Assessment and Improvement of Railway Track Safety

Ambika Prasad Patra[1*], Uday Kumar[1], P-O Larsson-Kråik[2]
[1] Luleå Railway Research Center, SE-97187, Luleå, Sweden
[2] Swedish National Rail Administration, SE-97102, Luleå, Sweden
E-mail: ambika.patra@ltu.se, uday.kumar@ltu.se, per-olof.larsson-kraik@banverket.se

Summary: In this paper, an approach has been developed to assess safety of the railway track by estimating the probability of derailment. Models for probability of derailment are developed based on undetected rail breaks and poor track quality using Petri-Nets and Monte Carlo simulations. The Effect of inspection intervals on lowering the probability has been analysed. The performance of the model is illustrated by an example from a track section of the iron ore line of Banverket (Swedish National Rail Administration).

Index Terms: Railway track safety, Maintenance, Petri-Net modelling

1. INTRODUCTION

Safety is the most important attribute of railway quality of service and operation. Infrastructure managers always try to reduce the number of potential risks areas that can lead to train accidents. Railway operations, that do not pay attention to reduce potential risks, face severe consequences. Risk has multi-fold consequences i.e., high society cost for compensation of deaths and injuries, material damages to infrastructure and rolling stock, cost of delay due to accidents and cost of damage to the environment. Proper maintenance planning helps infrastructure managers to reduce the potential risks. To study the effect of maintenance a case study was developed for a specific track section of the iron ore line of Banverket (Swedish National Rail Administration).The studied ore line Malmbanan, completed and operational by 1902, was later electrified with 15 kV 16 2/3 Hz, completed on 19th of January 1915, and remains so to this day. The studied track is a 1435 mm gauge. The track configuration is an electrified single track using block system. The signalling system (Low voltage DC track circuit), with its traffic control safety mechanisms, will detect any deviation that could be linked to a rail failure. However, the signalling system is not used as a maintenance planning/identification tool; it is a safety system for operating trains. Visual inspection is carried out separately by rail inspectors according to an inspection plan, recorded in a report and stored in a database. Visual inspection may also be carried out in an unplanned manner by the inspector to check the track condition between planned inspection intervals. Finally, track inspectors are obligated to report if they detect any deviation from normal rail condition, as they perform their daily maintenance work along the track.

Maintenance plays a vital role in improving safety performance of the track. In this paper the authors have tried to establish the relationship between maintenance intervals and safety performance. Petri-Net models have been used to model the safety performance of the track. The developed model in this work will estimate the maintenance investment required to achieve a specific safety level at a given point of time.

2. MODELLING TRACK SAFETY

Rail infrastructure consists of various sub-systems like track system, signalling and tele-communication system, and power system. Each of these sub-systems contributes to infrastructure safety.

Infrastructure managers use different indicators to measure the safety of the infrastructure e.g. number of accidents/per million train kilometres. Safety of the track is measured as number of derailments/per million kilometres as failures in track system leads to derailments not collisions. Broadly, performance indicators are classified as leading or lagging indicators. A leading, lead, or prospective indicator is a performance driver. The outcome measure itself is simply the lagging, lag, or retrospective indicator. Leading and lagging indicators can also relate to strategy or goals, and therefore it is important not to mix means and ends. These safety indicators are lagging indicator which only represents the current safety level of the track. If the infrastructure manager wants to improve the safety of track in future, it needs to have a lead indicator i.e., probability of derailment. Derailment because of track depends on the undetected rail breaks on track and poor track quality coupled with vehicle induced dynamic forces.

Let P_1 (t) = probability of undetected rail break on track at time t.
P_2 (t) = probability of track quality index falling below the maintenance limit at time t

Time here is expressed in Million Gross Tonnes (MGT). Probability of derailment due to rail breaks and poor track quality are given by K_1*P_1 and K_2*P_2 respectively. Factors K_1 and K_2 represent the external factors such as train speed, wheel condition, etc which induce dynamic forces. During winter time the trains have higher probability of getting wheel flats due to ice in the braking system. Wheel flats are major contributors to broken rail. In winter time the rail is in tensile stress due to low temperature which makes it more sensitive to external forces. It can be assumed that for a specific track section, K_1 and K_2 are constant because the track structure, speed ranges, climatic conditions do not change. Thus, if probability of derailment needs to be decreased, one needs to decrease P_1 and P_2. The model in this paper illustrates the effect of track inspection interval and track quality measurement interval on P_1 and P_2 respectively. The model relies on Petri-Nets and it provides dynamic means of modelling stochastic failure processes. A standard Petri-Net consists of a set of places, a set of transitions and a set of directed arcs. Directed arcs connect places to transitions and vice versa. The modelling is supported by software tool GRIF. Some of the data used in the models are taken from Banverket data bases **[1]** and some are hypothetical in nature. However, the assumed data are in close proximity to reality. The case study is based on a section of heavy haul line (10 kilometre in length) in north of Sweden.

