

## Field and Laboratory Evaluation of Reliability in a Novel Cone Deployment System for Safer Highway Operations

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(Received: 3 October 2025; Accepted: 29 January 2026; Published online: 10 May 2026)

**ABSTRACT:** This study evaluates the reliability and maintainability of the Cone Collecting and Laying (C2L) machine, developed to enhance safety and efficiency in highway maintenance operations by automating the deployment of traffic cones. The objective is to investigate the use of reliability metrics, which are Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), and Mean Time Between Failures (MTBF), as a systematic approach to assess the operational efficiency and failure behavior of the C2L machine in real highway maintenance scenarios. The methodology encompasses controlled laboratory and field testing conducted over 68 hours in Test Motion A and 3,192 hours in Test Motion B. During these tests, real-time failure data were recorded for six critical components of the C2L machine, namely the bearing, cone lifter, chain, sensor, PLC, and hook spring. Findings from Test Motion A revealed component vulnerabilities, including a low MTTF in bearings and a high MTTR in welded joints. In contrast, Test Motion B identified frequent failures in the PLC system, attributed to vibration stress, as well as a rare but critical hook spring failure caused by material fatigue. All reliability metrics were calculated from empirical failure and repair times, enabling accurate quantification of component durability and overall system availability. Failure data were further categorized into repairable and non-repairable types to inform targeted design improvements. In conclusion, integrating MTTF, MTTR, and MTBF into the evaluation of the C2L machine proved essential for identifying weaknesses and enhancing operational performance. The study recommends proactive maintenance scheduling, structural reinforcement, and redesign of vulnerable components to ensure system resilience. These findings contribute to improved worker safety, reduced operational downtime, and the enhanced long-term deployment potential of the C2L machine in highway maintenance applications.

**ABSTRAK:** Kajian ini menilai kebolehpercayaan dan kebolehselenggaraan mesin Pemungut dan Meletak Kon (C2L) bagi meningkatkan keselamatan dan kecekapan operasi penyelenggaraan lebuh raya melalui automasi proses meletak dan mengutip kon trafik. Objektif kajian ini adalah meneliti penggunaan metrik kebolehpercayaan seperti Masa Purata Sebelum Kegagalan (MTTF), Masa Purata Membaiki (MTTR) dan Masa Purata Antara Kegagalan (MTBF) sebagai satu pendekatan sistematik bagi menilai kecekapan operasi serta tingkah laku kegagalan mesin C2L dalam situasi penyelenggaraan lebuh raya sebenar. Kaedah

ini merangkumi ujian makmal dan ujian lapangan terkawal yang dijalankan selama 68 jam bagi Ujian Gerakan A dan 3,192 jam bagi Ujian Gerakan B. Sepanjang ujian tersebut, data kegagalan masa nyata direkodkan pada enam komponen kritikal mesin C2L, iaitu pengalas, pengangkat kon, rantai, pengesan, PLC dan spring cangkuk. Penemuan daripada Ujian Gerakan A menunjukkan kelemahan komponen termasuk MTTF yang rendah pada galas serta MTTR yang tinggi pada sambungan kimpalan. Sebaliknya, Ujian Gerakan B mengenal pasti kegagalan kerap pada sistem PLC akibat tekanan getaran, serta kegagalan kurang tetapi kritikal pada spring cangkuk disebabkan oleh kelemahan bahan. Semua metrik kebolehpercayaan dikira daripada data empirikal masa kegagalan dan masa pembaikan, sekaligus membolehkan pengukuran ketahanan komponen serta ketersediaan keseluruhan sistem. Data kegagalan turut dikategori pada jenis boleh dibaiki dan tidak boleh dibaiki bagi menyokong penambahbaikan reka bentuk terfokus. Kesimpulan, integrasi MTTF, MTTR dan MTBF dalam penilaian mesin C2L terbukti penting bagi mengenal pasti kelemahan serta meningkatkan prestasi operasi. Kajian ini mengesyorkan jadual penyelenggaraan proaktif, pengukuhan struktur, dan reka bentuk semula komponen yang lemah bagi memastikan daya tahan sistem. Dapatan ini menyumbang kepada peningkatan keselamatan pekerja, pengurangan masa henti operasi, serta potensi penggunaan jangka panjang mesin C2L dalam aplikasi penyelenggaraan lebuh raya.

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**KEYWORDS:** *C2L Machine, Failure Analysis, Reliability Metrics, MTTF, MTTR, MTBF.*

## 1. INTRODUCTION

Highway maintenance operations frequently involve manual handling of traffic cones, a task that poses significant safety risks to workers and contributes to physical fatigue. By addressing these issues, the Cone Collecting and Laying (C2L) machine was developed as a semi-automated solution capable of deploying and retrieving cones from a moving lorry. While this innovation improves operational safety and efficiency, ensuring the long-term reliability and maintainability of the C2L machine is essential for its successful integration into routine highway maintenance activities. This requires a systematic evaluation of its key components under realistic, simulated operational conditions.

Then, by quantifying the reliability and availability of the C2L machine, this study employs three fundamental reliability metrics: Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), and Mean Time Between Failures (MTBF). These time-based indicators provide important information on component durability, specifically, how long components operate before failing (MTTF), how quickly they can be repaired (MTTR), and the average duration between successive failures (MTBF). These metrics help determine whether the machine performs well during long highway operations and identify components that often fail or take a long time to fix. MTTF indicates how long a non-repairable part can operate before it fails. MTTR shows how long it takes to repair a part after it fails. MTBF combines both values to show the average time between failures for components that can be repaired. Therefore, by applying these metrics, the study aims to identify failure components of the C2L machine in real highway maintenance scenarios.

Therefore, to achieve this objective, comprehensive performance evaluations were conducted under two testing conditions: smooth (Test Motion A) and bumpy (Test Motion B) road surfaces. These tests assess how each component (bearings, welded joints, sensors, PLC units, chains, and hook springs) performs, responds to stress, and fails under different operating conditions, providing a complete understanding of the machine's reliability in real-world highway maintenance scenarios. MTTR, MTTF, and MTBF are widely recognized within engineering literature as critical metrics for evaluating system performance and availability [1].

The MTTR represents the average time required to detect, diagnose, repair, and restore a system or component to operational status, covering all stages from fault notification to post-repair testing.

