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Approach for Demonstrating Reliability Targets for Rail Transport during Low Mileage Accumulation in the Field: Methodology and Case Study

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Abstract**—**In railway industry, train sets are designed based on contractual requirements (mission profile), where reliability targets are measured in terms of mean distance between failures (MDBF). However, during the beginning of revenue services, trains do not achieve the designed mission profile distance (mileage) within the timeframe due to infrastructure constraints, scarcity of commuters or other operational challenges thereby not respecting the original design inputs. Since trains do not run sufficiently and do not achieve the designed mileage within the specified time, car builder has a risk of not achieving the contractual MDBF target. This paper proposes a constant failure rate based model to deal with the situations where mileage accumulation is not a part of the design mission profile. The model provides appropriate MDBF target to be demonstrated based on actual accumulated mileage. A case study of rolling stock running in the field is undertaken to analyze the failure data and MDBF target demonstration during low mileage accumulation. The results of case study prove that with the proposed method, reliability targets are achieved under low mileage accumulation.

Keywords**—**Mean distance between failures, mileage based reliability, reliability target normalization, rolling stock reliability.

I. Introduction

RAILWAY industry is one of the most efficient and environment friendly transportation system in the world. It is faster, comfortable, energy efficient, emits low percentage of CO_2 (less than 2%) and provides higher carrying capacity, reliable and safe services to commuters [1], [2]. In the Indian cities, metro rail is given preference over the other means of transportation system for the future mass rapid transit system (MRTS) [3]. The modern MRTS are evolving more multifaceted with high degree of automation in terms of state of art and technology. It is prerequisite of any automation to be safe and reliable. Safety and reliability of the metro rail system can only be ensured through the provision of reliable infrastructure, interfaces and rolling stock systems [4].

To be competitive in the market delivery of reliable rolling stock is an important part to be achieved by the car builder. Therefore, the manufactures are finding new ways to progress the subsystems performance and guaranteeing more reliability to system. In metro system, service reliability is of vital concern and it cannot be achieved if failures happen in the rolling stock beyond acceptable limit. Generally, the service reliability is measured in terms of train punctuality during service hours. If the failure occurred on the train and it impacts service punctuality, the failure is known as service affecting failure (SAF). The service reliability of the metro rail system is measured in terms of MDBF which is the ratio of distance accumulated by whole population of identical system (trains) to the total number of SAF occurred during the demonstration period. The reliability indicators and SAF definition vary as per the requirement of operating agencies of various countries and contract [5].

During the design phase, reliability requirements in line with service punctuality are allocated to train subsystem to meet the target at system level. In the later phase of product life cycle the allocated reliability target to rolling stock is demonstrated in the field. It is obligatory for the train builder to achieve the reliability target during the demonstration period.

To design, implement and manage reliability of the train system many international guideline/standards are available for the manufacturers such as, EN50126, EN 50128, IEC 61078, and IEC 62380 [6]-[9]. Further to assist the manufactures in the context of reliability for railway system, many studies have been published by various research groups such as, maintenance management of rolling stock fleets using failure statistics [10], reliability analysis using field failure data in selection of the preventive maintenance time intervals [4], high speed train traction system reliability assessment and management [11], derivation of lifetime distributions for cost-effective and efficient asset management using field failure data [12], maintenance policies creation by considering different reliability, availability, maintainability and safety (RAMS) parameters and failure characteristics [13] etc.

The aforementioned studies mainly focus on system design, RAMS analysis and asset maintenance management policy creation. It is also observed that the total distance travelled by the trains (fleet) is the basic parameter for the reliability target calculation. When trains are not running as per the design mileage in a given duration of time frame, it creates challenge for the car builder to demonstrate the target operational/ service reliability. As a result, operational MDBF target cannot be achieved. Incapability to demonstrate target MDBF may attract penalty to the manufacturer as failures have impact on the overall system reliability performance. If the number of failures is outside the acceptable limit, it is obvious that the

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manufacturer has to improve the system performance to meet the target. On the other hand, it is also important to respect the required test duration (total kilometer run) of the metro system during the demonstration period. Therefore, in this paper a typical issue of reliability demonstration in the field under scarcity of required mileage has been addressed. A case study of reliability demonstration using the field failure data and achieved mileage is presented. Based on the results of analysis, an approach is proposed to normalize the target value in relation with the operational distance travelled so that the target MDBF values can be reached.

