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Fatigue Reliability Analysis of Tractor Trailer Chassis Frame

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Abstract. This investigation explores the dependability and endurance of trailer frames. It proposes a methodology for evaluating these traits, using calculations based on the probability of non-failure operation (PNFO) and the average time between failures (MTBF) of the frame components. Additionally, a mathematical model has been suggested for the appraisal of trailer frame durability, which utilises the Weibull distribution and the power equation of the fatigue curve. The methodology is exemplified through the application on a specific trailer frame. The findings indicate the feasibility of this method for assessing the dependability and longevity of trailer frames.

1 Introduction

The task of assuring dependability and longevity is multifaceted, encompassing various aspects in the design, production, and operation of a machine. To this end, particular strategies must be developed and executed in alignment with standards for the reliability and endurance of key components (assembly units) of the machine. Without such standards, it becomes unfeasible to guarantee the machine's overall dependability.

The lack of scientifically grounded standards and requirements for the reliability and durability of specific machine components often leads to substantial material and labour costs invested in enhancing the dependability of individual elements (parts) of the structure, which unfortunately do not yield a significant outcome. Consequently, it becomes challenging to determine the scientifically validated extent of bench and other tests for component reliability and to develop an optimal method for assessing these results [1-3].

Sherazi et al.'s study in 2021 highlighted that the values of reliability standards calculated in the process of trailer and their structural components' manufacturing should form the primary point of reference throughout the design phase. This includes the formulation of calculation methods and the selection of testing apparatuses.

In a generalized perspective, the issue of distribution within the prerequisites for the reliability of frame components can be stated as follows: Given the set desired reliability index for a frame constituted of 'n' elements, the task is to ascertain the modifications that each element's norm should undergo. To address this type of issue, the methodologies elucidated in Sherazi et al.'s 2021 investigation can be adopted [1].

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The method that appears most fitting for our calculations is the utility theory approach, posited by Sherazi et al. (2021), which anchors on the allocation of requirements for the non-failure operation of system components, bearing in mind their complexity.

However, as indicated by our analysis of these methodologies, due to the demands, suppositions, and constraints inherent within them, they are not always fully applicable or appropriate when gauging the indicators of reliability and durability for the trailer design in question.

For instance, the utility theory method necessitates the complexity of each system component to be known. Nevertheless, such information is not always accessible or precise. Furthermore, this approach does not account for interactions amongst system components, which could result in an underestimation of the system's reliability.

Despite these constraints, the utility theory method serves as a valuable tool in calculating the reliability and durability of trailers. However, it is crucial to remain cognizant of the method's limitations and to utilise it in tandem with other methods.

2 Materials and methods

The benchmark values of the requisite indicators for a product's constituent parts can be gauged in multiple ways, contingent upon the accessible a priori data. The subsequent methods and principles may be utilised in the computation of the reliability and durability standards for some aspects of the projected trailer:

1. Uniform Distribution Method [1]: This technique allocates equal reliability requirements to all system elements.
2. Significance Distribution Method [3]: This method designates superior reliability requirements to elements that hold a higher significance to the comprehensive reliability of the system.
3. Method for Distributing the Reliability Requirements of System Elements Proportional to their Repair Costs [2]: This technique assigns elevated reliability requirements to elements that incur higher repair costs.
4. Sensitivity Method [4]: This method allocates increased reliability requirements to elements that are more susceptible to failures.
5. Lagrange Multiplier Method (GOST R 54471-2011): A more encompassing method that can be employed to assign reliability requirements to system elements, considering a myriad of factors.
6. Method for Distributing Reliability Requirements, Considering Element Importance (IEC 60300.0-3-11): This technique designates superior reliability requirements to elements that are crucial to the overall system performance.
7. Method for Distributing Reliability Requirements, Considering the Relative Vulnerability of Elements (MIL-STD-756): This method assigns elevated reliability requirements to elements that are more susceptible to failures.
8. Method for Determining the Standard Values of Reliability Indicators for Product Components, Considering the Use of A Priori Information about their Output Parameter Alterations (ISO 3720): This method employs a priori data on the alteration in output parameters of system elements to ascertain the standard reliability indicator values.
9. Reliability Distribution Accounting for the Weighting Factor [1]: This technique allocates superior reliability requirements to elements vital to the system's comprehensive reliability, with an adjustable weighting factor to reflect the system's specific needs.
10. Method for Determining the Reliability Requirements of Components, Based on their Achieved Reliability Level and the Complexity of Failure Remediation [3]: This method designates higher reliability requirements to elements that have a lower level of achieved reliability or are more challenging to repair.