Reducing MTTR is important because shorter repair durations directly improve availability and minimize downtime. Meanwhile, MTTF estimates the expected operational lifespan of non-repairable components [2], while MTBF reflects the average time between failures for repairable components and is a primary measure of overall system reliability [3]. These metrics are used to identify common failure modes, evaluate system robustness, and support predictive maintenance strategies. Moreover, Markov chain analysis has proven useful in modeling complex system reliability, offering valuable insights into performance prediction and maintenance scheduling [4].

Despite the importance of these metrics for assessing machinery reliability, a review of the existing literature reveals a notable research gap. Most studies on traffic cone deployment systems have focused on automation mechanisms, system design, or safety improvements, with little to no emphasis on thorough reliability analysis. Previous research lacks empirical investigations into the failure behavior and maintainability of such machines under realistic operational conditions. The study by Mehdi et al. is closely related because it highlights the importance of comprehensive reliability, availability, and maintainability (RAM) analysis in modern mechatronic systems [5]. It also demonstrates that such detailed analyses are still rarely applied in many domains of applied machinery, including traffic cone deployment systems. This gap highlights the need for a detailed, metric-driven evaluation of system durability and failure trends, an area this study directly addresses.

In the context of the C2L machine, these reliability metrics are especially applicable. High MTTF and MTBF values indicate that components can operate longer, uninterrupted, thereby improving efficiency. Conversely, a low MTTR suggests rapid recovery from failures, ensuring minimal downtime. As emphasized by [6], strategies to maximize MTBF (or MTTF) and minimize MTTR are important for achieving optimal system availability. Additionally, [7] notes that systems engineering practices incorporate these reliability and maintainability indicators within broader frameworks of system effectiveness. When combined, these metrics offer a holistic view of a machine's dependability and provide the data needed for evidence-based decision-making in maintenance planning and design refinement [8]. Therefore, by employing MTTR, MTTF, and MTBF in its research methodology, this study facilitates the systematic evaluation and continuous performance enhancement of the C2L machine. The results not only diagnose component-level vulnerabilities but also drive targeted design improvements. High MTTF and MTBF correlate with fewer disruptions, while low MTTR enables efficient maintenance response. The analysis of both repairable and non-repairable failures thus builds a strong case for design optimization. In turn, this study highlights the value of reliability engineering in advancing automation technologies for highway maintenance, improving worker safety, reducing downtime, and enhancing overall system sustainability.

## 2. METHODOLOGY

### 2.1. Determining reliability metrics from C2L machine failure data

An evaluation of the operational reliability and maintainability of the C2L machine was conducted through two structured field tests that replicated real-world highway maintenance scenarios. The C2L body serves as the main structural framework of the C2L machine, supporting and connecting all major components, including the cone-laying mechanism, control systems, and supporting elements. Built for strength and durability, the C2L body

enables the machine to operate safely and efficiently under the demanding conditions of highway maintenance. Its structurally reinforced design contributes significantly to the system's overall reliability and performance. Figure 1 presents the key components of the C2L machine, showing both the front and back views. Each component supports the automated functions of laying and collecting traffic cones.



Figure 1. C2L body.

Figure 2 shows the complete design of the laboratory test rig used to evaluate the C2L machine. The rig functions as a controlled platform that safely replicates real road conditions while enabling consistent test repetition. Its structure features a long, sturdy frame with parallel guiding rails that enable smooth, stable operation of the C2L machine. A motorized unit is installed at one end to drive or simulate the machine's motion along the rails. At the center of the rig, a supporting frame accommodates the tipping mechanism, guiding posts, and any other attachments required to assess the cone collection and laying functions.

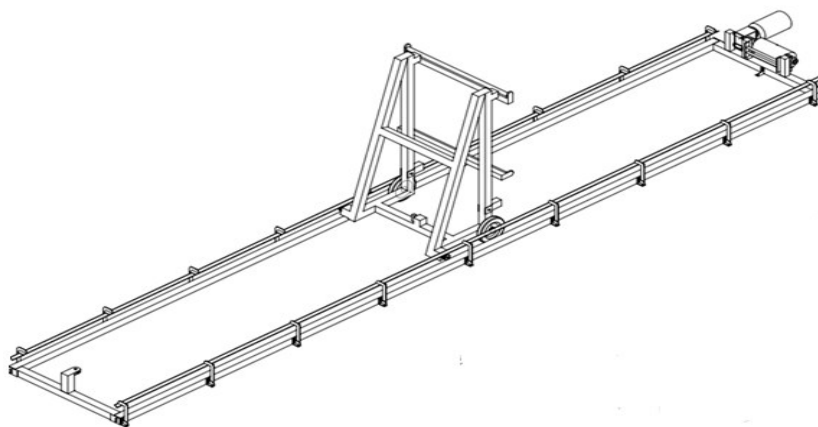


Figure 2. C2L machine laboratory test rig configuration.

Test Motion A examined the machine's performance over 68 hours on smooth road surfaces, while Test Motion B extended the evaluation to 3,192 hours on uneven, bumpy terrain. Each test is carried out in 12 sequences. Conducting 12 sequences for both motions ensured sufficient data for accurate, statistically meaningful analysis while keeping the testing process efficient in terms of time and resources. This approach enabled a thorough assessment of the C2L machine's performance, reliability, and operational consistency under both smooth and uneven surface conditions. For every sequence, the total testing time and the number of completed cycles were carefully recorded. These contrasting environments provided important information about the machine's performance under different stress conditions.

Reliability metrics, MTTF, MTTR, and MTBF were applied to assess the endurance and maintainability of six critical components: bearings, chains, sensors, cone lifter, PLC, and hook springs. These components were selected based on their significance to the machine's main operations. Table 1 summarizes the role of each part and presents quantitative data highlighting their durability, ease of maintenance, and contribution to overall system availability. Such measurements are essential in ensuring the C2L machine can function reliably in demanding roadside environments.

