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Advanced Failure Analysis of Hydraulic Systems in Volvo Articulated Haulers at Coal Mining Sites: Investigating Steering Cylinder Seal Failure and Brake Accumulator Degradation

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Abstract

The condition of hydraulic systems is critical to the productivity and safety of heavy equipment in coal mining operations. This study analyzes Hydraulic Systems in Volvo Articulated Haulers at coal mining sites in South Sumatra, Indonesia. Progressive failure of the steering cylinder seal on a Volvo ART A40F, manifested as hydraulic oil leakage and a drop in measured steering pressure from the standard 250 bar to 203 bar; and degradation of the brake accumulator unit on a Volvo ART A40G, causing a low brake pressure warning and a drop in pressure from the normal range of 145-245 bar to 118 bar. Both failures were caused by wear-induced mechanisms exacerbated by the harsh mining environment fine particle contamination, high thermal cycling, and continuous duty cycles. For the A40F, post-repair inspection revealed that the scraper / dust seal had thinned from 7.8 mm (new) to 6.1 mm, allowing the ingress of particles that accelerated piston rod seal wear. For the A40G, three of the seven accumulators had lost their hydraulic oil connections, reducing nitrogen precharge and eliminating pressure reserve capacity. Corrective interventions of seal kit replacement on the A40F and accumulator replacement on the A40G restored operating pressures to 250 bar and 247 bar, respectively. Maintenance records from 2024-2026 revealed that accumulator failures occurred repeatedly each year per unit, indicating inadequate inspection intervals. These findings support a transition to a condition-based maintenance strategy for both system types.

Keywords: Volvo Articulated Hauler; Steering Cylinder Seal; Brake Accumulator; Coal Mining Maintenance.

1. Introduction

The coal mining industry relies heavily on the smooth operation of heavy material handling equipment particularly off-road articulated trailers designed for operation in rugged and uneven terrain [1]. One of the units widely used in Indonesian coal mines is the Volvo Articulated Hauler (ART) A40F and A40G series, thanks to their large lifting capacity, all-wheel drive, and reliable electronic control systems [2]. Despite their robust design, these vehicles operate under extreme conditions, placing high loads on the hydraulic system. Continuous vibration, high hydraulic pressure, temperature changes, and fine particle contamination can accelerate the deterioration of hydraulic seals and accumulators [3]. If these components fail, steering response and braking performance will decrease, requiring the unit to be shut down for repair, ultimately impacting mine productivity [4], [5]. Extensive research has been conducted on heavy equipment hydraulic system failures, particularly regarding piston seal wear [6], [7], accumulator failure [8], and the effect of fluid contamination on component lifespan [9]. However, field studies examining simultaneous steering and braking system failures within a single fleet and operating environment are still very limited. In fact, research like this is important to help maintenance engineers determine repair priorities amidst limited workshop capacity [10].

Articulated haulers achieve high off-road performance through a hydraulic system that supports steering, braking, suspension damping, and body dumping functions simultaneously [11]. In Volvo ART A40F and A40G units, the hydraulic circuit operates as a closed-loop system where a variable-displacement pump supplies pressurized fluid to control valves, actuators, and accumulators based on Pascal's Law [12]. The ART A40F steering system uses an articulated-frame mechanism controlled by two hydraulic cylinders positioned between the front and rear frames, allowing a smaller turning radius that is well suited for narrow haul roads in mining areas [13]. Meanwhile, the A40G braking system is managed electronically through an ECU that monitors hydraulic pressure using dedicated sensors. For safety, the system activates a warning alarm when accumulator pressure falls below 145 bar and automatically engages the parking brake below 140 bar [14]. Hydraulic seals are elastomeric components that maintain pressure between moving surfaces and the external environment in hydraulic systems [15]. In the double-acting steering cylinder of the Volvo ART A40F, the seal assembly includes piston rod seals, scrapers, guide rings, O-rings, and back-up rings, each serving to prevent leakage, maintain alignment, and block contaminants [6]. A major cause of hydraulic seal failure is abrasive wear, which occurs when fine particles bypass the scraper and damage the seal surface [16]. Research has shown that seal wear increases significantly when contamination particles exceed 10 μm, a condition commonly found in dusty mining environments [3]. High operating temperatures further accelerate degradation by reducing the elasticity of seal materials such as polyurethane and nitrile rubber, making them less effective at preventing leakage [17]. This study, the scraper thickness decreased from 7.8 mm to 6.1 mm, reducing its ability to block contaminants. As a result, abrasive particles entered the cylinder, accelerated seal wear, and created leakage paths for pressurized fluid [18]. Previous hydraulic seal life testing also reported that contamination-related wear can shorten seal service life by 30-60% compared to clean operating conditions [9].

