oil Sampling and Root Cause Analysis. Their study associated fuel dilution, maintenance history, and operation beyond 22,000 h without overhaul with severe degradation. Caterpillar's C9 operating literature also emphasizes that failure to follow maintenance intervals and fluid and filter requirements can accelerate wear.<sup>[22]</sup> However, no published study was found that simultaneously used piston-ring, main-journal, crankpin, and liner measurements from a population of C9 engines in D6R dozers to predict service life.

In practice, repair decisions are often based on comparing each measured dimension with its tolerance. This approach describes the condition at teardown but does not exploit the relationship between wear and operating time or quantify consistency among cylinders or journals. Kapsiz, Durat, and Ficici<sup>[23]</sup> applied a Taguchi design to the piston-ring-liner pair and demonstrated that the effects of load, speed, temperature, and material can be ranked with fewer experiments. The Taguchi method uses the signal-to-noise (S/N) ratio to evaluate both the mean and variability; for a characteristic to be minimized, the "smaller-is-better" formulation is appropriate.<sup>[3-5]</sup>

The literature review reveals a research gap in exploiting actual teardown-inspection data from multiple C9 engines with different serial numbers and total operating hours to quantify component-group service life. The objectives of this study are to: (i) normalize wear in four component groups against their technical limits; (ii) determine wear trends versus operating hours; (iii) rank component groups using the Taguchi S/N ratio; (iv) predict threshold-crossing life; and (v) propose a reproducible Minitab procedure. The study's novelty lies in integrating teardown measurement records, a dimensionless damage index, Taguchi S/N ratios, and life regression within a verifiable workflow.

## 2. Data and Research Methods

### 2.1. Data source

**Table 1: Data structure and technical limits used in the study.**

| Variable       | Locations per engine | Nominal dimension | Wear limit | Wear convention    |
|----------------|----------------------|-------------------|------------|--------------------|
| Piston ring 1  | 6                    | 0.40 mm           | 0.50 mm    | End gap increases  |
| Piston ring 2  | 6                    | 1.000 mm          | 1.125 mm   | End gap increases  |
| Piston ring 3  | 6                    | 0.45 mm           | 0.60 mm    | End gap increases  |
| Main journal   | 7                    | 108.000 mm        | 107.980 mm | Diameter decreases |
| Crankpin       | 6                    | 89.000 mm         | 88.980 mm  | Diameter decreases |
| Cylinder liner | 6                    | 130.025 mm        | 130.050 mm | Diameter increases |

### 2.2. Normalized damage index

To compare variables measured on different scales, wear was divided by the allowable wear amount. Main-journal and crankpin diameters decrease with wear, whereas piston-ring end gaps and cylinder-liner diameter increase with wear.

$$D = (x - x_0) / (x_{\text{lim}} - x_0), \text{ for quantities that increase with wear} \quad (1)$$

$$D = (x_0 - x) / (x_0 - x_{\text{lim}}), \text{ for quantities that decrease with wear} \quad (2)$$

where  $x$  is the measured value,  $x_0$  is the nominal dimension, and  $x_{\text{lim}}$  is the technical limit.  $D < 1$  indicates remaining wear allowance,  $D = 1$  indicates that the threshold has been reached, and  $D > 1$  indicates that the threshold has been exceeded. For the piston-ring group, the index for each cylinder was taken as the maximum of the three ring types in accordance with the weakest-link principle.

### 2.3. Taguchi S/N-ratio analysis

Because the objective is to minimize normalized damage, the “smaller-is-better” S/N ratio was used. Minitab defines this metric as follows.<sup>[3,4]</sup>

$$S/N = -10 \log_{10} [(1/n) \sum (D_j^2)] \quad (3)$$

Here,  $D_j$  is the damage index at measurement location  $j$ , and  $n$  is the number of repeated locations. In all cases, a higher S/N ratio indicates a more robust condition. Cylinder/journal locations act as inherent noise factors because load, temperature, and lubrication are not completely uniform. ANOVA was performed on the S/N ratios to evaluate differences among the four component groups, with the engine treated as the replicate unit.