The primary aim of this methodology was to assess whether the C2L machine could effectively replace manual cone deployment and retrieval, thus enhancing safety and operational efficiency during highway maintenance. Reliability, as described by [9, 10], represents the likelihood that a component or system performs its intended function without failure over a defined period under specific conditions. In this study, MTTF, MTTR, and MTBF served as key performance indicators. Their application enables a clear understanding of both the frequency of failure and the effectiveness of repair processes. These findings support data-informed decisions to improve component design, refine maintenance strategies, and enhance the long-term dependability of the C2L machine in real-world operations, as stated in Eq. (1).

$$\begin{aligned} MTTR &= \text{Total Repair Time} - \text{Number of Failures} \\ MTTF &= \text{Total Operating Time} - \text{Number of Failures} \\ MTBF &= MTTF + MTTR \end{aligned} \quad (1)$$



These time-dependent metrics require accurate data collection under varied operational conditions to yield meaningful findings. Such a comprehensive approach enables accurate evaluation of component durability, identification of design vulnerabilities or structural weaknesses, and development of targeted strategies for system improvement. MTTF quantifies the average time-to-failure of non-repairable components. This measure is essential for understanding component reliability and supports the implementation of proactive maintenance schedules. Therefore, by identifying potential failures, system availability can be improved, and operational disruptions during highway maintenance activities can be significantly reduced.

The MTTR quantifies the average time required to detect, diagnose, repair, and verify a failed component before restoring it to full functionality. Minimizing MTTR is crucial for reducing system downtime and maximizing availability. As highlighted by [11], effective management of MTTR directly impacts operational continuity. Maintenance engineering frameworks often incorporate reliability metrics like MTTR to optimize lifecycle costs [12].

Meanwhile, the MTBF measures the average interval between successive failures of repairable components, serving as an important indicator of overall system reliability and guiding maintenance prioritization [13]. Additionally, [14] emphasizes that proactive maintenance substantially prolongs machine lifespan in industrial environments. In applying

these metrics to the C2L machine, systematic data collection was carried out during laboratory and field tests [15]. MTTF was calculated for non-repairable components such as sensors and motors, MTTR was derived from recorded repair durations following failures, and MTBF reflected the operational intervals between failures.

**Table 1.** The function of the component C2L machine in providing quantifiable data

Component	Function of Component C2L Machine
 Bearing	Roller bearings use cylindrical rollers to minimize friction and support rotating shafts or axles. They consist of cylindrical rollers arranged between an inner and an outer ring.
 Cone lifter	The cone lifter is designed to guide the cone during lifting, apply controlled force for stable handling, offer a defined path for cone movement, and ensure smooth lifting through its mechanical assembly.
 Chain	The chain consists of a series of interlinked metal segments positioned along the conveyor belt's centerline.
 Sensor	A motion sensor is a device that detects and reacts to particular environmental factors, such as light, heat, motion, moisture, and pressure. The sensors detect the C2L machine's position and send signals to control the motor's direction, ensuring it moves forward and backward along the test rig as required.
 PLC	The PLC accurately manages various components of mechanical equipment, such as motors, valves, and sensors. The damper box is a protective enclosure designed to safeguard the PLC from environmental and mechanical hazards.
 Hook spring	The coil hook spring is used as a connector linking the chain to the load, functioning as an integral part of the cone lifter. The hook spring helps maintain proper alignment and movement by absorbing forces, managing tension, and ensuring smooth operation.

This comprehensive reliability assessment identified mechanical weaknesses, including fatigue in welded joints and limitations within control systems, which informed targeted design

improvements such as reinforced welds and upgraded control units [16]. By integrating these reliability metrics into the methodology, the study adopts a data-driven approach to enhancing the C2L machine's operational dependability [17]. This not only improves reliability and availability but also contributes to safer, more efficient highway maintenance operations.

Reliability, denoted as  $R(t)$ , is defined as the probability that a system will perform its intended function without failure under specified conditions over a given time [18]. Typically, reliability follows an exponential failure distribution expressed as:

$$R(t) = e^{-\lambda t} \quad (2)$$

where  $\lambda$  represents a constant failure rate, and  $t$  denotes time.

This model reflects an exponential decline in reliability over time, with maximum dependability at the start of operation [19, 20]. In contrast, availability measures the likelihood that a system is operational at any given moment, considering repair times, and is mathematically defined as:

$$A = \frac{MTBF}{MTBF+MTTR} \quad (3)$$

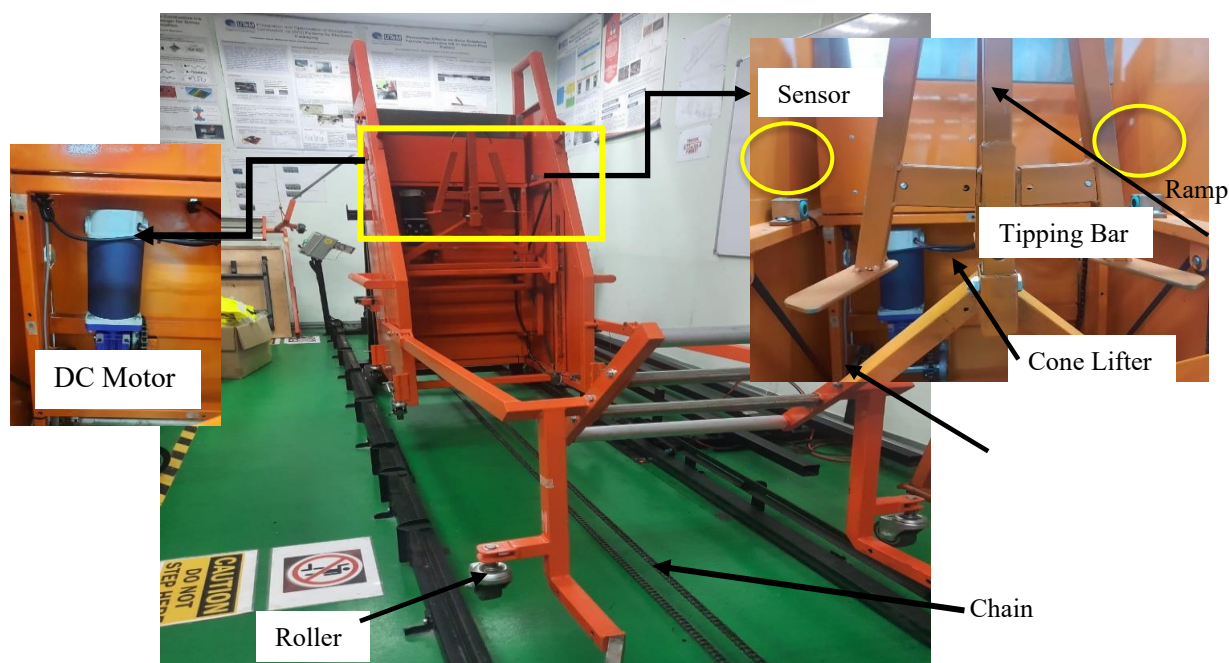
Here,  $MTBF$  and  $MTTR$  are key parameters derived from empirical testing, industry benchmarks, or expert evaluations. Besides, low reliability leads to frequent unplanned stoppages, reducing overall system availability by increasing downtime and operational interruptions [21-23].