A hydraulic accumulator is a hydro-pneumatic component used to store energy, stabilize pressure, and supply additional hydraulic flow when needed [19]. In the Volvo ART A40G brake system, bladder-type accumulators use nitrogen gas as pre-charge pressure. During operation, hydraulic fluid compresses the nitrogen inside the bladder, and the stored energy is released back into the system when extra flow is required, such as during emergency braking [20]. Accumulator failures generally occur due to nitrogen leakage, bladder rupture, or damage to connection ports, all of which reduce the system's ability to maintain stable pressure. Low pre-charge pressure can also increase pressure surges and accelerate wear on hydraulic components while reducing braking performance [8]. Previous studies reported that accumulator service life in mining operations typically ranges from 12 to 24 months [21]. In the maintenance data showed a similar failure pattern occurring approximately every 12 months, indicating that the current inspection interval may not be sufficient to detect early accumulator degradation before failure occurs. Mining activities are carried out on unpaved haul roads with steep gradients, loose gravel, and seasonal waterlogging, creating heavy demands on the steering and braking systems of haul trucks [22]. The maintenance workshop is responsible for both preventive and corrective maintenance of all heavy equipment units. For articulated haulers, maintenance activities include routine service every 250 operating hours, failure repairs reported by operators, and technical support from Volvo's authorized service partner, PT. Indotruck Utama.

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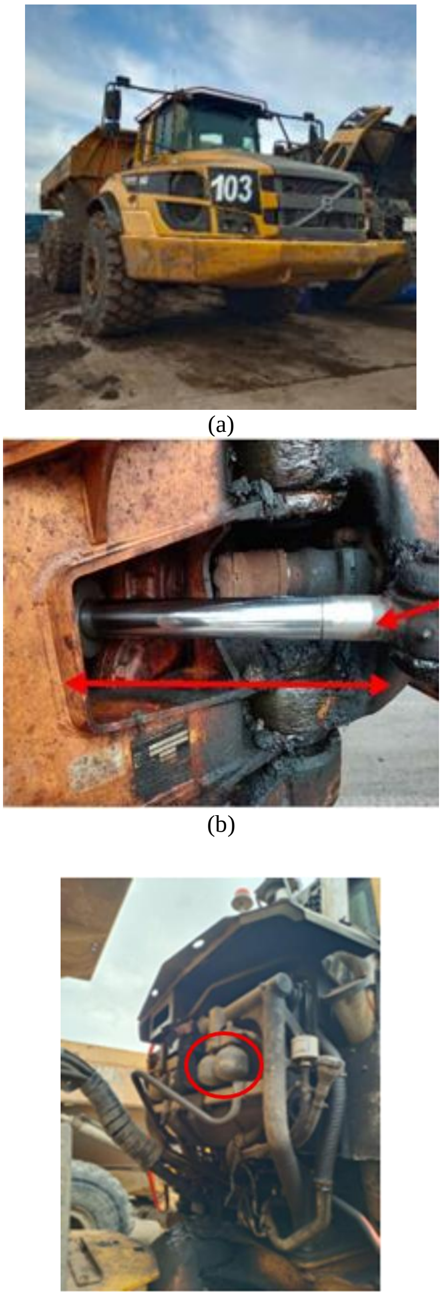
2. Materials and Methods

This study investigated two articulated hauler units operating a Volvo ART A40F (SN 11001-99999) with a hydraulic steering system operating at a maximum pressure of 250 bar (25.0 ± 0.4 MPa) [23], and a Volvo ART A40G equipped with an electronically controlled braking system and seven hydraulic accumulators [14], as shown in Figure 1



(a)

(b)

(c)

Figure 1. Volvo Articulated Hauler a). A40F (SN 11001-99999), b). Steering Cylinder Seal, c). Brake Accumulator