11. Reliability Requirement Distribution, Applying the Principle of Equal Potential Operational Losses for Each Machine Component, Given its Complexity and Work Share [2]: This technique assigns superior reliability requirements to elements with a higher potential for losses if they fail.
12. Method for Distributing Requirements for Mean Operational Time Between Failures of Product Components in the Absence of A Priori Information [4]: This method assigns equal reliability requirements to all system elements in the absence of any a priori data.
13. Reliability Requirements for Component Elements, Considering the Data from Operational Tests of Machines or their Analogues (GOST R 54622-2011): This method designates reliability requirements to system elements based on the operational test data of similar machines or their analogues.
14. Application of Utility Theory in the Distribution of Reliability Requirements for System Elements, Considering their Complexity (IEC 60300.0-3-11): This technique uses the utility theory to allocate reliability requirements to system elements, taking into account their complexity and functional importance.

The choice of method will depend on the specific needs of the system and the availability of a priori information.

The derived values of the standards within the production of trailers and their structural elements hold crucial significance, as they are intended to function as the principal guideline in the design process for the manufacture of trailers. This includes the evolution of calculation methodologies and the selection of testing equipment. This is of vital importance to the consumer, desiring their trailer to exhibit the necessary performance over an extended operational period.

A research study conducted by Sherazi et al. (2021) found that the probability of non-failure operation (PNFO) for any intricate technical system, comprising of 'n' elements, can be deduced using the following equation:

$$P_s = \prod_{i=1}^{n} P_{ei} \tag{1}$$

where P_{e1}, P_{e2}, P_{e3}, ..., P_{en} – represent the probabilities of non-failure operation (PNFO) for each individual element of the system.

Given that trailers are complex technical systems, composed of a vast array of elements, the estimation of their reliability utilising the aforementioned equation (1) poses a challenging mathematical problem. However, considering that the reliability of a system invariably falls below that of its most unreliable element, the structurally-functional scheme (SFS) of the trailer can be employed to distribute reliability requirements among its constituting elements.

The SFS provides data about the complexity of each element of the trailer, which can be employed to calculate the required probability of non-failure operation (PNFO) for each component. This approach towards distributing reliability requirements has been demonstrated to be effective in ensuring that trailers adhere to the necessary performance standards over an extensive operational duration. The required probability of non-failure operating (PNFO) of elements can be calculated using the following formula (2), as proposed by Sherazi et al. (2021):

$$P_{\mathrm{ei}} = P_s^{K_i}, \tag{2}$$

The intricacy of an element is given by the subsequent formula:

$$K_i = \frac{2(n-i+1)}{n(n+1)}; \tag{3}$$

where 'n' represents the total number of elements and 'i' denotes the position of the element in the ranked sequence.

Proposed by Sherazi et al. (2021), this formula hinges on the premise that a more complex element necessitates a correspondingly lower reliability level.

To ascertain the required probability of non-failure operating (PNFO) of elements, one can employ the steps outlined below:

1. **Designation of the Probability of Non-Failure Operating (PNFO) Ps for the entire trailer**: An initial step is to establish the overarching probability of non-failure operating (PNFO) for the complete trailer system.
2. **Composition of the Structurally-Functional Scheme (SFS) of the trailer**: The construction of the SFS aids in understanding the complexity and interrelationships of the various elements that constitute the trailer.
3. **Ranking of the trailer elements according to their complexity**: By ranking the elements based on their complexity, one can identify the most intricate components that may need special attention in terms of reliability.
4. **Defining the complexity coefficients Ki using the given formula**: Employing the provided formula, complexity coefficients Ki can be defined for each of the trailer's elements. These coefficients quantify the relative complexity of the individual elements, facilitating their comparison.
5. **Calculation of the required values Pei for each level of the trailer SFS using the formula PNFO = Ps^(K_i)**: This step utilises the previously calculated complexity coefficients Ki and the assigned PNFO of the entire trailer to derive the required probabilities of non-failure operation (PNFO) for each element.
6. **Determination of the mean time between failures (MTBF) for each element**: Finally, the mean time between failures (MTBF) is calculated for each element. This metric offers an estimate of the expected time of operation before a failure is likely to occur for each specific element.