## 2.2. Performance measurement and reliability assessment methodologies

The laboratory experiment was conducted in a controlled environment, with the room temperature consistently maintained at an average of 24°C to ensure stable testing conditions. The test rig, illustrated in Figure 3, was assembled in a secure area at the rear of the laboratory, with barricades installed to safeguard other users. The setup comprised several key components, including a DC motor, a roller, a chain, a sensor, a ramp, a cone lifter, and a tipping bar.

Although the laboratory test was conducted at an average room temperature of 24°C, the higher ambient temperatures typically experienced on highways, which can reach up to 45°C, are not expected to affect the C2L machine's cone collecting and laying functions. This is because its key mechanical and electrical components are engineered and rated to operate reliably across a broader temperature range. Therefore, the performance and motion behaviors observed at 24°C can be confidently expected to remain stable under higher real temperatures. During testing, data were recorded each time the C2L machine completed a full cycle, traveling from the test rig's starting point to the end and then returning to its original position.

This approach is consistent with the methodology employed by Lacarella et al. [24], which similarly regulates room temperatures during laboratory experiments to simulate natural stream conditions, thereby relating their findings to ecosystem restoration strategies aimed at mitigating temperature-related effects. In this study, the C2L machine was tested under dynamic operation by repeatedly moving between two motion sensors installed on a specially designed test rig. During each pass, the machine executed its designated cone pick-and-lay mechanism. The data were systematically recorded only after the completion of each full cycle, defined as movement from the starting point to the far end of the rig and back. Therefore, by preserving data integrity, only fully completed cycles were included in the analysis, except for static test runs specifically focused on evaluating the ramp's vertical movement.



**Figure 3.** Test rig configuration in the laboratory.

The experimental schedule for both Test Motion A and Test Motion B spanned 14 weeks. All testing was conducted during regular working hours, with a maximum runtime of eight hours per day, five days a week. These operational constraints ensured the testing was carried out under close supervision, thereby guaranteeing the reliability and safety of the experiments. Following the conclusion of Test Motion A and Test Motion B, data collection concentrated on key parameters to evaluate the C2L machine's reliability and to identify potential design improvements. One primary metric recorded was the number of hours the machine operated daily during testing. A counter installed within the control box tracked the total number of completed runs. Throughout the testing phase, various performance metrics were recorded, including MTTF, MTBF, MTTR, Reliability Function (RF), and Non-Reliability Function (NRF). On the other hand, Żyluk et al. [25] advocate the use of the MTTF indicator as a strategic tool to enhance logistical support management within operational processes, optimize maintenance scheduling, and improve system reliability. These methodologies draw upon the approaches detailed in the references.

All experimental data, including recorded failures, were systematically compiled and analyzed. Tests were performed under varying conditions and repeated multiple times to ensure accuracy and reliability. In the event of failure, repairs were promptly conducted before resuming tests. By further refining the design and eliminating NRFs, the TRIZ methodology was applied to resolve technical contradictions and enhance overall system efficiency. Ultimately, the reliability analysis assessed the C2L machine's performance by evaluating the strength and durability of its components throughout operational use.

### 3. RESULTS AND DISCUSSION

#### 3.1. Component failure analysis from Test Motion A

The C2L machine encountered four critical failures during 68 hours of testing under smooth road conditions (Test Motion A). The bearing failure, as detailed in Table 2 (15 minutes' repair), was most likely caused by friction-induced wear resulting from repeated

bidirectional rail movement. This issue occurred because the bearing had a low thread count, which weakened its ability to remain securely fixed under repetitive motion. This form of wear can lead to increased play within the bearing housing, elevating the risk of misalignment and subsequent operational jamming. Therefore, to enhance durability, it is recommended to use sealed, high-load-capacity bearings with improved lubrication retention, along with regular condition monitoring via vibration or thermal analysis. The welded joint failure, located below the cone lifter, which cracked due to fatigue, required the longest repair time (60 minutes) and revealed a significant structural vulnerability. The repeated cyclic stresses induced by operational vibration may have led to fatigue cracking at weld toes, common initiation points for structural failure. Employing full-penetration welds, improving joint geometry to distribute stress more evenly, and incorporating non-destructive testing (NDT) methods such as ultrasonic inspection during fabrication can significantly bolster reliability in these areas.

**Table 2.** Summary of failure components and repair data for the C2L machine during Test Motion A

Component	Total failures (count)	Total Repairs (count)	Repair Time (minutes)	Total testing time (hours)
Bearing	1	1	15	68
Welded Joint	1	1	60	68
Chain	1	1	40	68
Sensor	1	1	30	68

The chain failure (40 minutes' repair) dislodged from the gear during the test was attributed to tensile overload during cone-laying cycles, which may have caused elongation or breakage of links, in turn risking damage to neighboring drivetrain components. Enhancing chain durability could involve selecting high-tensile alloy chains with wear-resistant coatings, ensuring correct tensioning, and introducing guided sprockets to minimize lateral movement and misalignment. The sensor failure (30 minutes' repair) occurred when it was unable to generate the signal needed to continue the motion cycle, causing the operation to stop. This malfunction was likely due to either an electrical fault or mechanical stress from environmental vibrations. MTTF, MMTR, and MTBF provide important information on component durability, maintainability, and overall system reliability, which are essential for ensuring safe and efficient highway maintenance operations.

Firstly, the MTTF quantifies the expected service life of non-repairable components such as sensors and welded joints. In Test Motion A, all components had an MTTF of 68 hours, calculated as the total test duration divided by the number of failures per component. This exceptionally low MTTF, especially for the welded joint, indicates a structural weakness under cyclic loading conditions. Such failures are often attributed to fatigue-induced microcracking at stress-concentration points within the weld. Enhancing MTTF may involve material upgrades, such as switching to high-grade structural steel with superior fatigue resistance, or implementing design changes inspired by TRIZ, for instance, replacing welded connections with bolted joints that enable modular disassembly and more uniform stress distribution. Increasing MTTF directly reduces the likelihood of premature in-service failures, thus improving operational safety and minimizing unplanned maintenance costs [26].