II. System Description, Reliability Measurement and Demonstration Challenges

A. System Description

The Metro Rail under consideration is of 4-car configuration with design average annual mileage of 600000 cumulative car km per train. Additional details of metro rails such as, client, location, actual configuration and data have been sanitized in the study undertaken to maintain the confidentiality of the company and source of metro rail system.

B. Service Punctuality Measurement

As described in Section I, service punctuality is measured using MDBF index which is well accepted key performance index of the MRTS. In the present study MDBF has been calculated using (1):

$$MDBF_C = \frac{\sum_{i=1}^{n} KM_i}{\sum_{i=1}^{n} SAF_{ci}} \quad (1)$$

where subscript C (C = 1, 2… k) represents failure category type, KM_i is the total mileage travelled by ith train, and SAF_{ci} is the total service affecting SAF on the ith train for c^{th} category in a given duration of time. Service failure categories and their respective MDBF targets over a period of one-year demonstration window are defined as follows:

- Minor: Failure resulting in a delay to service is < 2 minutes with target $MDBF_{C=1}$ of 6500 KM.
- Major: 2 minutes < service delay > 5 minutes with target $MDBF_{C=2}$ of 25800 KM.
- Significant: Service delay ≥ 5 minutes with target $MDBF_{C=3}$ of 52000 KM.

C. Reliability Demonstration Challenges

Nowadays MRTS design consists of very intricate electronic systems and the timeline of train delivery from the manufacture to the operator is very short (ca. 2–3 years). Therefore, the service reliability is generally demonstrated in the field during the commercial operations. The initial stage of the service is characterized as stabilization or burn-in period. Failures related to infant mortality is revealed and addressed in the stabilization period of train operation. The definition and duration of stabilization period varies according to the various operating agencies and contracts. Nevertheless, this period generally lasts through the duration of initial six months of revenue operation. If any failure occurs then those shall be corrected and required design or process modifications are done through the change management process on the whole fleet of trains. After that, the next phase of constant failure rate begins. In this phase, operational failures are minimized, and the reliability statistics are calculated over the defined period to demonstrate MDBF.

The reliability of electronic component is heavily influenced by the electrical, climatic and mechanical environmental conditions [9]. Influencing factors involve various field use conditions such as, on/off phase, permanent-working phase, storage or dormant phase, temperature swings seen by the equipment etc. As a result, field use conditions have been taken into the consideration at the time of system design and reliability estimation. Under such scenario the reliability shall be calculated based on powered-on hour basis not kilometer. If trains are powered-on and put in standby mode it will not achieve required number of kilometers in a day. Even though trains are not powered-on their reliability is influenced by the environment conditions in storage or dormant phase. However mechanical components in general hardly fail unless there is a serious design or process/quality issue.

An example is shown in Table I where two trains are powered-on for equal time duration and have equal number of failures but the distance travelled by both the trains is different. Consequently, the calculated MDBF will not be same. It will become difficult to demonstrate MDBF over a demonstration period in case the total distance is less than the designed mission profile distance.

TABLE I
Failures during Power-On Hours

Train Number	Number of Failures	Power-on Hours	Distance Achieved in a Day (KM)	MTBF	MDBF (MKBF)
TS#1	2	20	300	10	150
TS#2	2	20	420	10	210

In next section, a case study is under taken to study the problem faced in the field related to the mileage accumulation and how to demonstrate MDBF in such situations.

III. Case Study

The field data collection and analysis is based on the new metro line started in the metropolitan city with few number of trains. Additional trains were put in the commercial operation after their validation testing and field trails. The methodology followed for the reliability analysis comprises of collection of field data, calculation of failure rate (FR) and MDBF statistics.

A. Data Collection

Day to day occurrence of the failures for all the trains is managed using the failure reporting analysis and corrective action system (FRACAS). The FRACAS manages failure database and reports the MDBF at subsystem and train level. In monthly meeting failure category, relevant failures and subsystem wise classification has been discussed among all the stake holders to decide on the failure counting. Thereafter, a required mitigation/corrective action is taken to resolve the failure issues.

