Physics of Failure (POF) for Complex Repairable Systems

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Abstract
The system performance depends on the availability, efficiency of maintenance and operating conditions. The industrial systems are designed, manufactured and tested/simulated under laboratory/ideal conditions. But the conditions in which the systems are working in real-time industries/companies are different. Due to this, the components of each system will fail well before the schedule given by the company even though the periodic maintenance is carried out as per the manufacturer's standard operating procedures (SOP). The complexity of the system will increase failure probability and the effect of these failures on system performance. Therefore, it is important to know the critical components of the system. In this paper, a methodology proposes an integrated approach for availability estimation and physics of failure (POF) of repairable systems. The presented methodology is applied to on-road vehicles in Andhra Pradesh State Road Transport Corporation (APSRTC) as a case study. The availabilities of the buses are estimated and identified the transmission subsystem is a bottleneck in TVG, SML SL and EXP-type vehicles.

Keywords: *Repairable Systems, Physics of Failure, Availability, Failure Probability*

1. Introduction

Many complex systems such as passenger buses, locomotives, aircraft, mining equipment, auto motives, plant machinery etc., are maintained on a regular and continuous basis to ensure a certain level of availability and safety therein. These systems are generally repaired rather than replaced on failure to serve the intended function satisfactorily through the restoration process involving any manual or automatic actions that is other than replacing the system as a whole [1]. Therefore, the task of the maintenance department is concerned with is to ensure that the system/fleet would meet and continue to meet its established performance goals.

It is often desirable to assess and analyse the various reliability measures, viz., expected availability characteristic, frequency of failure, downtime/number of failure, cost of maintenance or any other characteristics influenced and can be assessed by the system age, usage, and operation based on the data accumulated in the customers' use environment. Such analysis also enables to optimise of the maintenance schedule tasks and planning & take action to improve the effectiveness of maintenance actions. These systems are ubiquitous in all walks of life, however, the techniques available to analyse them are not so vogue as compared to the techniques available for analysing non-repairable systems. This situation often leads to the application of incorrect analysis approaches and decisions thereof by knowingly or unknowingly applying the terminology, which is exclusively reserved for non-repairable systems [2]

The literature on repairable system reliability is vast and most often the techniques & models applied to analyse repairable systems have been Markov models, renewal theory approach, stochastic point process models (HPP, NHPP, GRP…by ignoring the downtime), and lastly, the simulation - for the more complex cases. These techniques invariably require experience, a substantial degree of knowledge in probability and statistics, statistical sophistication, assumptions, and an iterative procedure to solve analytical equations necessitating the use of special software on the part of analysts and practitioners. Summarily, these techniques are complex and computationally cumbersome for a variety of reasons and not intuitive to an engineer/manager supporting his customers. Additionally, the inability to justify various assumptions, ideas, and results to the management while doing such analysis has further forbidden its widespread use within an organization.
Therefore, it becomes imperative to employ a simple and statistically valid approach whose results can be well explained and communicative with the management and engineers.

To our knowledge, the Literature is hardly available that considers the downtime in analysis and assesses the availability of a system/fleet except for a brief mention found in. However, one can find several other practical scenarios & examples provided and well-presented therein [2].

The purpose of this work is to apply the non-parametric method for continuously varying the performance of passenger vehicles from the maintenance data collected for about three years. Note that many models ignore the maintenance downtime due to system failure or preventive maintenance, however, in practice the downtime for the systems like buses constitutes a significant part of their operational time that may affect the decision-making process. In such cases, a non-parametric approach plays an important role in the performance analysing of complex repairable systems without involving infeasible assumptions. The non-parametric models are useful in tracking field failures, identifying underlying failure causes, anomalous systems, unusual behaviour, and the effect of various parameters on the performance and failure of systems at the fleet level.

The rest of the paper explains the non-parametric method for availability estimation. A Non-Parametric method is applied to a real scenario of buses used for passenger transportation. Next applied physics of failure to identify the underline causes for the frequent failures in bottlenecks and concluded with possible solutions to mitigate the failures.