Secondly, the MTTR assesses the ease and speed with which failed components can be restored to working condition. The welded joint exhibited the highest MTTR of 60 minutes, reflecting the complexity of structural repairs, which often involve grinding, re-welding, and post-weld inspection. Long MTTRs negatively impact system availability. Reducing MTTR, such as redesigning components for easier access or adopting quick-release fasteners,

significantly improves maintainability. For example, halving the MTTR for sensor replacements (from 30 to 15 minutes) could increase overall system availability by approximately 8%, ensuring the machine can resume highway operations with minimal downtime.

Thirdly, MTBF applies to repairable components such as chains and bearings. It combines MTTF and MTTR to represent the average interval between failures. The chain's MTBF of 68.67 hours suggests frequent operational disruptions, potentially due to inadequate lubrication, misalignment, or material fatigue. Implementing scheduled lubrication regimes, using corrosion-resistant alloy chains, or installing chain tensioners can significantly enhance MTBF. A 20% improvement in MTBF not only extends service intervals but can also reduce spare part inventory by up to 15%, lowering lifecycle costs. When MTBF increases, the number of breakdowns over a given period naturally decreases. As a result, maintenance teams do not need to replace components as frequently, which directly affects inventory planning. For consistent field performance, an MTBF target exceeding 100 hours is advisable to ensure uninterrupted deployment over extended highway maintenance shifts. Therefore, improving these reliability metrics through targeted design, maintenance planning, and material selection will substantially enhance the C2L machine's dependability, reduce operational interruptions, and promote long-term cost efficiency.

### 3.2. Reliability metrics for failed components in Test Motion A

The analysis of reliability metrics for the C2L machine during Test Motion A provides important insights into the performance, durability, and failure characteristics of its major components. The evaluation, based on MTTF, MTTR, and MTBF, focuses on four critical parts: the bearing, welded joint, chain, and sensor. The results highlight key vulnerabilities and focus on the importance of proactive maintenance strategies, informed design improvements, and enhanced diagnostic practices to support long-term field deployment.

The bearings recorded in Table 3 show the lowest MTTF (2.25 hours), indicating a higher likelihood of early failure compared to the other components. Although the failure was resolved quickly with an MTTR of just 15 minutes, the early breakdown emphasizes the need for regular pre-operation checks and predictive maintenance. Common issues associated with bearings, such as dynamic loads, poor lubrication, and misalignment, make them vulnerable under prolonged use. Despite this, the bearings also demonstrated a high MTBF, suggesting that when properly aligned, lubricated, and maintained, they can deliver stable performance with minimal recurrent failure. This dual behavior highlights the role of proper installation and routine inspection in optimizing bearing lifespan. Implementing condition-based monitoring, such as vibration sensors or thermal tracking, would further increase reliability and reduce downtime.

**Table 3.** Reliability metrics for component failures during Test Motion A

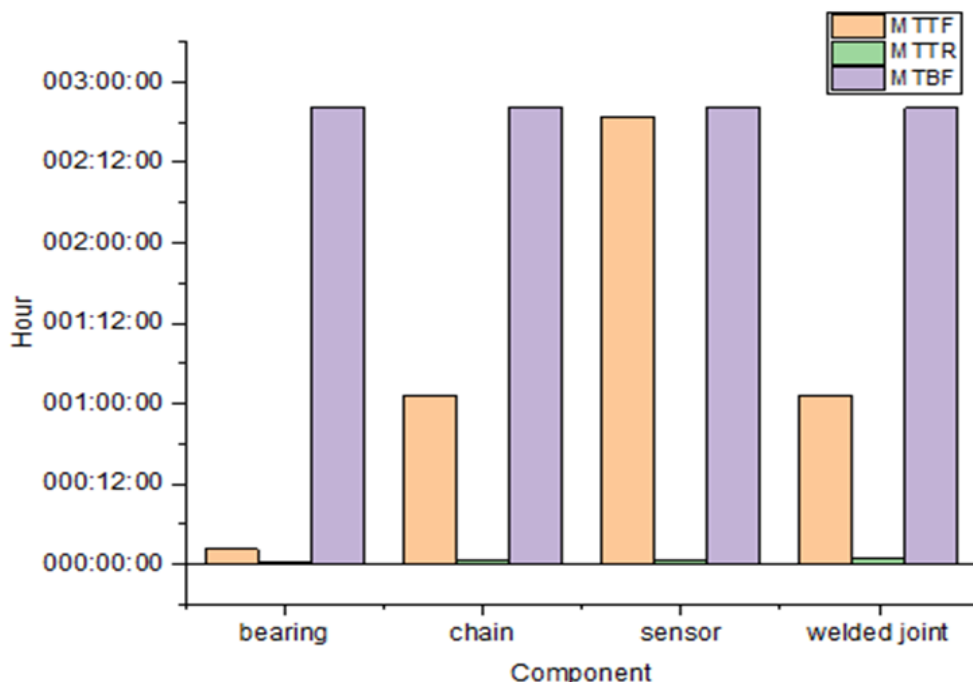
Component	MTTF	MTTR	MTBF
Bearing	2:15:00	0:15:00	68:08:00
Welded Joint	25:16:00	1:00:00	68:08:00
Chain	25:16:00	0:40:00	68:08:00
Sensor	66:45:00	0:30:00	68:08:00

In comparison, welded joints exhibited a significantly higher MTTF of over 25 hours, indicating greater durability. However, their MTTR was the highest (approximately 60 minutes), primarily because of the complexity of structural repair work. Fixing a welded joint typically requires specialized tools, skilled labor, and additional time for inspection and

verification of integrity. The primary root cause of welded joint failure is fatigue accumulation under repeated mechanical loading. Because welded joints are structurally critical elements, even minor cracks can progress rapidly into major failures. Adopting non-destructive testing (NDT) techniques such as ultrasonic testing or dye-penetrant inspection during scheduled maintenance could help detect cracks at early stages. Preventing such failures would greatly reduce repair time, improve machine uptime, and eliminate the need for field welding, which is often impractical during live highway operations.