2.1 Modelling rail breaks

There are many stresses that operate on rail and can influence rail defects and rail failure. Rail defects mainly consist of surface initiated defects, internal defects and weld defects. All these defects can potentially lead to rail breaks which are termed as rail failure **[2].** Fig. 1 describes the development derailments due to rail defects.

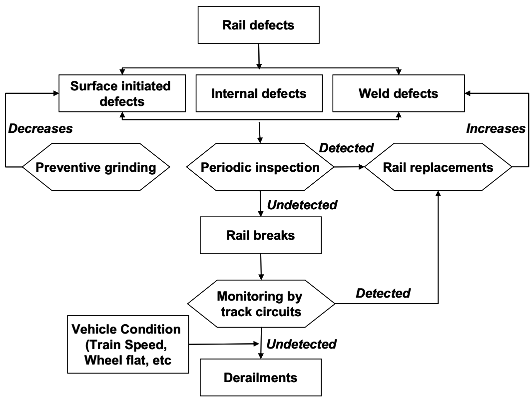

Figure 1: Logic flow of train derailment due to rail defects

Preventive grinding on the rail removes the rail surface initiates cracks in their initial phase and thereby stops their growth. Thus, formation of surface initiated rail defects such as head check, squats, etc are minimised. Internal defects (sub-surface initiated), such as shell and transverse defects, are associated primarily with heavy-haul railways. Though grinding is not used in general to remove embryonic cracks that cause shell formation, transverse re-profiling of the rail reduces stresses causing crack growth and hence shell formation **[3].** Weld defects are quite common on a heavy haul line especially the thermite welds. Until 2006 Banverket used flash butt welding to weld 40m rail to 320m and then 320 meter rails were welded by thermite welding. Today 60m rails are flash butt welded to 420 m and then 420 m rails are thermite welded. This decreases the number of thermite welds on track. In the proposed model only defects in thermite welds have been considered. Flash butt weld defects have not been considered as they show very low failure rate. On a heavy haul line, thermite welds on the rail become defective due to high axle loads in combination with cyclic loading. When a defective weld is repaired one more new weld is introduced and when a rail defect is removed additional two welds are added to the rail. Thus, the rate of thermite weld defect increases due to increase in number of welds. Periodic inspections are made to detect rail defects and remove them; however, there is a probability of detection attached to the ultrasonic inspection depending on the size of defect.

The P-F (Potential failure to Failure) interval of the rail defects is an important factor as it denotes the time interval between potential detection of rail defects till a failure (rail break) occurs **[4]**. The P-F interval for the rail defects is given in Table 1. Rail breaks are primarily detected by track circuits. However, not all rail breaks are detected by track circuits if rail breaks do not create a gap between the rails. These rail breaks remain undetected on the track until the next periodic inspection i.e., NDT or visual inspection. It is assumed in the paper that NDT inspection detects the rail breaks 100% of the time where as visual inspection detects 10% of the time. Undetected rail breaks on the track pose a serious threat to derailments. The probability of derailment should also consider the vehicle dynamics along with undetected rail breaks on track. In this paper contribution of vehicle dynamics to derailment has not been discussed. Authors have tried to reduce the probability of derailment by reducing the probability of undetected rail breaks by keeping the speed factor as constant as discussed earlier.