#### 2.4. Service-life prediction model

For each variable, the engine-level mean was linearly regressed against operating hours.

$$\bar{x}(t) = \beta_0 + \beta_1 t + \varepsilon \quad (4)$$

The threshold life  $T$  was determined from the intersection of the regression line and the technical limit.

$$T = (x_{lim} - \beta_0) / \beta_1 \quad (5)$$

Goodness of fit was assessed using  $R^2$ , a slope test, and residual plots. The 95% confidence interval for  $T$  was determined by bootstrapping 10,000 engine samples with a fixed random seed. System life was calculated according to the weakest-link principle.

$$T_{system} = \min(T_{R1}, T_{R2}, T_{R3}, T_{main\ journal}, T_{crankpin}, T_{liner}) \quad (6)$$

### 3. RESULTS AND DISCUSSION

#### 3.1. Sample characteristics and wear trends

The sample comprised 18 engines with operating times ranging from 10,651 to 20,991 h and a mean of 14,986 h. Figure 1 presents the mean measurement data, regression lines, and technical limits. The piston-ring types and cylinder liner exhibited very strong, nearly linear relationships with operating hours ( $R^2 = 0.983$ -1.000). The main journals also showed a clear trend ( $R^2 = 0.968$ ), whereas the crankpins showed greater scatter ( $R^2 = 0.685$ ).

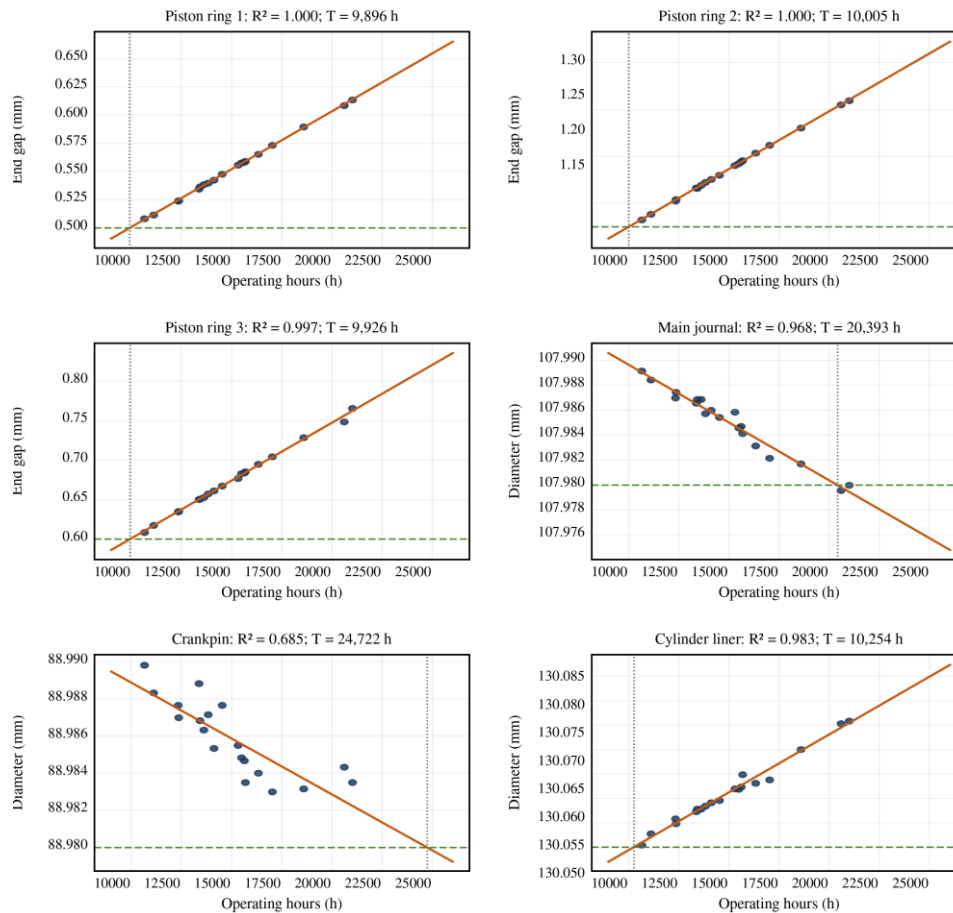


Figure 1: Relationships among mean dimensions, operating hours, and technical limits.