The units operated continuously in three daily shifts, making hydraulic system reliability critical for maintaining fleet productivity. Data collection was conducted through direct observation, hydraulic pressure measurements, component inspections, maintenance record analysis, and corrective maintenance procedures. Investigation in the steering system pressure was measured using a Volvo digital pressure gauge at maximum steering lock and 1200 rpm engine speed, while hydraulic oil levels and seal dimensions were inspected after component removal. The steering seal replacement procedure followed Volvo standards, including piston rod removal, seal disassembly, component cleaning, installation of a new seal kit, system reassembly, and hydraulic oil refilling to the specified 245 liter capacity [23]. Investigation in the brake system pressure was monitored through the ECU-based operator display, and all accumulators were visually inspected to identify leakage, physical damage, and connection issues. The accumulator replacement procedure included brake system depressurization, removal of damaged accumulators, installation of new units with verified nitrogen pre-charge pressure, and functional verification through pressure monitoring [14]. Maintenance records from 2024-2026 were also reviewed to evaluate recurring accumulator failures across the fleet. All inspection and measurement results were compared with Volvo CE service manual specifications provided by PT. Indotruck Utama.

3. Results and Discussion

3.1 Volvo ART A40F

The investigation of the Volvo ART A40F steering system began after operators reported that the steering had become heavy and less responsive over several operating shifts. Visual inspection identified active hydraulic oil leakage from the left steering cylinder, indicated by oil contamination around the cylinder body, articulation frame area, and oil accumulation beneath the unit. Pressure testing showed that the steering system operated at only 203 bar at full steering lock and 1200 rpm, which was below the Volvo standard specification of 250 ± 4 bar [23], pressure drop can be shown in the Figure 2. This condition indicated a pressure reduction of approximately 19% from the normal operating value.

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Figure 2. Hydraulic Pressure Measurement in Steering System

Based on the analysis of the standard specification data on the Volvo A40F, there is a significant decrease in pressure, the normal standard shown in the Table 1 and the results of the measurement analysis are explained in the following Figure 3.

Table 1. Steering Pressure Standard Specification Volvo A40F SN 11001-99999

No.	Parameter	MPa	bar	psi	Pressure check conection
1	Steering pressure (Left)	25 ±0.4	250 ±4	3625 ±58	M7
2	Anti-cavitation pressure (MTRV1)	1.8	18	261	—
3	Steering pressure (Right)	25 ±0.4	250 ±4	3625 ±58	M8
4	Anti-cavitation pressure (MTRV1)	1.8	18	261	(plugged)

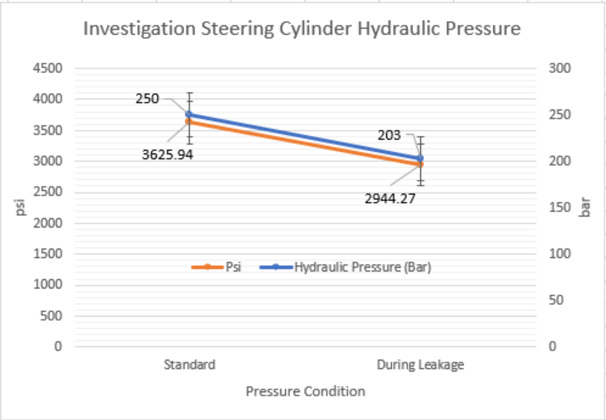


Figure 3. Investigation Steering Cylinder Hydraulic Pressure

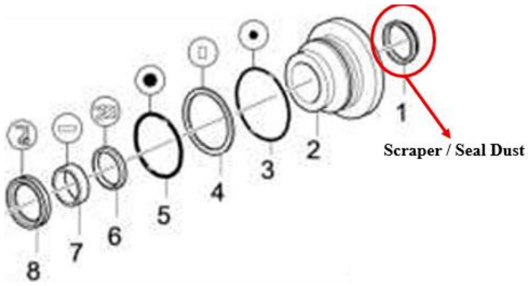
In addition, the hydraulic oil level in the reservoir was measured at around 203 liters compared to the standard capacity of 245 liters, confirming a loss of about 42 liters of hydraulic fluid caused by the seal leakage as shown in the Figure 4.