Sherazi et al. (2021) demonstrated the above computation method using a trailer as an example. The outcomes of the calculation indicated that this method effectively ensures that trailers satisfy the demanded performance standards over an extended duration of operation.

In the academic investigation by Sherazi, Muminov, and Abdunazarov (2021), a technique for deducing the mean time between failures (MTBF) for trailer components employing the Weibull distribution was put forth. Originating in 1939 by Waloddi Weibull, this distribution is widely utilised to exemplify reliability data. Its equation is presented as follows:

$$P(t) = e^{-\left(\frac{t-c}{a}\right)^{b}}, \tag{4}$$

where 'a' denotes the scale parameter, 'b' signifies the shape parameter, and 'c' stands for the shift parameter.

The computation commences with the establishment of the present operating time 't', which corresponds to a specified probability of non-failure operating (PNFO). For instance, to determine the MTBF for a trailer with a PNFO of 0.7, 't' is set at 8500 km.

Following this, the MTBF for each component of the trailer is calculated. This necessitates an assumption that the operating time leading to the first failure or between failures for each component also adheres to the Weibull distribution. Consequently, the MTBF is computed using the subsequent equation:

MTBF = a / b

where 'a' and 'b' are the Weibull distribution parameters.

The computation's outcomes assist in evaluating the trailer's reliability. As an illustration, if a specific component's MTBF amounts to 10,000 km, it implies that the component has a 0.7 likelihood of not failing within the first 10,000 km of operation.

While the process of computing the MTBF of trailer components using the Weibull distribution is intricate, it facilitates obtaining accurate estimates of trailer reliability. Sherazi et al.'s (2021) research corroborated the accuracy of employing the Weibull distribution to estimate the MTBF of trailer components, a valuable tool in refining trailer design and ensuring adherence to required reliability benchmarks.

Tractor trailers, as an integral part of agricultural production, are typically subject to traversal on roads presenting rough surfaces. In order to emulate such challenging conditions, researchers employed a device designed with three imitation irregularities, the elevation of which could be adjusted to reflect the sort of unevenness one might encounter on real-life agricultural routes. These artificial irregularities, therefore, served as a stress-inducing factor to effectively ascertain the pressure exerted on the key load-bearing elements within the structure of the trailer.

The frequency of the irregularities, alongside the speed at which the trailer was moving, and the duration of fatigue tests were meticulously taken into account, all serving as critical factors in this examination. The comprehensive data obtained from these tests provided enlightening insights into the stress and strain the trailer elements were subjected to. Interestingly, the outcome of this rigorous simulation indicated that the second cross-beam appeared to be the most likely point of failure within the trailer's structure. This information proves invaluable in the continual quest to enhance the durability and reliability of tractor trailers for agricultural purposes.

In a bid to replicate the movement of a trailer on less than favourable road conditions typically encountered in real-world scenarios, researchers utilised a specially designed device [5]. This contraption was crafted to mimic roads with rough surfaces, featuring adjustable irregularities whose height could be varied as needed. This served a key role in evaluating the level of stress exerted on the integral load-bearing elements forming the structure of the trailer. It was thus possible to generate an accurate simulation of the harsh conditions the trailer would have to contend with.

In order to gain further insights into the structural integrity of the trailer, particular attention was paid to the nodes of the frame and body of the trailer. Here, the average stress endured by these crucial points was meticulously calculated, offering a clear picture of how these key components would fare under significant strain. Furthermore, the number of cycles leading up to the onset of destruction was assessed, presenting a timeline for potential component failure. This vital data helps us to not only understand the potential weak points of the trailer but also to envisage how long it may be before damage becomes evident, thus providing a path for potential preventative measures.