### 3.2. Regression results and threshold-crossing life

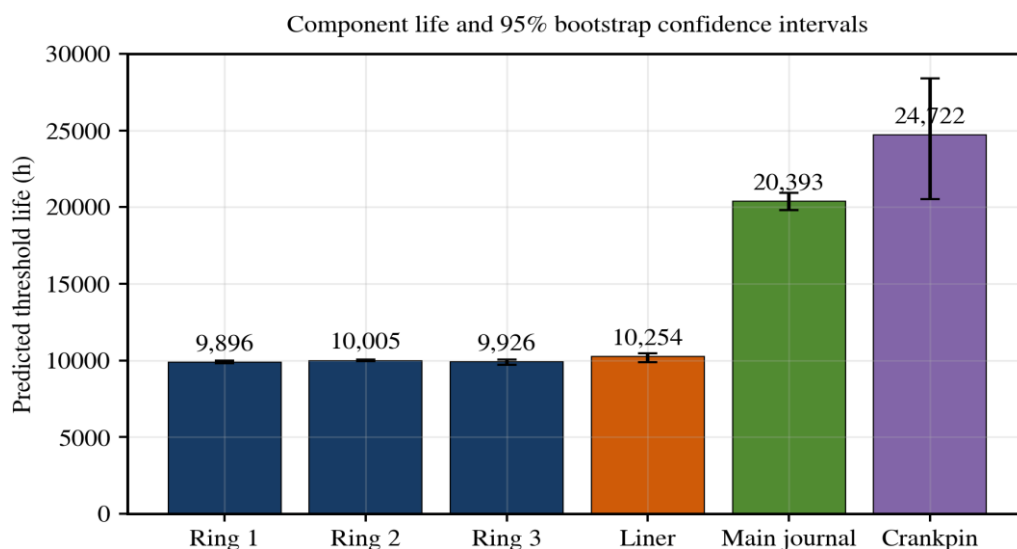
Table 2: Regression models and predicted threshold lives.

| Component      | $\beta_1$ (mm/h) | $R^2$ | p        | T (h)  | 95% CI (h)    |
|----------------|------------------|-------|----------|--------|---------------|
| Piston ring 1  | 1.023e-05        | 1.000 | 1.61e-29 | 9,896  | 9,833-9,976   |
| Piston ring 2  | 1.233e-05        | 1.000 | 1.25e-31 | 10,005 | 9,958-10,064  |
| Piston ring 3  | 1.463e-05        | 0.997 | 5.74e-23 | 9,926  | 9,727-10,063  |
| Main journal   | -9.274e-07       | 0.968 | 3.55e-14 | 20,393 | 19,801-20,918 |
| Crankpin       | -6.027e-07       | 0.685 | 1.22e-05 | 24,722 | 20,523-28,396 |
| Cylinder liner | 2.372e-06        | 0.983 | 1.79e-16 | 10,254 | 9,889-10,468  |

Table 3: Regression equations for reproducing the analysis.

| Variable       | Equation (t in hours)                    | $R^2$  | Limit    |
|----------------|------------------------------------------|--------|----------|
| Piston ring 1  | $\bar{x} = 0.39871786 + 0.0000102342t$   | 0.9995 | 0.5000   |
| Piston ring 2  | $\bar{x} = 1.00169229 + 0.0000123250t$   | 0.9997 | 1.1250   |
| Piston ring 3  | $\bar{x} = 0.45475639 + 0.0000146323t$   | 0.9971 | 0.6000   |
| Main journal   | $\bar{x} = 107.99891350 - 0.0000009274t$ | 0.9683 | 107.9800 |
| Crankpin       | $\bar{x} = 88.99490094 - 0.0000006027t$  | 0.6851 | 88.9800  |
| Cylinder liner | $\bar{x} = 130.02567364 + 0.0000023723t$ | 0.9829 | 130.0500 |