Figure 4. Hydraulic Oil Level

Table 2. Oil Level Standard Specification Volvo A40F SN 11001-99999

No.	Capacities	When changing
1	Engine incl. filter, A35F/A35F FS	50 litres (13.2 US gal)
2	Engine incl. filter, A40F/A40F FS	54 litres (14.3 US gal)
3	Cooling system	75 litres (19.8 US gal)
4	Transmission incl. filter	40 litres (10.6 US gal)
5	Drop box	9 litres (2.4 US gal)
6	Front axle	26 litres (6.9 US gal)
7	Front bogie axle	30 litres (7.9 US gal)
8	Rear bogie axle	26 litres (6.9 US gal)
9	**Hydraulic oil tank, A35F/A40F**	**245 litres (64.7 US gal)**
10	Hydraulic oil tank, A35F FS/A40F FS	262 litres (69.2 US gal)
11	Brake cooling oil	24 litres (6.3 US gal)
12	Air pump oil [1][10]	45 millilitres (0.012 US gal)
13	Automatic greasing (optional equipment)	2 litres (0.5 US gal)
14	Oil-bath air cleaner (optional equipment), A35F/A35F FS	9.1 litres (2.4 US gal)
15	Oil-bath air cleaner (optional equipment), A40F/A40F FS	18.2 litres (4.8 US gal)

Inspection after disassembly revealed two main failure patterns in the steering cylinder seal kit. The primary piston rod seals showed circumferential wear and material loss on the dynamic lip surface, indicating abrasive wear caused by continuous contact between the seal and piston rod, shown in the Figure 5. This failure pattern is consistent with previous studies on hydraulic seal degradation under contaminated operating conditions [24].



(a)

(b)

Figure 5. Scraper /Seal Dust, a). Desain, b). Condition

The most significant finding was observed on the scraper component. Measurement showed that the scraper thickness had decreased from 7.8 mm to 6.1 mm, representing a 22% reduction in material, shown in the Figure 6. Since the scraper functions to remove dust and particles from the piston rod surface before entering the cylinder, this reduction weakened its sealing effectiveness and allowed fine contaminants from the mining environment to enter the seal area, accelerating wear and leakage [18], [25].

(a) (b)

Figure 6. Comparation Scraper/Seal Dust, a). New, b). Old

Investigation based on pressure testing showed that the steering system operated at only 203 bar at full steering lock and 1200 rpm, which was below the Volvo standard specification of 250 ± 4 bar and In addition, the hydraulic oil level in the reservoir was measured at around 203 liters compared to the standard capacity of 245 liters. investigation based on Standard Specification Volvo A40F SN 11001-99999, shows the need for component improvements based on research data on scraper / seal dust which has experienced a reduction in dimensions from standard size of 7.8 mm. Scraper / seal dust repair is shown in the Figure 7, and the comparative measurement results are shown in the graphic Figure 8.

(a) (b) (c)

Figure 7. Repair Volvo Articulated Hauler a). Piston Rod Guide, b). Scraper/Seal Dust, c). Installation

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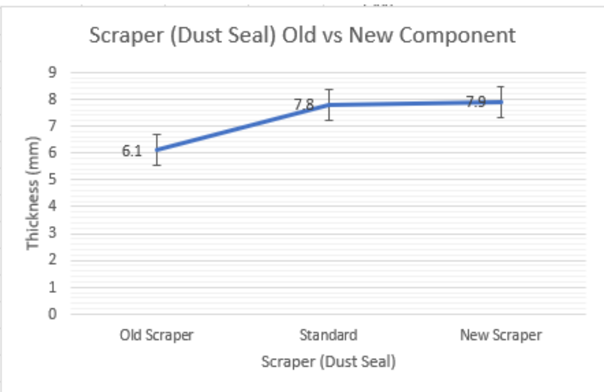

Figure 8. Scraper (dust seal) thickness comparison: old component (6.1 mm), standard (7.8) and new replacement (7.9 mm)

The observed failure sequence beginning with scraper wear, followed by contamination ingress and accelerated seal abrasion aligns with the multi-stage hydraulic seal degradation model reported by Shanbhag et al. [18]. Previous studies also showed that severe seal wear can develop long before major leakage becomes visible, highlighting the importance of early maintenance methods such as oil contamination analysis and acoustic emission monitoring [26]. After replacement of the seal kit, restoration of the hydraulic oil level to 243 liters, and system reassembly, the steering pressure returned to 250 bar, matching the Volvo standard specification, Analysis of hydraulic oil level data after replacing the scraper/seal dust is shown in the Figure 9. Operators also reported improved steering performance, with lighter steering effort and more stable directional control during turning operations on haul roads [17].