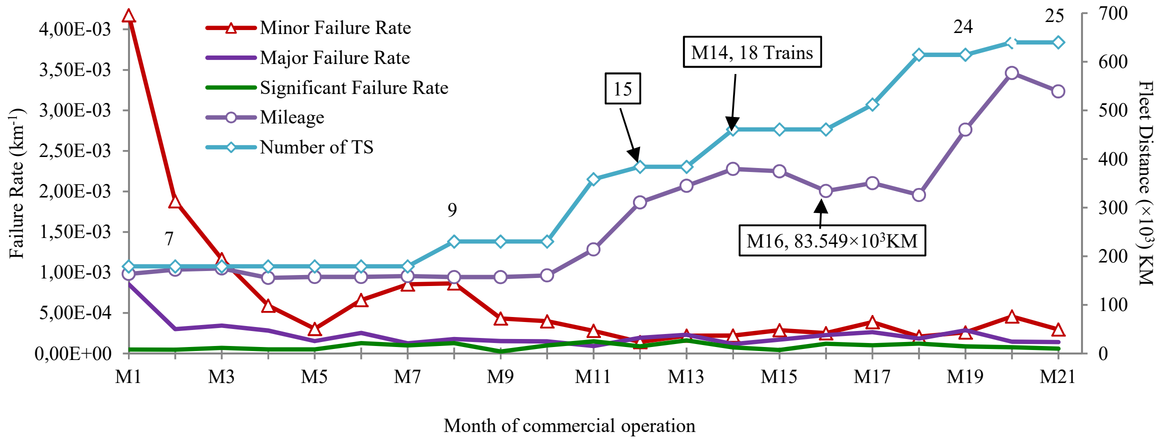

Fig. 1 Month of commercial operation versus FR, fleet distance travelled and no of trains

Failure data considered in this study are collected during twenty-one-month post five month of burn-in period. Field data are shown in Table II where Ci (i=1, 2, 3) and Ci/Train represent failure category and No. of failures per train, respectively.

TABLE II
FAILURE DATA COLLECTED FROM FIELD

Month	Distance travelled	No. of Trains	C1	C1/ Train	C2	C2 /Train	C3	C3 /Train
M1	163812	7	169	24.1	36	5.1	2	0.3
M2	172388	7	78	11.1	14	2.0	3	0.4
M3	174964	7	53	7.6	14	2.0	3	0.4
M4	155552	7	23	3.3	12	1.7	3	0.4
M5	157548	7	13	1.9	7	1.0	3	0.4
M6	157524	7	25	3.6	9	1.3	4	0.6
M7	159352	7	33	4.7	6	0.9	4	0.6
M8	157136	9	35	3.9	7	0.8	4	0.4
M9	157256	9	16	1.8	6	0.7	2	0.2
M10	160688	9	17	1.9	6	0.7	4	0.4
M11	214084	14	14	1.0	4	0.3	7	0.5
M12	310924	15	12	0.8	16	1.1	6	0.4
M13	344928	15	20	1.3	19	1.3	13	0.9
M14	379576	18	20	1.1	12	0.7	8	0.4
M15	374908	18	26	1.4	15	0.8	5	0.3
M16	334196	18	22	1.2	20	1.1	9	0.5
M17	350528	20	33	1.7	22	1.1	8	0.4
M18	326116	24	18	0.8	16	0.7	11	0.5
M19	460552	24	31	1.3	32	1.3	9	0.4
M20	576932	25	67	2.7	23	0.9	10	0.4
M21	539172	25	41	1.6	21	0.8	9	0.4

B. *Analysis of Failure Data*

FR is calculated using the failure data shown in Table II. The FR (km^{-1}) is defined as the ratio of total SAF to the total mileage accumulated by the fleet during the one-month period. Fig. 1 shows the FR of each failure category (C= 1, 2, 3), total monthly distance covered by the fleet and number of trains running in the commercial operation. It can be observed that the minor and major failures are decreasing from M1 to M5. Decreasing trend represents that the stabilization period is not yet over. There could be multiple reasons for not completing the stabilization period such that trains were not running adequately, failure understanding and resolution is not efficient, lack of operator experience to handle failures etc. During the period of M5 to M9 more number of minor failures reported and the reason identified was lack of operator experience to handle and report the relevant failures.

Failures per train set (TS) for the C1, C2, and C3 are calculated in the column 5, 7, and 9 of Table II and shown in Fig. 2. Number of failures is increasing proportionately as a consequence of addition of new trains in the commercial operation. This implies that the number of failures is increasing proportionately with respect to increase in total distance. It can also be explained using the FR equation (2):

$$FR_C = \frac{\sum_{i=1}^{n} SAF_{ci}}{\sum_{i=1}^{n} KM_i} = \frac{No.of\ TS \times \left(\frac{SAF_{ci}}{TS}\right)}{\sum_{i=1}^{n} KM_i} \quad (2)$$

Description of the subscripts can be found in (1). The numerator of (2) shows the direct proportionality between number of SAF and the failures per train multiplied by the total number of TS. It indicates that the increase in the number of failures is due to increase in the no of trains in the operation however the FR is constant.