2. Availability Estimation

The repairable systems use availability as a performance index and include component or system reliability and maintainability. Availability is categorized based on the types of downtimes includes in computation [3]. Inherent availability (A_{Inh})will consider only corrective maintenance downtimes, where Achieved Availability (A_{ach}) considers only active maintenance time. But, in case of operational availability (A_{op}) considers the total down time required. This can also be termed as posterior availability based on actual events happened to the system when it had been in operation.

$$A_{op} = \frac{Actual\ Cumulative\ uptime}{Total\ time}$$

$$A_{Inh} = \frac{Actual\ Cumulative\ uptime}{CM\ time + Actual\ cumulative\ uptime}$$

$$A_{ach} = \frac{Actual\ Cumulative\ uptime}{CM\ time + PM\ time + Actual\ cumulative\ uptime}$$

In the above definitions, the efficiency and speed of the maintenance personnel will be indexed in Corrective maintenance (CM), as well as their expertise and training level. Preventive maintenance time (PM) is to prolong or mitigate failures of a component or system. But the total downtime includes Corrective Maintenance time, Preventive Maintenance time and Logistic delay time.

3. Data Collection

Buses have been used to haul both passengers, and freight on the country's road transportation. To maintain healthy and reliable systems with high availability proper maintenance is required for almost all types of its subsystems.

In this article, a problem that has not been addressed well in the literature is considered for the availability and physics of failure of Road transport systems with real-time operational data from maintenance sheds[4]The manufacturer desires to assess the availability of its buses from the maintenance record gathered from 2018 to 2021 to assess the availability of such vehicles and to determine some of the critical areas to improve upon.

Data should preferably be collected for individual components and equipment since data can always be combined, if appropriate, but it cannot always be disaggregated. In general, maintenance data collected on a timely basis may be either discrete or continuous. Field data collection should include the relevant technical information necessary such as unit id, operation time, failure mode and type of maintenance action etcetera for conducting a target analysis. Any analysis is said to be successful only when a rigorous, proper and authentic field data collection system is in place to avoid the situation of “GIGO-garbage in-garbage out” that majority of the industries forgo. This is a major challenge faced by any analyst to pre-process the data scattered all over in a useful and meaningful form and this study is also not an exception.

Table1. Available Vehicles for analysis.

S. NO	TYPE OF VEHICLE	COMPANY	NO. OF BUSES
1	Metro	Ashok Leyland	16
2	SML	Isuzu	05
3	Express	Ashok Leyland/ TATA	07
4	Super Luxury	Ashok Leyland/ TATA/ Eicher	15
5	TVG	Ashok Leyland/ TATA	31
6	Ultra-Deluxe	Ashok Leyland/ TATA	9
7	A/C	Volvo/Isuzu	5

Table 2: Sample Data Template

<table>
<tr><th>S. No</th><th>Date</th><th>Vehicle No</th><th>Company Name</th><th>Type</th><th>Schedule Maintenance</th><th>Remarks</th></tr>
<tr><td rowspan="2">1</td><td>11/10/2018</td><td rowspan="2">243</td><td rowspan="2">TATA</td><td rowspan="2">SL</td><td>complaint</td><td>clutch plate, ATF oil leak, fuse issue,
gear rod issue,</td></tr>
<tr><td>11/11/2018</td><td>complaint</td><td>cabin sound, acceleration plate, gear slip</td></tr>
</table>

4. Data Sorting

After collecting the data from the maintenance sheds it should be sorted as per data templates used to calculate availability.

Table 3. Data template for sorting data

S. No	Date	Type	Time of failure	Time of relief arranged	Completed time	Repair time (Hr)	Logistic delay (Hr)	TBF (Hr)	Total time (Hr)	Availability
1	24.1.18	TVG	18:30:00	19:30:00	14:20:00	5.10	1.00	570.3	576.4	98.94%
2	17.10.17	SML	19:00:00	20:00:00	04:00:00	16.00	1.00	6979	6996	99.76%

5. Results and discussion

From the analysis of maintenance data obtained from APSRTC shed, TVG (class of local bus), collected in the year 2019-21, it follows that about 25% of all the failures are found in TVG vehicle transmission problems and break problems (27%).
Each vehicle has different system failures shown in table 3, which gives detailed information like no. of failures in transmission failures, engine failures, brake failures, suspension failures, electrical failures, airlocks, oil leaks and other failures.