(a) (b)

Figure 9. After condition a). Oil Level Hydraulic, b). Pressure

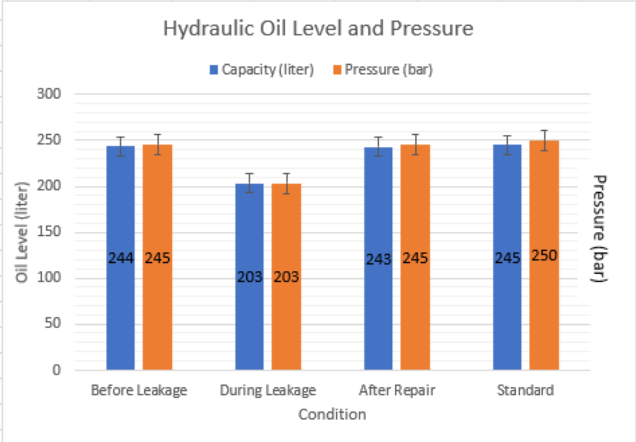

Figure 10. Hydraulic oil volume changes during the steering seal failure event. Leakage reduced the reservoir level from a pre-failure baseline of 244 liters to 203 liters-a 41-liter deficit that directly impaired the system's ability to maintain design pressure

3.2 Volvo ART A40G

Investigation in the Brake Accumulator Degradation on the Volvo Articulated Hauler (ART) type A40G, the occurrence of failure on the Volvo ART A40G was detected after investigation red low-pressure warning alarm accompanied by automatic parking brake activation. Monitor data showed that the front accumulator pressure had dropped to 118 bar, below both the warning limit of 145 bar and the automatic parking brake threshold of 140 bar [14], shown in Table 3 and Figure 11. As a result, the unit could not be operated and required immediate maintenance intervention. Initial inspections of the hydraulic pump, control valves, solenoids, and hydraulic lines showed no signs of leakage or malfunction. After these components were ruled out, the investigation identified the accumulator bank as the main cause of the pressure loss. This troubleshooting sequence follows standard hydraulic brake diagnostic procedures commonly applied in heavy equipment maintenance [27].

Table 3. Specification Normal Brake Pressure

No.	Parameter	Specification
1	Normal brake pressure	145 bar-245 bar ±5
2	Parking brake emergency	<140 bar
3	Brake charging activation	195 bar
4	Hydraulic Oil	Super 68

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Table 4. Low-Pressure Warning Alarm

No.	Parameter	Value 1	Value 2
1	Warning, low pressure accumulator	<14.5	<145
2	Warning, high pressure accumulator	>27.5	>275
3	Parking brake, emergency application	<14.0	<140
Note : Both front and rear circuit shall be below the limit value			

Figure 11. Actual Measurement Results on Monitor Unit

After the brake system was fully depressurized, with monitor readings showing 2 bar at the front and 1 bar at the rear, inspection of the seven accumulators revealed that three units had damaged hydraulic oil connection ports. This damage prevented hydraulic fluid from entering the accumulator chamber, causing the affected accumulators to lose their pressure storage capability. The remaining four accumulators were visually in good condition with intact oil connections. The loss of three out of seven accumulators significantly reduced the brake system's pressure reserve capacity. In the ART A40G, accumulators play an important role in maintaining stable braking pressure during high-demand conditions and when pump supply temporarily decreases [28], as shown in the Figure 12. Previous studies showed that a 43% reduction in accumulator capacity can increase low-pressure warning events by 35-55% during intensive braking operations [19].