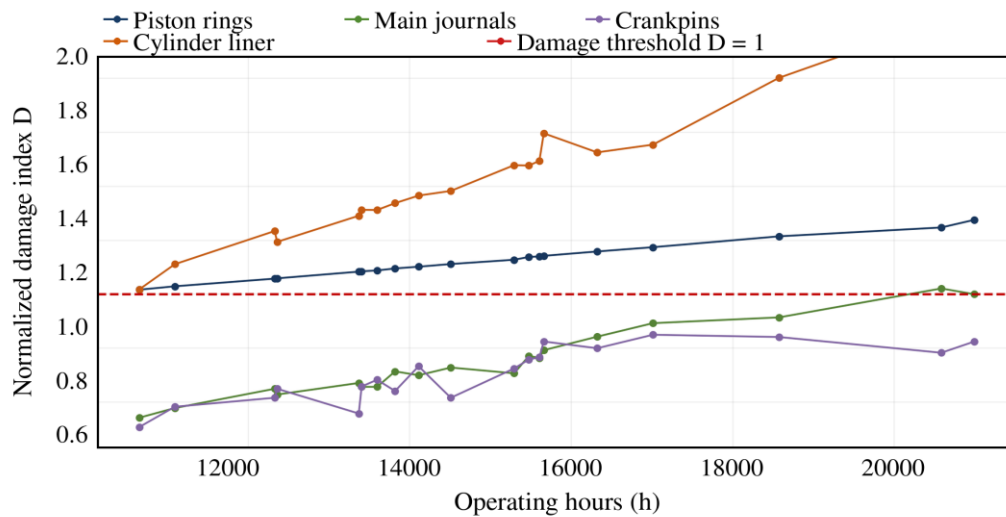
The three piston-ring types reached their limits at approximately 9,896-10,005 h, and the cylinder liner reached its limit at 10,254 h. In contrast, the main journals and crankpins reached their limits at approximately 20,393 and 24,722 h, respectively. Thus, if all components are installed new at the same time, the overhaul interval is governed first by the piston rings and then by the cylinder liner. This result agrees with the inspection-sheet conclusions: most piston rings and liners required replacement, whereas many crankshafts remained serviceable.



**Figure 2: Predicted threshold lives of the components.**

The system life calculated from Eq. (6) is 9,896 h and is governed by piston ring 1; piston ring 3 has the lowest bootstrap lower bound of 9,727 h. Because of measurement error, load differences, and the linearity assumption, 9,896 h should not be treated as an absolute limit. A range of 9,500-10,000 h is more appropriate for proactive inspection; overhaul decisions should also consider oil analysis, compression pressure, crankcase blow-by, oil consumption, and load history.