As discussed in Section II that the reliability of electronic system is influenced by the various field use conditions other than the distance travelled. If trains are running less number of kilometers compared to operational profile the target reliability demonstration statistics cannot be attained. Refer to Fig. 3 where MDBF has been calculated considering one year rolling window using the actual distance travelled by the trains during the commercial services and compared with the target MDBF. The MDBF target corresponding to C1 failures is achieved by the rolling window of M2–13 and exceeded thereafter. Remaining two targets corresponding to C2 and C3 are not achieved till the month M21 (M10–M21).

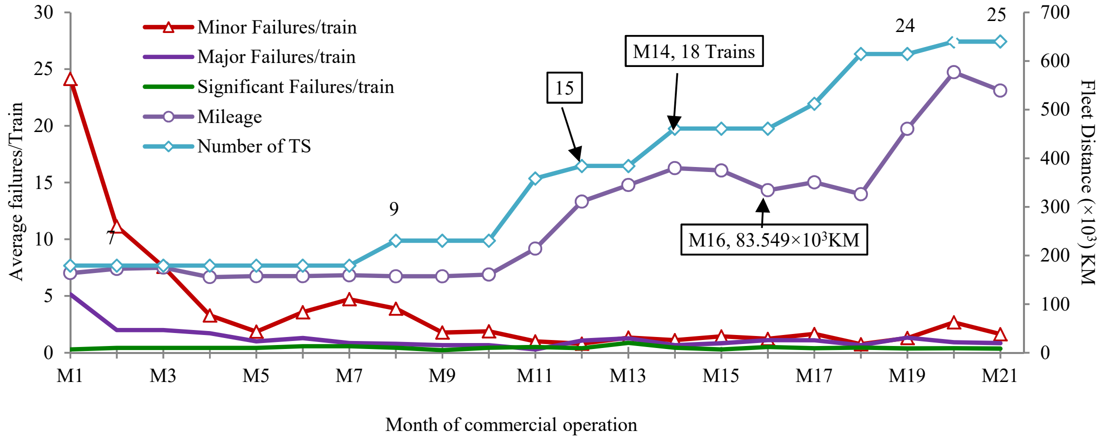

Fig. 2 Month of commercial operation versus average failure per TS, fleet distance travelled and no of trains

