Dr. Veena Rani, 2026, 14:1
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

A Comprehensive Study of the Bathtub Curve in Reliability Engineering

Dr. Veena Rani
Associate Professor G.N.C. Sirsa

Abstract - The Bathtub curve is one of the commonly used recognized models in reliability engineering, used to describe the failure rate of systems and components over time. The curve illustrates three distinct life-cycle phases of a system: early failures (infant mortality), a constant failure period (useful life), and wear-out failures. This paper reviews the theoretical basis, practical applications, and critical viewpoints of the bathtub curve. It also discusses reliability improvement strategies of this model.

Keywords - Bathtub Curve, Failures, Maintenance Strategies, Reliability.

I. INTRODUCTION

In reliability engineering, the bathtub curve represents the failure rate of a system or product plotted against time. The name bathtub comes from the curve resembling its shape to a bathtub- high at the beginning, low and constant in the middle, and rising again towards the end of life. As it is clear from the graph given below:

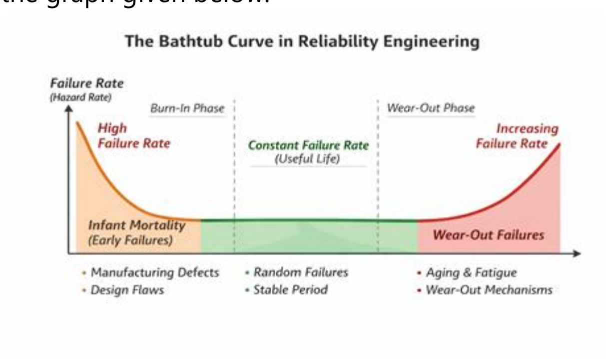

Fig. 1.1

Theoretical Background: There are three phases of the bathtub curve relating to its functions.
Infant mortality Phase: It is also called early failure period. It occurs when a product or system is used for the first time. It is clear from the graph that this period starts with high failure occurrence but then decreases slowly and eventually plateaus. Common causes of failures in this period are manufacturing defects, design issues, material defects or installation errors etc.

Useful Life Phase: It is also called constant failure phase or normal life period which starts after the initial operation. Most products spend the majority of their operational life in this state. It is clear from the graph that the product is still experiencing failure but at a very low and normal rate. In this period failures occur due to human errors, accidental breakdown, overloading or collision with other objects. For different products, failure rate may be different.

Wear Out Phase: It is also called the aging period. During this period the product and system enter in the final stage of its life cycle. It is also known as the end of life period. There is a gradual increase in the failure rate of products with increasing time. In this period failure occurs due to fatigue, wear, gradual deterioration, corrosion etc. These failures are predictable. Some manufacturers specify the useful life of products and components in their documentation.

Practical Applications: The Bathtub Curve is applied in:
Reliability Assessment of Electronic Components: The Bathtub Curve assesses electronic component reliability by predicting failures, identifying root causes, and implementing preventive maintenance (like burn-in testing) to shift products into the stable useful life phase, ensuring better quality and longevity for electronics.

Maintenance Scheduling & Warranty Analysis: The primary strategy is burn-in testing to eliminate weak products before they reach the customer. Reliability-Centered Maintenance and preventive maintenance based on scheduled intervals are suitable strategies to address random failures and maintain a stable failure rate. Predictive maintenance and condition-based monitoring are crucial to detect early signs of degradation. The goal is to perform major overhauls or replacements before catastrophic failure occurs, often using the P-F curve (Potential Failure to Functional Failure interval) to guide decisions.

Lifecycle Cost Modelling: Lifecycle Cost Modelling using the bathtub curve integrates cost management with asset reliability, mapping costs across the Infant Mortality, Normal Life, and Wear-Out phases, allowing for proactive maintenance strategies to optimize total expenditure, from high initial failure costs to rising end-of-life repair expenses, minimizing disruptions and extending profitable operation.

Accelerated Life testing and Quality Improvement: Accelerated Life testing is a method used to quickly determine a product's life characteristics and uncover potential failure risks by subjecting it to stress conditions like high temperature, vibration and voltage more severe than normal use conditions. The goal is to induce failures faster and then use analytical models to extrapolate the data and predict the product's reliability and lifespan under normal operating conditions. The Bathtub curve plays a very important role in this test. By applying insights from Accelerated Life Testing and quality control throughout the product lifecycle, organizations can effectively lower the overall failure rate and extend the useful life of assets.

Maintenance Strategies: Common maintenance strategies to prevent failures in different phases of bathtub curve are as follows:

- Perform preliminary tests using sensors or automatic technologies to decide whether to discard defective equipment or send them for repair/ replacement.
- Run acceptance and reliability tests to re-evaluate equipment or to check replaced parts of the product.
- Using burn- in –tests to understand how products perform in more demanding or stressful conditions than usual.
- The best way to prevent infant mortality is to use breakdown maintenance strategy.
- The preventive maintenance strategy is the most appropriate strategy for products in the useful life phase. We can also use predictive maintenance strategy to maximize product life in this period.
- Maintaining external conditions like temperature and air humidity level to keep product in its best working conditions.
- Repair of product in place of replacement to increase the product life.

Limitations:
The Bathtub curve has some limitations given below:
Oversimplification: The curve assumes three distinct sequential failure phases, but some products like complex systems or those with high repair rates, don't fit this pattern.

Inaccuracy for Modern Hardware: This model is inaccurate for complex hardware like servers, and doesn't always capture real-world factors like early retirement or maintenance effects. Also it does not show a clear wear-out period within their operational lifespan.

Ignore Maintenance & Usage: It doesn't fully account for factors like predictive maintenance or early retirement, which can distort the curve's shape.

Questionable Infant Mortality: The initial high failure rate (infant mortality) can be minimized by burn-in testing, making the curve's early part less representative of actual field failures.

Misleading Wear-Out Phase: Many items, particularly in aviation, show no significant wear-out period before retirement, contradicting the curve's increasing failure rate at the end.

Not for All Systems: This model is applied on a small percentage of applications, and it struggles with repairable systems where failures are constantly addressed.

II. CONCLUSION

A bathtub curve is an excellent model for measuring product failure risk levels. It projects the failure rates of products over their lifetime. By deeply, the reasons behind failure, we can adopt right preventive and predictive maintenance strategies. We can also decide whether to repair or replace the product based understanding on the root causes. This model helps to understand different failure mechanisms and thereafter to design Maintenance strategies. For minimizing wear out section, we can modernize products before the wear out period. Despite its popularity it can be seen that it is less applicable for systems with high repair ability, components without significant aging or fatigue.

REFERENCES

1. Balagurusamy, E. (1984): “Reliability Engineering”, Tata McGraw Hill Publishing Co. Ltd., India.
2. Rani. V. (2021), “Performance Analysis on Some Stochastic Models of Paper Mill Machines,” Ph.D. Thesis, B.M. University, Rohtak.
3. Sam Mannan, (2005): “Reliability Engineering” , Lees' Loss Prevention in the Process Industries (Third Edition), Butterworth-Heinemann,
4. https://accendoreliability.com/bathtub-curve-and-human-mortality.
5. Barlow, R.E. and Proschan, F. (1965), “Mathematical Theory of Reliability,” JohnWiley, New York.