Chains, although secondary in the failure sequence, were relatively easy to repair (MTTR of 40 minutes) due to their modular nature and straightforward reconnection to gear assemblies. However, they remain vulnerable to tensile overloads and misalignment, especially if chain tension is improperly maintained. Introducing routine chain tension checks, particularly during welded joint inspections, can prevent cascading failures and preserve overall mechanical integrity. The use of automatic chain tensioners or upgraded wear-resistant materials, such as heat-treated steel, would further enhance operational resilience.

Among all components, the sensor exhibited the highest MTTF (approximately 66.75 hours), demonstrating strong reliability within the controlled laboratory environment. The sensor benefits from minimal mechanical loading and a protective casing. Nevertheless, sensors remain prone to electrical noise, vibration sensitivity, and environmental exposure, especially in real-world highway conditions. The introduction of shielded wiring, vibration-isolating mounts, and weather-resistant enclosures would enhance long-term reliability and reduce vulnerability during field operations. Although the sensor's MTTR was the shortest at 30 minutes, any malfunction still causes an immediate operational stop because the system relies heavily on accurate sensor signals to maintain continuous movement.



**Figure 4.** Comparison of MTTF, MTTR, and MTBF for C2L machine components during Test Motion A.

Figure 4 visually compares the MTTF, MTTR, and MTBF for the bearing, welded joint, chain, and sensor. It highlights the sharp contrast between the bearing's low MTTF and the much higher values for the other components. The figure also emphasizes the significantly

longer MTTR of welded joints compared to the relatively quick repair times of chains and sensors. The MTBF across all components illustrates the equal test duration rather than equivalent reliability performance. Overall, the figure effectively demonstrates component-level strengths and weaknesses, guiding engineers toward targeted areas for design enhancements and maintenance planning.

The reliability assessment of Test Motion A clearly identifies bearings and welded joints as priority components for improvement, given their susceptibility to early failure and the longer repair times required. Chains and sensors show promising reliability but still require targeted enhancements to sustain long-term field operation. Together, these findings emphasize the need for predictive maintenance, improved material selection, and expanded field data collection to refine MTBF estimates and support dependable deployment of the C2L machine in highway maintenance operations.

### 3.3. Component failure analysis from Test Motion B

Empirical data derived from 3,192 hours of simulated bumpy road operation during Test Motion B, as detailed in Table 4, expose critical reliability issues encountered by the C2L machine under prolonged mechanical stress. The PLC had the most breakdowns, with 249. Repairs for these failures took a total of 516 minutes. This makes the PLC the biggest problem component in the system. The PLC failure in the C2L machine stems from a hard rubber passive component used for vibration damping, insulation, or shock protection of sensitive electronics. However, this rubber degrades over time, losing flexibility and failing to absorb vibrations effectively. In dynamic environments like the C2L's cone-handling operations, continuous vibrations and impacts from moving parts are transmitted directly to the internal board, causing loose connections and cracked solder joints. These issues result in intermittent signals, logic errors, and complete PLC malfunctions during highway maintenance tasks.

**Table 4.** Summary of failure and repair data for C2L Machine components during Test Motion B

Component	Total failures (count)	Total Repairs (count)	Repair Time (minutes)	Total testing time (hours)
PLC	249	249	516	3192
Hook spring	1	1	110	3192

Therefore, to improve the PLC's durability, several practical solutions can be implemented. First, using vibration-isolating mounts or shock-absorbing housings such as elastomer or rubber-gasket enclosures can help reduce the amount of vibration reaching the PLC. Second, applying protective conformal coatings, such as acrylic or silicone, to the circuit boards can prevent damage from moisture and dust. Third, updating the firmware with watchdog timers and better error-handling features can help the system recover automatically from temporary faults. Together, these improvements would increase the PLC's MTTF and make the control system more stable during real operation. On the other hand, the hook spring showed very high reliability, failing only once over the entire test period, achieving an MTTF of 3,192 hours. However, when it did fail, the repair took 110 minutes, indicating a high MTTR. Even though the failure was rare, it remains a major risk because the hook spring is integral to the cone-handling mechanism. If it breaks, the C2L machine cannot lay or collect cones, which may stop maintenance operations during busy traffic periods.

The analysis shows that the hook spring failed because the metal became tired over time, especially at the points where it was attached and repeatedly stretched and compressed. This

fatigue worsened due to design issues such as sharp edges, uneven force distribution, and the use of materials that were not strong enough for long-term, repeated loading. To prevent this type of failure, two main improvements are recommended. First, using stronger spring materials, such as silicon-chrome, would help the spring last much longer. Second, redesigning the hook mechanism to use two springs in tandem would ensure the system continues to function even if one spring weakens. This follows TRIZ principles by adding redundancy to improve system reliability. This is approved by Becker, who highlights TRIZ as an effective framework for solving complex engineering problems and improving project outcomes [27]. Making the hook spring assembly modular with quick-release connectors would also reduce repair time and make replacement easier in the field. Overall, the failure analysis from Test Motion B shows key reliability weaknesses: the PLC is easily affected by vibration and electrical issues, and the hook spring, although rarely failing, can cause major disruption when it does. Fixing these weaknesses with proper engineering improvements will greatly increase the reliability and continuous performance of the C2L machine in real highway conditions.