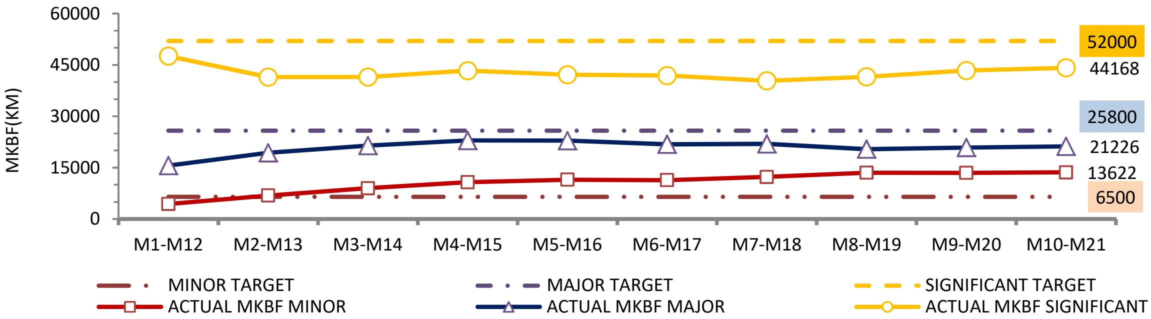

Fig. 3 Reliability demonstration based on actual fleet distance achieved

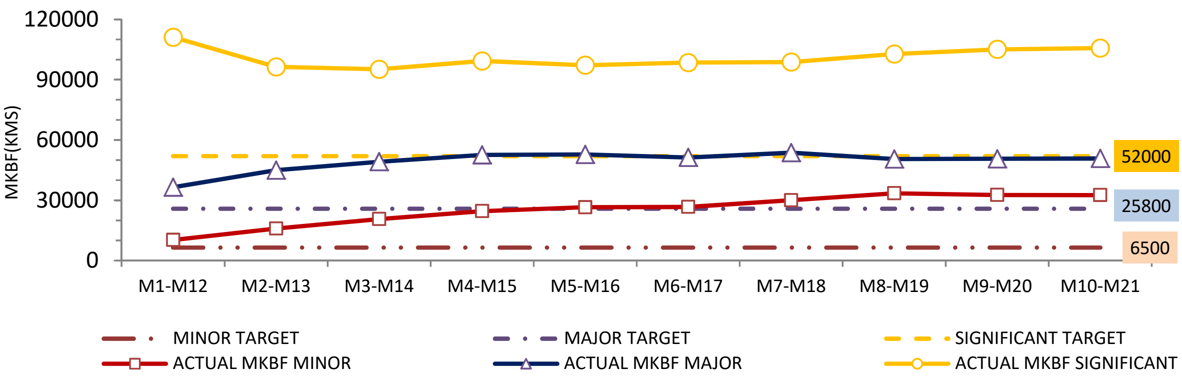

Fig. 4 Reliability demonstration based on design operational profile

IV. Proposed Solution

Considering the dependency of the demonstration on the fleet kilometers, two approaches are proposed to take into account of low fleet distance and reliability demonstration.

A. Direct Extrapolation of Kilometers

In this approach, total distance travelled by the fleet of trains is extrapolated based on the total distance expected in the design parameter. For example, each train is designed to travel 600000 cumulative car km per year. The fleet distance travelled is calculated based on the inception of each train in the commercial operation and expected distance to be covered. Refer to Fig. 4 for the reliability demonstration using the expected distance travelled by the fleet. It is observed that all three targets are achieved within the one year of rolling window M1–M12.

B. Normalizing Demonstration Target

If the failures are within the allowable failure limit which is defined from the design operational distance and MDBF target, then normalized target can be calculated using the actual distance travelled by fleet. In this approach, Chi-Squared distribution has been used to normalize demonstration target. It is well known that Chi-Squared distribution can be used in design of reliability tests when the failure time of system/parts follow an exponential distribution [14]. Equation (3) provides the confidence limit on Mean time to failure.

$$\chi^2_{1-CL,2f+2} = \frac{2n.T}{MTTF} \tag{3}$$

where: $\chi^2_{1-CL,2f+2}$ is the 1-CL percentile of a Chi-squared distribution with 2f+2 degrees of freedom, f is number of failures allowed, n represents number of test samples, T is test duration and MTTF represents mean time to failure.

The acceptable no of failures depends on the target MDBF and operational distance travelled. Test duration of one year and no of sample (i.e., trains) are already known in the case study undertaken in Section III. With the given information, (3) can be used to get the value of CL. Thereafter, new/ normalized target can be calculated using the CL identified and acceptable no of failures within the given test duration.

Above approach provides linear curves and normalize the target MDBF based on the actual distance covered by the fleet. For example, the allowed failure for C1, C2, and C3 failure category is 2308, 581, and 288, respectively. These failures are calculated for the 25 train sample with the expected fleet distance travel of 15,000,000 km in a year. The expected number of failures and expected distance travelled by the fleet provides the expected MDBF to be achieved during the rolling window, refer to Fig. 5.

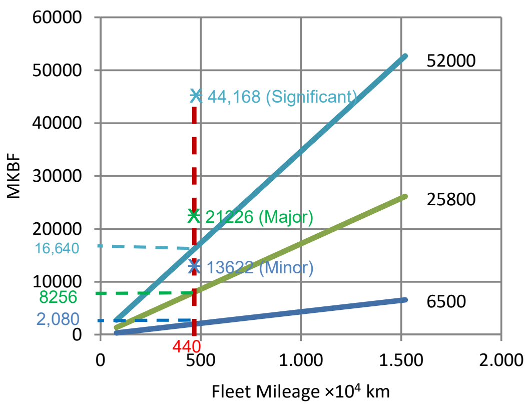

Fig. 5 Yearly Distance accumulated versus MDBF target

In Section III case study, the total distance accumulated by the fleet for window M10-M21 is 440×10^4 km (ca.), in that case normalized MDBF target to demonstrate the corresponding C1, C2 and C3 targets will be 2080, 8256 and 16640 kilometers, respectively as shown by dashed lines. However, as per Fig. 3, the actual MDBF achieved by fleet for period M10-M21 is 13622, 21226 and 44168 kilometers. Hence, by normalizing the target as illustrated, it is observed that all three targets are achieved for window M10–M21 and same can be illustrated for other earlier windows as well (e.g. M1-M12 etc.).

V. Conclusion

This paper presents the analysis methodologies to deal with the low fleet distance impacting reliability demonstration in railway industry. The problem has been identified and presented using the actual field failures data. Failure analysis has indicated that the failures are independent of distance travelled. The methodology presented in this paper provides the argument and justification to normalize the demonstration target.

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