Table 4. Number of failures in each class of vehicles

S. NO	TYPE OF VEHICLE	ENGINE	TRANSMISSION	BRAKES	SUSPENSION	ELECTRICAL	AIR LOCK	OIL LEAK	OTHERS	TOTAL FAILURES
1	TVG	11	43	28	2	22	12	5	44	167
2	UD	4	8	30	0	10	0	2	13	67
3	SL	21	12	18	12	8	7	1	25	104
4	SML	5	3	0	0	4	1	1	6	20
5	ME	4	22	4	5	4	2	1	7	49
6	EXP	13	25	25	0	20	6	5	45	139
7	A/C	1	0	3	0	4	0	0	2	10
TOTAL		59	113	108	19	72	28	15	142	**556**
% of failures by each subsystem		**10.61 %**	**20.32 %**	**19.42 %**	**3.42%**	**12.95%**	**5.04 %**	**2.70 %**	**25.54 %**	

According to the information given in table 3, TVG vehicles have more failures in specific, and transmission failures are more in all vehicles. In that, Express and metro express vehicles face more no. of failures followed by TVG. Brakes failures are taking position two, for system failures in Ultra-Deluxe followed by TVG. The following pie charts give the detailed failure percentage for each class of vehicles.

Table5. Times data for availability estimation for each vehicle

VEHICLE TYPE	TIME TO REPAIR (HR)	LOGISTIC DELAY (HR)	TIME BETWEEN FAILURE (HR)	TOTAL TIME(HR)
TVG	88.20	24.05	74519.35	74631.60
SML	80.30	17.96	57301.65	57399.91
UD	14.60	3.90	16219.60	16238.10
SL	58.00	11.00	25224.00	25293.00
EXP	2.21	1.64	7283.00	7286.85

Table 6. Availability estimation for each vehicle

	AVAILABILITIES		
Type of Bus	**Inherent Availability (A_I) %**	**Operational Availability (A_o) %**	**Achieved Availability (A_A)%**
TVG	99	97	96
SML	99	96	99
UD	98	96	95
SL	99	97	96
EXP	99	**85**	**81**

It is observed from the data analysis and availability estimation the number of failures of express vehicles is less compared to TVG vehicles, the availability is less. This is due to either more repair time or the logistic delay [9].

Table 7. Code for each class of vehicle

Class of vehicle	Code
Express	A
Telugu Velugu	B
SML	C
Super Luxury	D
Ultra-Deluxe	E

Table 8. Type of failure-based vehicle sequence

S. No	Type of failure	Sequence
1	Transmission system failure	**A**-B-D-E-C
2	Brake failures	E-**A**-B-D-C
3	Engine failures	D-**A**-C-B-E
4	Suspension failures	D-**A**-B-E-C
5	Electrical failures	**A**-B-E-D-C
	Criticality sequence of buses	**A-B-D-E-C**

Based on the type of failures, the sequence of buses is A-B-D-E-C (Express-TVG-SL-UD-SML). The first failure system is A, i.e., an Express class vehicle facing transmission problem followed by braking system and transmission system in a class vehicle, Super Luxury, Ultra Deluxe and vehicles. This priority selection gives information regarding the maintenance and availability of the components for each type of system failure in all classes of vehicles.

6. Physics of failure

The physics of failure technique is used to understand the knowledge, underlying processes and mechanisms that lead to failures to improve the performance of the product [6].

The physical characteristics of the product and their variations in the manufacturing process have a relation in terms of the performance of the part. Under loading conditions, the responsibility of the product and materials to stressors is explained by the physics of failure. Also, evaluates the fattiness of use in terms of influencing parameter loads or stressors by POF [7].

Visual inspection, metallurgical characterization and finite element analysis can be used for the failure investigation of critical components in complex systems. The mechanism of the failures and their interference with the performance are examined and the influencing parameters of the transmission system are listed with the POF strategy. The cause of the failure of clutch packs is shown in **Fig: 1&2** based on visual inspection, components are separated from the concerning failure and severity are shown in **Fig: 3, 4, & 5&**. The inspection and analysis are carried out on critical components. [8].