### 3.4. Reliability metrics for failed components in Test Motion B

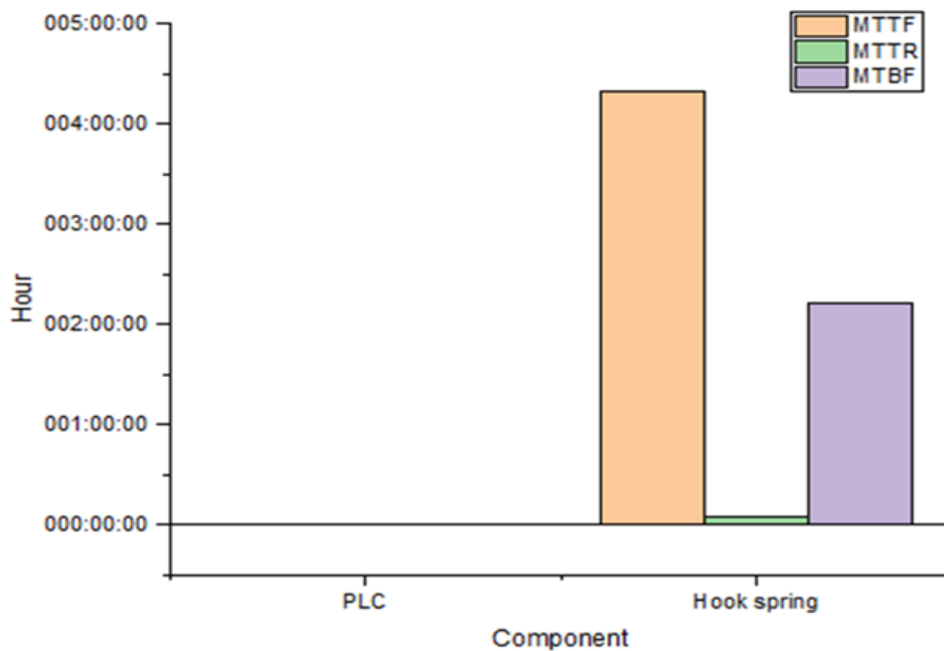
Table 5 presents the reliability metrics for component failures observed during Test Motion B of the C2L machine. The PLC exhibited an MTTF of 10 minutes and 12 seconds, indicating that this electronic control unit experienced relatively frequent faults during the testing period. However, its MTTR was greatly low at just 2 minutes, suggesting that the issues encountered were minor and could be swiftly rectified, likely through simple interventions such as system resets or minor adjustments. The corresponding MTBF for the PLC was recorded at 12 minutes and 16 seconds, representing the total operational interval, including both uptime and repair duration. In contrast, the hook spring exhibited markedly different reliability characteristics, with significant implications for the C2L machine's operational performance. The component recorded an MTTF of 104 hours, demonstrating exceptional durability and the ability to operate for extended periods without failure. This high reliability makes the hook spring well-suited for continuous deployment in highway maintenance operations, where sustained mechanical performance is critical. However, its MTTR was recorded at 110 minutes, reflecting the more complex, time-consuming nature of mechanical repairs when failure occurs. These metrics underscore the need for tailored maintenance strategies, frequent but quickly resolved issues affecting the PLC, and infrequent but high-impact failures linked to the Hook Spring. Both cases highlight the importance of improving component resilience and maintainability to ensure the C2L machine can meet the demanding requirements of real operational environments.

Table 5: Reliability metrics for component failures during Test Motion B

Component	MTTF	MTTR	MTBF
PLC	0:10:12	0:02:00	0:12:16
Hook spring	104:00:00	1:50:00	53:12:00

However, when failures do occur, the hook spring MTTR requires significantly more time at 1 hour and 50 minutes to complete repairs, likely involving mechanical adjustments, component replacement, or detailed fault diagnostics. The MTBF of 53 hours and 12 minutes reflects the component's overall operational reliability. These metrics indicate that although the Hook Spring is less likely to fail, its complex repair process could lead to extended machine downtime. This has the potential to disrupt highway maintenance schedules and underscores the importance of strategic maintenance planning to minimize operational interruptions during critical cone laying and collection tasks. Figure 5 illustrates the reliability metrics for two C2L

machine components: the PLC and the hook spring. While MTTR values are not clearly visible in this figure, they represent the time required to repair a failure, thereby directly affecting equipment downtime and overall operational efficiency.



**Figure 5.** Comparison of MTTF, MTTR, and MTBF for C2L machine components during Test Motion B.

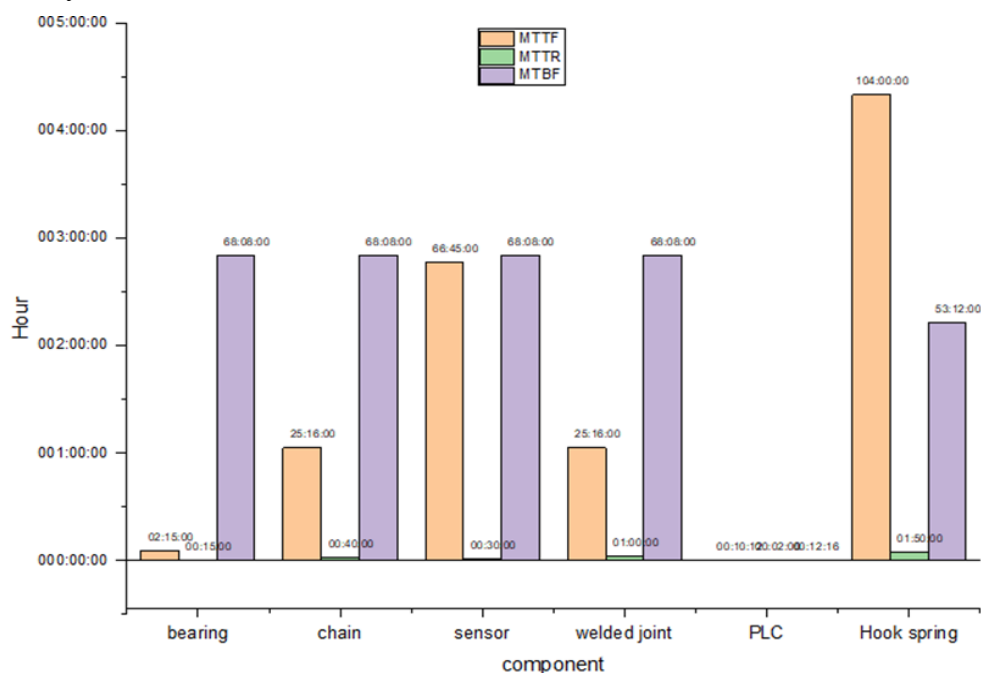
The reliability metrics depicted in this graph have critical implications for the operational performance of the C2L machine in highway maintenance settings. The very short MTTF of the hook spring indicates that it is prone to more frequent failures, necessitating regular maintenance. This can disrupt the machine's cone laying and collection cycles, reduce uptime, and compromise its availability during time-sensitive safety operations. The underlying cause is likely material fatigue from repetitive mechanical loading, suggesting the need for design modifications, such as stress-distributing geometries or high-tensile spring alloys.