### 3.3. Normalized damage index



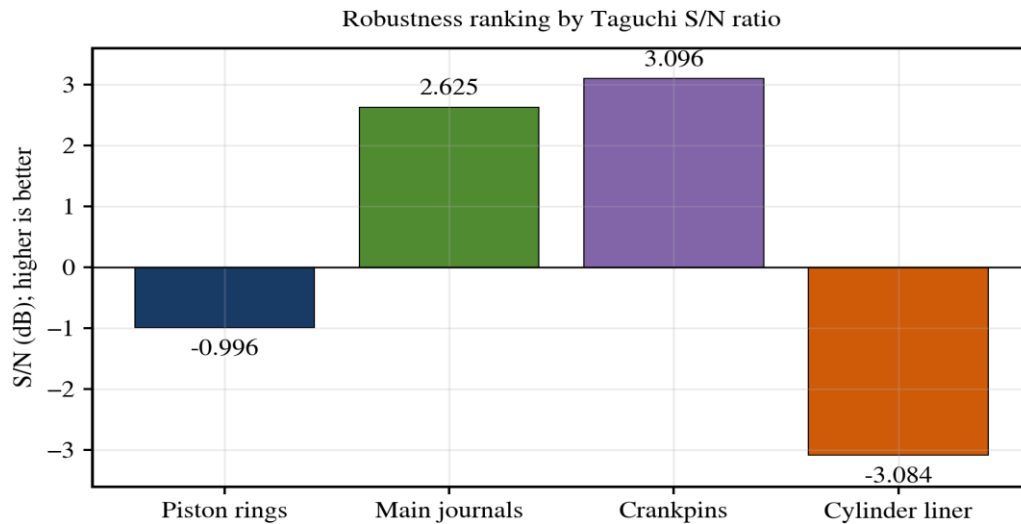
**Figure 3: Variation in the normalized damage index with operating hours.**

At the overall sample mean,  $D$  was 1.449 for the cylinder liner and 1.124 for the piston rings, indicating that both groups had exceeded their limits. The mean  $D$  values for the main journals and crankpins were 0.749 and 0.707, respectively, indicating remaining wear allowance. The data also show that above 18,000 h, liner wear may exceed approximately twice the allowable amount, whereas the main journals are only approaching the threshold.

### 3.4. Taguchi S/N analysis results

**Table 4: Ranking of component groups by Taguchi S/N ratio.**

| Component group | Mean D | Mean S/N (dB) | Robustness rank |
|-----------------|--------|---------------|-----------------|
| Piston rings    | 1.124  | -0.996        | 3               |
| Main journals   | 0.749  | 2.625         | 2               |
| Crankpins       | 0.707  | 3.096         | 1               |
| Cylinder liners | 1.449  | -3.084        | 4               |



**Figure 4: Mean S/N ratio by component group.**

One-way ANOVA of the S/N ratios yielded  $F = 99.008$  and  $p = 1.74e-25$ ; between-group variation accounted for 80.5% of the total described variation. The crankpins had the highest S/N ratio (3.096 dB), followed by the main journals (2.625 dB), piston rings (-0.996 dB), and cylinder liner (-3.084 dB). Because the S/N ratio is to be maximized, the cylinder liner was the least robust group, whereas the crankpins were the most stable within the data domain.

The S/N and regression results do not give exactly the same ranking: piston ring 1 governs the threshold-crossing time, whereas the cylinder liner has the lowest mean S/N ratio. This is not contradictory. Threshold-crossing life reflects the time at which the mean reaches the limit; S/N additionally penalizes both squared magnitude and variability among measurement locations. The cylinder liner therefore exhibits a greater nonuniformity risk after the threshold has been exceeded.

### 3.5. Maintenance and repair prediction

**Table 5: Recommendations by operating-hour range for fleets under conditions similar to the sample.**

| Operating-hour range | Management level            | Main actions                                                                                                  |
|----------------------|-----------------------------|---------------------------------------------------------------------------------------------------------------|
| < 8,000 h            | Routine monitoring          | Oil analysis; oil consumption; crankcase blow-by; temperature; compression pressure.                          |
| 8,000-9,500 h        | Increase frequency          | Shorten the oil-sampling interval; check blow-by; inspect cylinders with a borescope if symptoms are present. |
| 9,500-10,000 h       | Proactive inspection window | Measure compression/cylinder leakage; prepare piston rings and liners; consider planned                       |

|                 |                                        |                                                                                                         |
|-----------------|----------------------------------------|---------------------------------------------------------------------------------------------------------|
|                 |                                        | shutdown.                                                                                               |
| 10,000-20,000 h | Post-threshold piston-group management | Prioritize piston-ring/liner replacement; measure the crankshaft before deciding on undersize grinding. |
| $\geq 20,000$ h | Increased crankshaft risk              | Inspect 100% of main journals/crankpins for ovality, taper, cracks, and alignment.                      |

These recommendations apply only to populations with fuel, lubricating oil, load, environment, and repair histories similar to those of the sample. They should not be interpreted as replacing manufacturer limits or workshop inspection procedures. In particular, crankshaft undersize grinding must be based on multidirectional dimensional measurements, ovality/taper, nondestructive testing, and allowable undersize bearing-shell grades.