A Petri-Net model for estimation of undetected rail break has been developed (see Fig. 2). The model calculates the probability of undetected rail break(s) at any given point of time. Some of the parameters used by the model are given in Table 1. Table 1 illustrates the four types of defects that lead to rail break in the current study. UIC 421 is a thermite weld defect where as the other three are rail defects. The description of these defects can be found in UIC-712R i.e., catalogue of rail defects. As shown in Table 1, all these defects follow 2-parameter Weibull distribution. Detection probabilities of these defects by NDT car as well as visual inspection are also mentioned in Table 1. The rail is inspected by NDT car at every 12 MGT and visually every 0.5 MGT with the annual tonnage on the line is 24 MGT. If a rail break occurs, it is detected by track circuits. However, in case of rail breaks that do not separate the rails or rail gaps are small and are not detected by track circuits. In this model rail break detection probability of track circuits is assumed to be 0.98. Initial number of thermite welds for 10 km track is considered to be 32.

Table 1: Parameters for rail defects

Defect type	Scale parameter (η) in MGT	Shape parameter (β)	Detection probability by NDT Car	Detection probability by visual inspection	P-F interval in MGT
UIC 135	225	2.5	0.90	0.06	8
UIC 211	338	2.5			
UIC 2321	375	3.6			
UIC 421	333	3.1			

There can be a number of places on the rail where defects (surface initiated and internal) may occur and these places will change with respect to time. In case of weld defect (UIC 421), the number of welds will determine the number of defects.
Number of potential defect locations (PD) can be calculated from the equation given below

PD (t) = cumulative number of defects in time t / cumulative probability of defects in time t

Here time is considered in terms of MGT.
As defect is following a Weibull distribution, probability of defect in time t is given by
$F(t) = 1 - \exp(t / \eta)^{\beta}$

Cumulative numbers of defects are calculated from the inspection data of the rail. After each inspection the numbers of defects found on the rail are known. These defects are the defects that are detected by the NDT as well as visual inspections. When these defects are divided by detection probability, we get the probable number of defects that may have occurred during that inspection interval. When we add these defects with the defects of previous inspection intervals, we get the cumulative number of defects.