From the above, we conclude that most of the failures are happening in the Express class followed by TVG, SL, UD and SML. Based on the company i.e., Ashoke Leyland or Tata, most of the transmission issues are concurred in Ashoke Leyland vehicles (Automated manual Gear system) and followed by brakes in Tata vehicles.

Causes for Transmission failure in Express class of vehicles:

- Clutch kit in passenger buses includes clutch disc, pressure plate and release bearing. And the transmission will be smooth if all the parts have follows standards and preferably from the same supplier. The release problem is due to a mismatch of parts.
- The clutch won’t release if the hydraulic fluid has leaked out from the cylinder, or the worn piston seal in a master clutch cylinder is. To fix the defective part has to be replaced.
- It is also important that the condition of the flywheel for smooth running. Resurfacing or replacement may be required if the surface is not clean, flat and free of creaks.
- Looseness of bolts (Bearings)
- Low, worn out or burned transmission fluid
- Solenoid problem
- Worn out gears
- Torque converter issues, etc.

Table 9. Express vehicle failure reasons

S.No	Vehicle Class	Company	Nature of failure	Reason
1	EXPRESS	TATA	Transmission	Clutch plate, gear rod displaced
2	EXPRESS	AL	Transmission	Gearbox
3	EXPRESS	AL	Transmission	Gearbox, clutch plate, clutch place boosters
4	EXPRESS	AL	Transmission	Gear slip, clutch boosters
5	EXPRESS	TATA	Transmission	Gear struck, clutch hard
6	EXPRESS	TATA	Brakes	Brake weak
7	EXPRESS	TATA	Brakes	Brake weak
8	EXPRESS	AL	Brakes	Brake weak
9	EXPRESS	TATA	Electrical	fuse
10	EXPRESS	TATA	Electrical	fuse, self-problem
11	EXPRESS	AL	Suspension	Axial Bolts
12	EXPRESS	AL	Suspension	Balloon suspension

Causes for brake failure in Express class of vehicles:

- Airlock
- brake pads wear out
- Pedal issues

Causes for brake failure in Express class of vehicles:

- High battery voltage, the life of the component

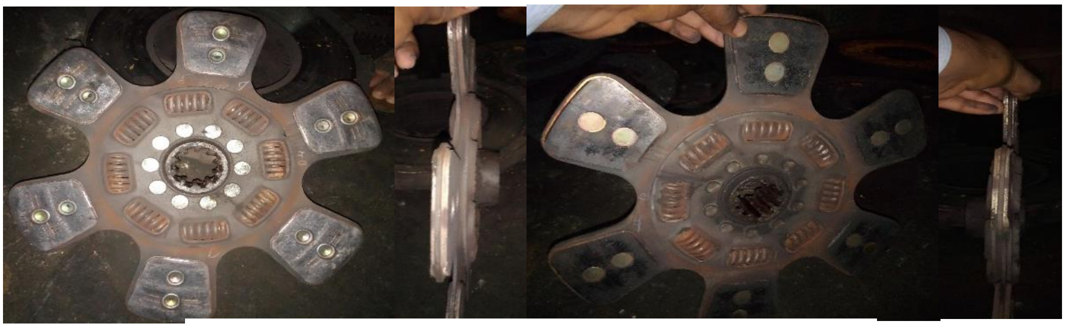


Fig1: TATA BS3 Clutch plate

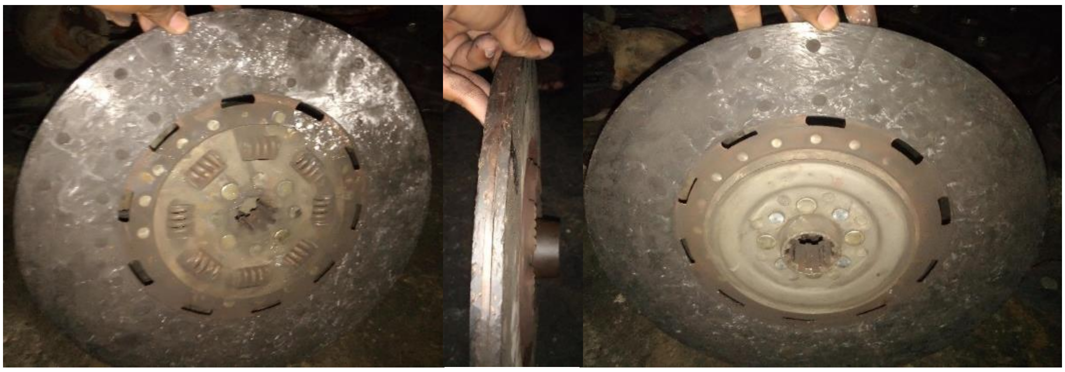
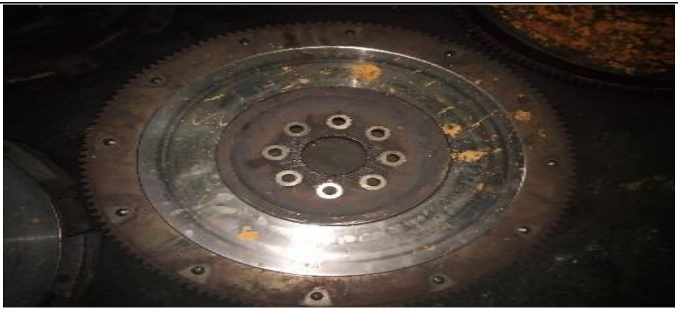
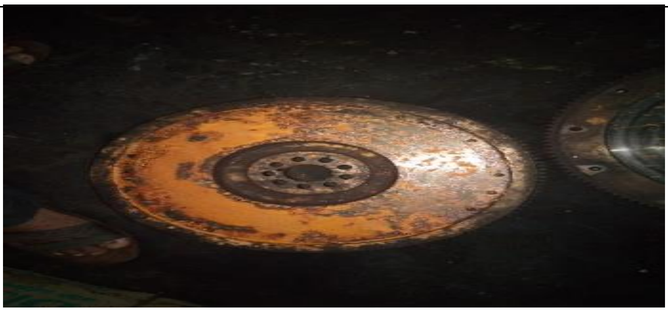


Fig 2: AL Clutch Plate

	**Fig3:Fly Wheel (Ashok Leyland)**
	**Fig 4: Fly Wheel (TATA)**
	**Fig 5: Pressure Plate**

The above failures can push the maintenance cost and time to repair. It can be avoided by a good maintenance strategy to prolong the life of components and also the life of an entire system. Some of the preventive steps are to be taken, Transmission fluid has to be changed at regular intervals, Defective solenoids are to replace for an automatic gear drive, Transmission bands and clutch has to engage and released in an exactly controlled time for the transmission to execute optimally. To repair this, defective bands have to be replaced (sometimes bands are fine and only need adjustment) and the torque converter may become worn or burned out from inadequate transmission fluid.

7. Conclusion

In the practical and theoretical analysis of the availability and physics of failure of vehicles of passenger buses in APSRTC, it is found that the availability of express vehicles is less compared to other classes of vehicles. This is due to more frequent failures in the transmission of express vehicles.

From the physics of failure, it is identified that transmission failures are more in Ashoke Leyland Express Class of Vehicles. In that, clutch problems are more. In Ashok Leyland, the Clutch plate was designed to transmit the full engine power. Due to that, the weight of the clutch is more than the TATA's vehicle's clutch plate and it will have more contact area that leads to friction failures like wear and tear.

Ashoke Leyland express class of vehicles are experiencing gear slip and gear struck due to Gear wear, improper engage and disengage of the clutch, low level of transmission fluids and inexperience of a driver.

Also, TATA vehicles are undergone frequent brake system failures. This is due to improper cleaning of water while maintenance will mix with the grease in airlines and form slug in the airlines this lead the vehicles to break down due to airlock. TATA vehicles undergo breaks down not only due to braking systems but also due to engine failures. TATA vehicles are using water pumps for engine cooling. If the pump is not working properly or not maintained desired water level leads to overheating of an engine that causes the engine to break down.

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