The PLC exhibits a comparatively higher MTTF, signifying greater operational stability. However, the PLC serves as the central hub for automation and control; thus, its failure, although less frequent, results in a complete operational halt. This elevates the PLC's criticality in the system hierarchy, reinforcing the need for redundancy planning, fault-tolerant firmware, and shock-resistant housing to mitigate vibrational damage during field deployment. Then the MTBF, which integrates both the time to failure and the time to repair, offers a holistic view of each component's overall reliability in live operational conditions. Components with higher MTBF values contribute to prolonged maintenance intervals and reduced system downtime, thereby lowering lifecycle costs and enhancing deployment efficiency. Conversely, components with low MTBF values demand closer monitoring and may benefit from predictive maintenance technologies, such as sensor-based diagnostics and condition-based alerts. This integrated graph presents the reliability data for six essential components of the C2L machine, combining results from both Test Motion A and Test Motion B. The variations in MTTF, MTTR, and MTBF highlight the distinct stress responses of each component, offering crucial insights into where structural reinforcements, material upgrades, or redesigns are warranted. Understanding and acting on these reliability metrics is fundamental not only to improving operational efficiency but also to ensuring safety, minimizing unplanned downtime, and maintaining smooth traffic flow during roadside interventions.

### 3.5. Evaluation and interpretation of reliability metrics for C2L machine components in Test Motion A and B

Figure 6 provides a comprehensive visualization of the reliability metrics for six critical components of the C2L machine, compiled from the combined results of Test Motion A and B. This detailed analysis utilizes MTTF, MTTR, and MTBF to assess component performance, highlighting distinct variations that critically influence the machine's overall operational efficiency. The bearing component, despite its very low MTTF of approximately 2 minutes and 15 seconds, exhibits an equally brief MTTR of around 15 seconds, resulting in a high MTBF close to 68 hours. This indicates that while bearing failures may occur relatively frequently, they are likely to wear from continuous rotational and load stresses, which can be addressed very swiftly through rapid maintenance or replacement, minimizing operational downtime. The rapid repair time reflects both the bearing's accessibility and the simplicity of its maintenance procedures.

Similarly, the chain component demonstrates a moderate MTTF of about 25 minutes and 10 seconds and a low MTTR of 40 seconds, achieving a comparable MTBF of about 68 hours. This suggests reliable mechanical power transmission, with failures such as link wear or tension loss occurring periodically but quickly remedied, ensuring consistent functionality in cone-laying operations. The sensor component presents a very high MTTF of approximately 66 hours and 45 minutes, reflecting robust operational durability under variable conditions. The short MTTR of 30 seconds further indicates that sensor-related faults are typically minor, such as signal interruptions or calibration errors, and can be resolved promptly, maintaining automation accuracy with minimal service interruption. The welded joint exhibits an MTTF similar to the chain at around 25 minutes and 10 seconds, but with a minimal MTTR, yielding an MTBF close to 68 hours. This suggests that although fatigue-related micro-cracking may arise under cyclic loading, repairs can be executed efficiently, especially when early detection enables timely intervention.



**Figure 6.** Summary of reliability metrics of failed components during Test Motion A and B.

The PLC component experiences frequent failures, indicated by a very low MTTF. However, its correspondingly low MTTR signifies that these electronic faults, often triggered

by vibration-induced glitches or transient software errors, are swiftly recovered, typically through resets or minor adjustments. This balance results in an MTBF around 68 hours, reflecting a system that, while sensitive, is manageable within operational protocols. The hook spring stands out with the highest MTTF of 104 hours, underscoring its superior durability and resistance to fatigue under repeated cone-handling loads. However, its repair time is substantially longer, approximately 1 hour and 50 minutes, because of the complexity of mechanical adjustments or replacements required, often involving disassembly or precise alignment. Despite this, the hook spring maintains a robust MTBF of about 53 hours and 12 minutes, making it one of the machine's most reliable components overall. This highlights a critical trade-off between longevity and repair complexity, emphasizing the importance of predictive maintenance and potential design optimizations such as modular spring units or improved material selection to further enhance maintainability without compromising durability. Overall, these metrics provide invaluable information on component-specific vulnerabilities and maintenance needs, guiding targeted reliability improvements that can significantly boost the C2L machine's operational uptime, safety, and cost-effectiveness during highway maintenance activities.

#### 4. CONCLUSIONS

The study clearly demonstrates that reliability metrics such as MTTF, MTTR, and MTBF are important tools for assessing the operational efficiency and maintainability of the C2L machine. Through laboratory and field testing, marked variations were observed among components in terms of failure frequency, repair times, and overall resilience under operational conditions. The sensor emerged as the most reliable component, exhibiting a high MTTF alongside a short MTTR, while the bearing, despite having the shortest MTTF, benefited from swift and straightforward repairs. In contrast, the PLC posed the greatest reliability challenges, with frequent failures and a particularly low MTTF, although its issues were often resolved through rapid resets or minor repairs. These findings represent a considerable ongoing operational cost despite its quick repair time of only 2 minutes per failure, as the cumulative downtime and repeated maintenance interventions add up to 516 minutes of total repair time, resulting in lost productivity and increased labor costs for frequent technician callouts. In contrast, the hook spring, while failing only once during the entire test period, poses a different financial challenge due to its lengthy repair time of 110 minutes, which translates to nearly two hours of machine downtime that could disrupt scheduled highway maintenance operations and potentially require expensive emergency repairs or rush-order replacement parts. Therefore, the reliability of the C2L machine depends on how well each component performs.

Based on the reliability metrics obtained from Test Motion B, the C2L machine's performance can be benchmarked against similar automated highway maintenance systems and industrial machinery operating under comparable conditions. The hook spring's MTTF of 104 hours demonstrates exceptional durability, exceeding that of typical mechanical components in mobile road equipment, suggesting it meets or surpasses industry standards for field-deployed machinery subjected to continuous mechanical loading. To improve the machine, two things must be done simultaneously: extend component life (increase MTTF) and reduce repair time and effort (reduce MTTR). Implementing proactive preventive maintenance programs, advancing component robustness through improved materials and design, and ensuring thorough training for maintenance personnel will collectively help maximize machine uptime and operational safety during critical highway maintenance tasks. Furthermore, integrating innovative methodologies, such as TRIZ-based design improvements [28], together with extended and varied testing regimes, will enable more accurate MTBF estimates and foster the

development of a more resilient, efficient, and dependable C2L machine for real-highway applications.

## ACKNOWLEDGMENT

This research was conducted in collaboration between Universiti Teknikal Malaysia Melaka (UTeM) and PLUS Malaysia Berhad, and was partially funded by PLUS Malaysia Berhad, as stated in the RFA document PLUS/RFA/2019-00241/COE/AD-COR.

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