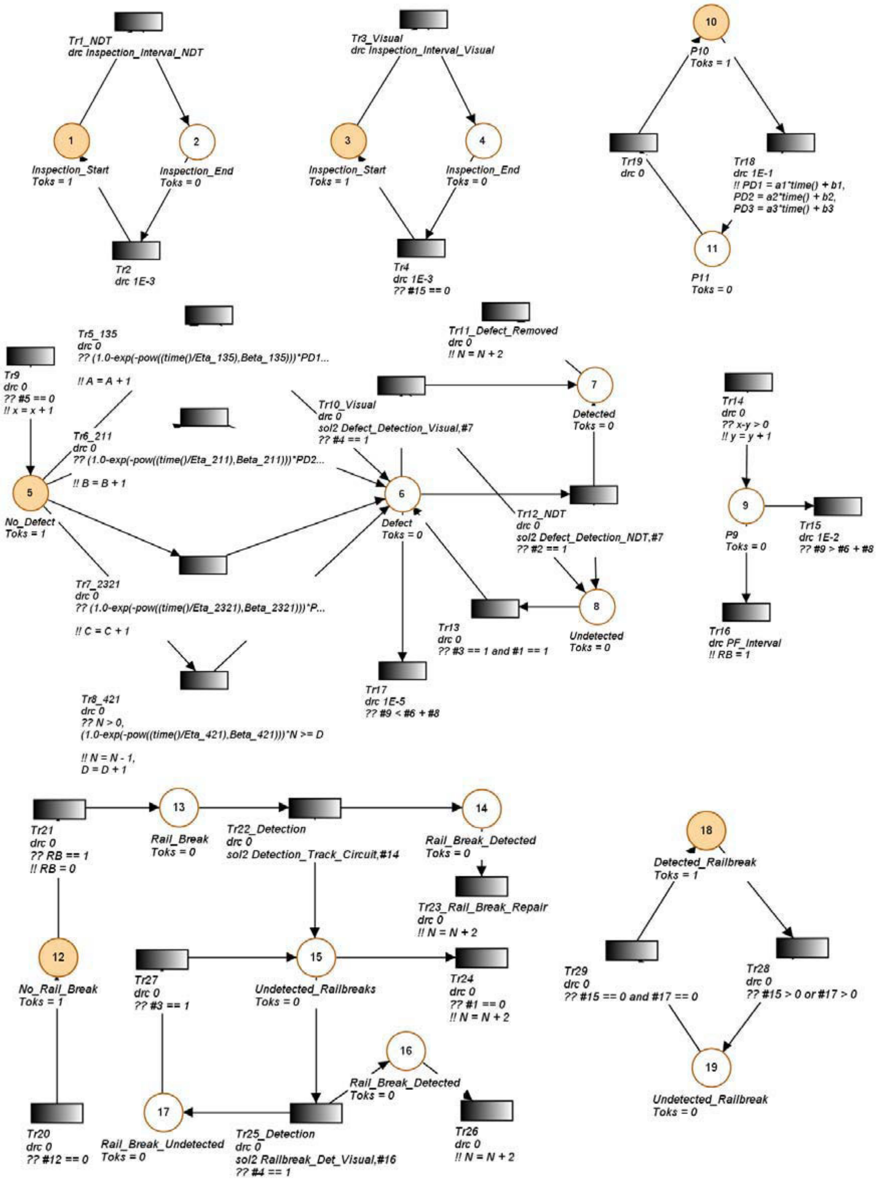

Figure 2: Petri-Net model for determination of undetected rail breaks

If we plot the values of PD with respect to time, we can get the trend for PD. When we multiply PD (t) with F (t), we can estimate the number of defects that we can expect at a given point of time. Table 2 explains the different places and transitions Petri-net model.

Table 2: Description of places and transitions of Petri-Net model for rail break

Places	Transitions
1: Start of NDT car inspection, 2: End of inspection, 3: Start of Visual inspection, 4: End of inspection	Tr1 and Tr3 fire at each inspection interval. Tr2 and Tr4 fire when the inspection is over
5: No Defect on rail, 6: Defects on rail, 7: Defects of rail that are detected by NDT or Visual inspection, 8: Defects that are undetected	Tr5, Tr6, Tr7 and Tr8 fire everytime a defect of either type occurs. Tr9 feeds the place 5 with 1 token each time a defect occurs.Tr10 fires when visual inspection is done and Tr12 fires when NDT inspection is done. Tr10 and Tr12 fire with detection probabilities mentioned in Table 1. Firing of Tr11 repairs the detected defects. Tr13 fires when defects are not detected by NDT or visual inspection. Those defects come to place 6 for next inspection.
9: Defects	Tr14 fires whenever a defect occurs. Tr15 fires when a defect is removed. Tr16 fires when an unremoved defect reaches its P-F interval. Firing of Tr16 initiates a rail break. Firing of Tr17 occurs when a rail break happens.
10 & 11: Act as counter for potential defect locations	Firing of Tr18 abd Tr19 calculate the potential defect locations for three types of defects in Table 1
12: No rail breaks, 13: Rail break, 14: Rail break detected by track circuit, 15: Rail break not detected by track circuit, 16: Rail break detected by visual inspection, 17: rail break undetected by visual inspection.	Tr21 fires when a rail break occurs. Tr20 feeds the place 12 with 1 token each time a rail break occurs.Tr22 fires with track circuit detection probability of detecting a rail break. Firing of Tr23 repairs the rail break. Tr25 fires with visual detection probability of a rail break. Firing of Tr26 repairs the rail break.Firing of Tr27 occurs when rail breaks are undeteced by rail visual inspection. Tr24 fires when NDT car inspection takes place and it repairs all the undetcted rail breaks from the track.
18: Rail break detected, 19: Rail break undetected	Tr28 fires when rail break(s) remain undetected. Tr29 fires when rail breaks are detected and repaired.

The incidences of rail defects are random in nature and the time for these defects to become rail breaks depend on the P-F interval of the defects. In this model it is assumed that if a number of rail defects occur during a period of time and remain undetected, the incidence of rail break depends on the P-F interval from the time of occurrence of the 1st defect. By performing Monte Carlo simulation on the Petri-Net model, probability of undetected rail breaks (with 90% confidence interval) with respect to increase in MGT on track has been found out (see Fig. 3). As seen in the figure, the probability of undetected rail breaks increases 5 times, when MGT increases from 200 to 300. The increase in probability is due to the fact that numbers of defects keep on increasing with increase in MGT. Thus, if proper maintenance measures are not taken with increase on accumulated tonnage on track, safety levels of the track will go down and more derailments will be expected to occur. Fig. 4 depicts the change in probability of undetected rail breaks with change in inspection interval from 12 to 6 MGT for MGT 250 to 300. Mean value of the probability was considered. While doing this sensitivity analysis all other parameters were kept constant. With increase in inspection frequency, infrastructure manager can estimate the extra maintenance investment that it has to put so that it can achieve the desired safety level.