#### 4. Reliability Checks and Limitations

First, the study uses cross-sectional data: each engine was observed only once, at teardown. Therefore, the slope reflects differences among engines more strongly than the longitudinal wear trajectory of an individual engine.

Second, the paper does not account for mean load, power-utilization factor, ambient temperature, oil type, oil-change interval, dust concentration, overheating history, or previous repairs. These variables may act as confounders.

Third, the piston-ring limits in the inspection sheets were recorded as nominal dimensions  $\pm$  tolerances; the upper bounds were used as thresholds. For the cylinder liner, the upper bound of 130.050 mm was used as the wear limit.

Fourth, the Taguchi S/N ratio was applied to repeated measurement locations rather than to an orthogonal array of control factors. The results therefore rank robustness among component groups but do not establish the causes of wear. Future research will use an L9 or L18 array with factors such as load level, oil-change interval, dust level, coolant temperature, and oil type; operating conditions/cylinders may be arranged as noise factors. These factors will represent component wear and service life more accurately.

#### 5. CONCLUSIONS

- The wear variables were statistically significantly related to operating hours.  $R^2$  was 0.997-1.000 for the piston rings, 0.983 for the cylinder liner, 0.968 for the main journals, and 0.685 for the crankpins.

- The threshold lives of the three piston-ring types were 9,896-10,005 h; the cylinder-liner life was approximately 10,254 h; and the main-journal and crankpin lives were approximately 20,393 and 24,722 h, respectively.
- Under the Taguchi “smaller-is-better” criterion, the cylinder liner had the lowest S/N ratio (-3.084 dB), followed by the piston rings (-0.996 dB); these are the two groups governing the overhaul interval.
- System life was estimated at approximately 9,900 h. A proactive inspection interval of 9,500-10,000 h is recommended under conditions similar to those represented by the sample, combined with condition diagnosis before an overhaul decision.

## REFERENCES

1. PHUTHAI CAT Corporation, “Appendix 1 - Statistical data for basic C9 engine components,” inspection records for 20 engines, document supplied by the authors, 2026.
2. Caterpillar Inc., “D6R2 Dozers - Key specifications: Cat C9 engine,” [https://www.cat.com/en\\_AU/products/new/equipment/dozers/medium-dozers/112920.html](https://www.cat.com/en_AU/products/new/equipment/dozers/medium-dozers/112920.html), accessed Aug. 14, 2026.
3. Minitab, LLC, “What is the signal-to-noise ratio in a Taguchi design?,” <https://support.minitab.com/en-us/minitab/help-and-how-to/statistical-modeling/doe/supporting-topics/taguchi-designs/what-is-the-signal-to-noise-ratio/>, accessed Aug. 14, 2026.
4. Minitab, LLC, “Methods and formulas for Analyze Taguchi Design,” <https://support.minitab.com/en-us/minitab/help-and-how-to/statistical-modeling/doe/how-to/taguchi/analyze-taguchi-design/methods-and-formulas/methods-and-formulas/>, accessed Aug. 14, 2026.
5. Minitab, LLC, “Steps for conducting a Taguchi designed experiment,” <https://support.minitab.com/en-us/minitab/help-and-how-to/statistical-modeling/doe/supporting-topics/taguchi-designs/steps-for-conducting-a-taguchi-designed-experiment/>, accessed Aug. 14, 2026.
6. G. Taguchi, *Introduction to Quality Engineering: Designing Quality into Products and Processes*. Tokyo: Asian Productivity Organization, 1986.
7. M. S. Phadke, *Quality Engineering Using Robust Design*. Englewood Cliffs, NJ: Prentice Hall, 1989.
8. D. C. Montgomery, *Design and Analysis of Experiments*, 10th ed. Hoboken, NJ: Wiley, 2020.