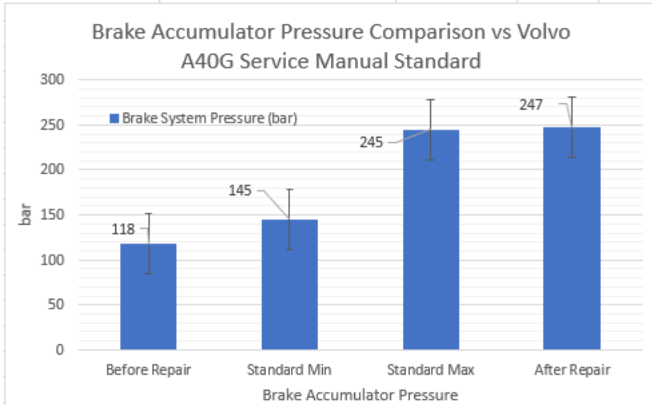

Figure 12. Brake accumulator pressure compared with Volvo A40G service manual thresholds

Parameters were identified and synthesized through a comprehensive evaluation of field observations, operational data, and relevant technical literature. The following parameters provide an overview of the critical factors contributing to accumulator performance degradation, including operational conditions, material characteristics, and system-related variables. By integrating practical field evidence with established theoretical and experimental findings from previous studies, this compilation offers a clearer understanding of the dominant degradation mechanisms affecting accumulator reliability and service life. As shown in the following Table 5.

Table 5. Parameters Influencing Accumulator Performance Degradation

No.	Parameter	Effect on Accumulator Performance
1	Nitrogen pre-charge pressure	Pressure drop causes inability to store energy; system pressure falls below safe limits
2	System hydraulic pressure	Too low: insufficient reserve; too high: damages bladder or internal seals
3	Accumulator duty cycle	High frequency charge/discharge cycles accelerate material fatigue
4	Hydraulic fluid condition	Contaminated fluid degrades internal components and connection seals
5	Operating temperature	Elevated temperatures accelerate seal degradation and nitrogen leakage
6	Service age	Long-term use without inspection leads to gradual performance decline
7	System leakage	Leakage at connections reduces reserve pressure, triggers low-pressure warnings
8	Maintenance interval	Infrequent inspections allow undetected faults to escalate

After the three damaged accumulators were replaced with new units containing the correct \nitrogen pre-charge pressure, the brake system was recharged and tested. The front circuit pressure increased to 247 bar, which was within the normal operating specification of 245 ± 5 bar. The low brake pressure warning changed from YES to NO, and the parking brake was released successfully, allowing the unit to return to operation. These results confirmed that the failed accumulators were the main cause of the brake system failure [17]. A comparison of key performance indicators for Steering Cylinder Seal Failure and Brake Accumulator Degradation allows for a clearer evaluation of the magnitude of the failure, operational impact, and repair effectiveness. The summarized data highlights the differences in system condition before and after corrective action, allowing for a direct assessment of the severity of the degradation and the extent of performance recovery achieved through the repair process. This comparison also facilitates a more comprehensive understanding of the factors affecting accumulator reliability and overall system performance, as shown in the Table 6.

Table 6. Combined Hydraulic System Performance Parameters: Steering (A40F) and Brake (A40G)

No.	Parameter	Steering System (A40F)	Brake System (A40G)	Standard
1	Pressure before repair (bar)	203	118	145–250
2	Pressure after repair (bar)	250	247	145–250
3	Oil volume before repair (L)	203	N/A	245
4	Oil volume after repair (L)	243	N/A	245
5	Damaged components	2 piston rod seals	3 accumulators	Intact
6	Scraper thickness – old (mm)	6.1	N/A	≥7.0
7	Scraper thickness – new (mm)	7.8	N/A	≥7.0

Both case studies showed that component wear combined with harsh mining conditions accelerated hydraulic system degradation. In the steering system, worn scrapers allowed contaminants to enter and accelerate seal abrasion, while in the brake system, continuous pressure cycling and limited inspection access contributed to accumulator connection failure. These failures occurred earlier than the expected component service life, indicating that standard time-based maintenance intervals may not be sufficient under severe mining operating conditions [10], [18]. Historical maintenance data from 2024-2026 also showed that five hauler units experienced low brake pressure failures caused by damaged accumulators within a 26 month period. The average failure interval was approximately 12 months per unit, which is shorter than the normal maintenance cycle for accumulator components [21].