In order to gain a deeper understanding of a trailer's lifespan and key stress points, accelerated resource tests were implemented, simulating the movement of a trailer on challenging, rough surface roads. The findings revealed that the Mean Time Between Failures (MTBF) of the trailer came in at 2.46 years, equating to a respectable 18,120 kilometres of standard operation. In addition, these tests illuminated that the second cross-beam was the element most likely to succumb to failure, thereby providing key information for future improvements.

In terms of the methodology of these tests, the number of cycles preceding the emergence of destruction within the trailer structure was meticulously counted. This detailed approach served to offer an anticipated timeline for potential component failures. Furthermore, the tests also determined the reduced (corrected) yield strength of the steel utilised in the manufacturing of the trailer frame. This analysis of the material's resilience under various stresses can be extremely helpful for manufacturing and engineering enhancements.

The insights gleaned from such rigorous testing offer invaluable data on the robustness and dependability of trailers. Through the analysis of the accumulated data, opportunities to augment the design of trailers can be identified, ensuring they meet and exceed the requisite reliability standards. By understanding where and why components might fail, these tests not only help to mitigate future failures but also contribute to the creation of more resilient, efficient, and safer trailers in the long run.

3 Results and Discussion

Analysing and comparing specific coefficients with experimental data, it was discovered that a specific correction factor is most fitting for the frame structures of trailers. For a practical example, let's take into consideration a frame structure created from a certain grade of rolled steel, which has a defined yield strength. This allows for the establishment of a reduced yield stress. Using this and certain other calculations, the number of loading cycles can be approximated, which aligns with the calculated value found using the correct formula and experimental [6].

Thus, when estimating the lifespan of trailers made from steel elements of various grades, the correct formula with a specific correction factor can be used. In theory and in practice, different models have been developed for estimating machine resources. These models include calculations for tolerance, where the tolerance field is seen as a random process, and calculations for fatigue resistance, which uses a damage accumulation hypothesis [6]. The latter assumes that damage from a stress cycle accumulates and is independent of the part's state at the time or any previous loading processes.

A large quantity of random stress processes in frames and other metallic structures of mobile machines, over 10,000 to be precise, were analysed [7]. The findings from this analysis revealed that the variation coefficient of the amplitude distributions of complete cycles falls within a specific range. Within this range, it is possible to determine the values of certain parameters with a level of accuracy suitable for practical applications. To estimate the resources of the frame using this complex formula, a numerical computation programme was created using specific software.

In the final analysis, this research has shown the dependencies of the predicted number of stress cycles of a trailer frame on the stress level for a specific grade of steel. Various factors were considered in the calculations, including stress maximum, cycle number, variation coefficient, and more.

4 Conclusion

In their comprehensive 2021 study, Sherazi and his associates probed the durability and reliability of trailer frames. The research utilised a diverse array of methodologies, most notably the accelerated resource tests, as a means to replicate the movement of a trailer on uneven road surfaces. The conclusions drawn from the study indicate an average period of approximately 2.5 years before a trailer experiences failure. Furthermore, the research identified the cross-beam as the most likely point of structural failure.

These insights gleaned from the investigation hold significant potential for informing the enhancement of trailer frame design and reliability. The findings could provide crucial data to facilitate the conception and development of trailers that display increased durability and reliability, thus meeting the requirements of the contemporary transportation sector more effectively.

The investigation also provides some key implications beyond its primary findings. Firstly, it suggests that a trailer's anticipated lifespan can be calculated via a formula that considers the type of steel used in the frame construction and the conditions under which the frame is loaded. This is particularly valuable for manufacturers and regulators within the industry, providing a predictive tool to manage the life-cycle and efficiency of trailers.

Moreover, the study proposed a novel equation for estimating the endurance of a trailer frame. This equation, based on the Weibull distribution in conjunction with the power equation of the fatigue curve, could revolutionise how we evaluate the stamina of a trailer frame. Such an equation could significantly improve not only the planning and manufacturing processes, but also the cost-efficiency and environmental impact of trailer production.

Undeniably, Sherazi et al.'s (2021) research carries substantial potential to shape the future of trailer frame design and reliability. The study sets a precedent for developing more robust and reliable trailers, thus better equipping them to fulfil the demands of the transportation industry. Furthermore, by improving our understanding of frame durability, the study also contributes to the broader academic discourse on structural reliability and design.

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