9. C. M. Taylor, "Automobile engine tribology - design considerations for efficiency and durability," *Wear*, 1998; 221(1): 1-8, doi: 10.1016/S0043-1648(98)00253-1.
10. M. Priest, D. Dowson, and C. M. Taylor, "Predictive wear modelling of lubricated piston rings in a diesel engine," *Wear*, 1999; 231(1): 89-101, doi:10.1016/S0043-1648(99)00125-8.
11. M. Priest and C. M. Taylor, "Automobile engine tribology - approaching the surface," *Wear*, 2000; 241(2): 193-203, doi:10.1016/S0043-1648(00)00375-6.
12. P. Andersson, J. Tamminen, and C.-E. Sandström, *Piston Ring Tribology: A Literature Survey*. VTT Tiedotteita - Research Notes 2178, Espoo: VTT Technical Research Centre of Finland, 2002.
13. S. C. Tung and M. L. McMillan, "Automotive tribology overview of current advances and challenges for the future," *Tribology International*, 2004; 37(7): 517-536, doi: 10.1016/j.triboint.2004.01.013.
14. J. J. Truhan, J. Qu, and P. J. Blau, "The effect of lubricating oil condition on the friction and wear of piston ring and cylinder liner materials in a reciprocating bench test," *Wear*, 2005; 259: 1048-1055.
15. C. Delprete and A. Razavykia, "Piston ring-liner lubrication and tribological performance evaluation: A review," *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 2018; 232(2): 193-209, doi:10.1177/1350650117706269.
16. N. D. S. A. Santos, V. R. Roso, and M. T. C. Faria, "Review of engine journal bearing tribology in start-stop applications," *Engineering Failure Analysis*, 2020; 108: art. 104344, doi: 10.1016/j.engfailanal.2019.104344.
17. G. Koszałka, "Predicting the durability of the piston-rings-cylinder assembly of a diesel engine using a piston ring pack model," *Eksplotacja i Niezawodność - Maintenance and Reliability*, 2011; 3: 40-44.
18. Z. Chmielewski, "Cylinder liner wear as a function of selected physicochemical indicators of engine oil," *Combustion Engines*, 2021; 187(4): 60-64, doi: 10.19206/CE-141878.
19. A. K. S. Jardine, D. Lin, and D. Banjevic, "A review on machinery diagnostics and prognostics implementing condition-based maintenance," *Mechanical Systems and Signal Processing*, 2006; 20(7): 1483-1510, doi:10.1016/j.ymssp.2005.09.012.

20. X.-S. Si, W. Wang, C.-H. Hu, and D.-H. Zhou, "Remaining useful life estimation - A review on the statistical data driven approaches," *European Journal of Operational Research*, 2011; 213(1): 1-14, doi: 10.1016/j.ejor.2010.11.018.
21. T. Vikky, N. Aisyah, Sugiyanto, and B. D. Prihadianto, "Failure Analysis of Caterpillar C9 Engine in Hydraulic Drill Unit Due to Fuel Dilution Through Scheduled Oil Sampling (SOS) Data Evaluation and Root Cause Analysis (RCA) Approach," *Journal of Failure Analysis and Prevention*, 2026; 26: 26-40, , doi:10.1007/s11668-026-02376-y.
22. Caterpillar Inc., *Operation and Maintenance Manual: C9 Marine Engine*, publication SEBU7719-12, July 2009.
23. M. Kapsiz, M. Durat, and F. Ficici, "Friction and wear studies between cylinder liner and piston ring pair using Taguchi design method," *Advances in Engineering Software*, 2011; 42(8): 595-603, doi: 10.1016/j.advengsoft.2011.04.008.