Table 7. Historical Low Brake Pressure Events Attributed to Accumulator Failure (2024–2026)

No.	Unit	Problem	Action	Date
1	L-109	Low brake pressure	Replace accumulator	12 Apr 2024
2	L-108	Low brake pressure	Replace accumulator	25 Apr 2024
3	L-107	Low brake	Replace	03 Oct

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		pressure	accumulator	2024
4	L-104	Low brake pressure	Replace accumulator	22 Oct 2024
5	L-103	Low brake pressure	Replace accumulator	29 Dec 2024
6	L-109	Low brake pressure	Replace accumulator	26 Apr 2025
7	L-108	Low brake pressure	Replace accumulator	13 Apr 2025
8	L-107	Low brake pressure	Replace accumulator	01 Sep 2025
9	L-104	Low brake pressure	Replace accumulator	02 Sep 2025
10	L-103	Low brake pressure	Replace accumulator	21 Jan 2026

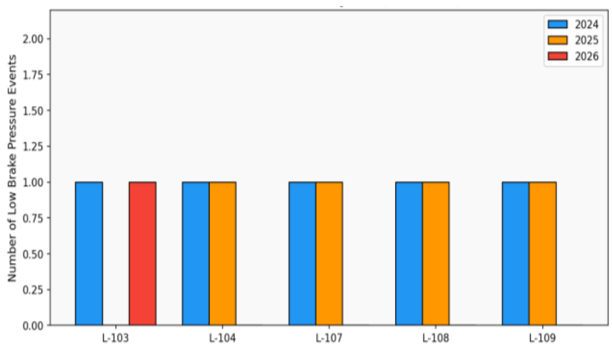

Figure 13. Low Brake Pressure Events Attributed to Accumulator Failure Across Articulated Hauler Fleet from 2024 to 2026

The results of both case studies provide important recommendations for maintenance practices. The repeated accumulator failures within an average interval of 12 months indicate that annual accumulator inspections, including nitrogen pre-charge and connection port checks, should be added to the preventive maintenance schedule [19]. Special attention is needed for the lower-chassis accumulator, which was found to receive limited inspection due to difficult access. The significant reduction in scraper thickness, from 7.8 mm to 6.1 mm, also suggests that seal inspections should adopt a dimensional replacement limit. Replacing the scraper before it reaches critical wear could prevent further seal damage and reduce unexpected failures. This condition-based maintenance approach has been shown to reduce unplanned downtime compared with purely corrective maintenance strategies [26], [10]. In addition, hydraulic fluid cleanliness plays a major role in component durability. The dusty mining environment increases the risk of contamination entering the hydraulic system, accelerating seal and accumulator wear. Regular oil cleanliness monitoring and particle analysis during each 250-hour service interval could help detect contamination earlier [9], [3]. This study also confirmed that the use of Volvo-standard seal kits and properly nitrogen-charged accumulators successfully restored system pressure to specification after repairs. This highlights the importance of using OEM or specification-compliant components, as lower-quality replacement parts may shorten component life and increase failure frequency [15], [24].

4. Conclusion

This study analyzed hydraulic failures in the articulated hauler fleet coal mining operation. The first analysis showed that the steering failure in a Volvo ART A40F was caused by abrasive wear on the piston rod seal due to contamination entering through a worn scraper, which had decreased from 7.8 mm to 6.1 mm. This condition reduced the steering pressure from the standard 250 bar to 203 bar and resulted in a loss of approximately 41 liters of hydraulic oil. After replacing the scraper / dust seal, the steering pressure returned to normal at 250 bar. The second analysis examined the braking system failure in a Volvo ART A40G, where three of the seven accumulators lost their hydraulic oil connection and could no longer store pressure. This caused the system pressure to drop to 118 bar, below the warning threshold of 145 bar, which automatically engaged the parking brake and stopped the unit. Replacing the faulty accumulator restored the pressure to 247 bar and returned the unit to service. Maintenance data from 2024-2026 shows that accumulator failures occurred repeatedly at approximately 12-month intervals across five trailers, indicating that the current inspection schedule is inadequate for actual operating conditions. The study suggests that early detection can be achieved through condition-based maintenance, including seal and scraper dimension inspections, nitrogen pre-charge inspections on all accumulators, and monitoring for hydraulic oil contamination. Implementing this preventative maintenance strategy is expected to reduce unplanned downtime, increase component life, and improve operational safety for the trailer fleet.

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Conflicts of Interest

The authors declare that there are no conflicts of interest related to this study. The research was carried out under academic supervision, company approval and did not influence the analysis, interpretation, or conclusions presented in this paper.

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