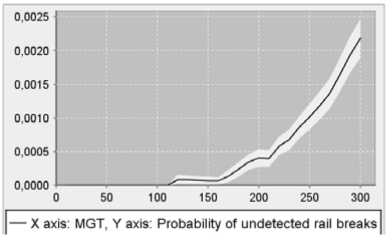

Figure 3: Probability of undetected rail breaks vs. MGT

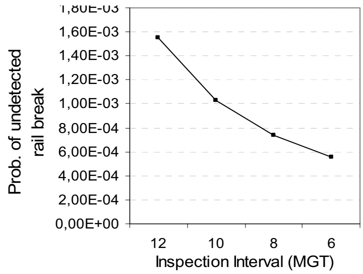

Figure 4: Change in probability of undetected rail breaks with change in inspection interval for MGT 250-300

As discussed earlier currently Banverket is reducing number of thermite welds by welding 420 m rails instead of 320 m. Also the manufacturing quality of rails has increased considerably which reduces defects like tache ovale (UIC 211). Fig. 5 illustrates the probability of rail break in the current practice. As these are newly laid rails, the defect statistics are not obtained yet. Thus, the same potential defect locations that were considered for old rails have also been considered in Fig. 5.

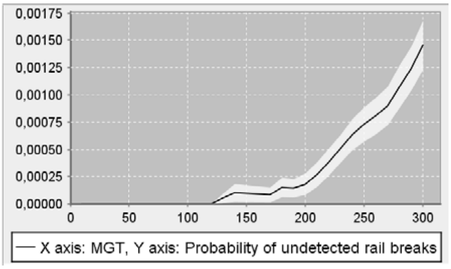

Figure 5: Probability of undetected rail breaks vs. MGT for newly laid rails

If we compare the probability of Fig. 5 with Fig. 3 at 250 MGT, we can see that in the newly laid rails there has been 25% decrease in probability.

2.2 Modelling track geometry deterioration

Track geometry deteriorates primarily due to the influence of dynamic loads exerted by vehicles. Continuous measurements of track geometry are necessary in order to make decisions on maintenance. Banverket has a number of condition indices to describe the condition of their infrastructure facilities. The main condition indices are known as K-value and Q-value. These are calculated from detailed inspection car measurements of the track. The inspection car measures relative rail position (lateral and vertical), rail profile and rail gauge. The Q-value is a weighted index of the standard deviation of two inspection car measures calculated as deviation from geometric comfort limits set for specific track class. The Q-value is calculated per kilometre track as:

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H\,\lim}} + 2.\frac{\sigma_S}{\sigma_{S\,\lim}}\right]/3$$

where σ_H and σ_S are the average standard deviation of height and interaction on the section measured. The standard deviation for interaction is calculated as a combined effect from cant and side position of the rail. σ_{Hlim} and σ_{Slim} are the comfort limits for a given track class. Track class classifications are based on the speed of the train. Banverket uses the following levels for a specific class of track **[5]**.

- A: New built or recently adjusted track
- B: Lower quality limit. It states target value for maintenance actions. The track irregularities should normally be adjusted before this level attains. This limit is often related to comfort aspects.
- C: This limit should not be exceeded. The track irregularity must be corrected as soon as possible. Reduced speed limits should be taken into consideration until the irregularities have been corrected.

In this paper Q value for maintenance limit for the track is taken as 82. If the Q value falls below maintenance limit and tamping is not performed then probability of derailment increases. Q value is measured by the measuring wagon at every 24 MGT. Table 3 provides the Q value with passing tonnage and the time when tamping was preformed on track.

Table 3: Data of track quality measurement and tamping

Measurement (MGT)	Track Quality Index (Q)	Measurement (MGT)	Track Quality Index (Q)
24	95	144	79
48	88	168	92
72	81	192	85
96	94	216	78
120	86		
Tamping: 72 MGT, 144 MGT, 216 MGT			

By treating the data provided in the Table 3, the slope of Q value with MGT and the effectiveness of tamping were calculated. These values were used in the Petri-Net model described in Fig.6. Table 4 describes the different places and transitions mentioned in Fig. 6. Fig. 7 illustrates the change of Q value with passing MGT where as Fig. 8 depicts the probability (P_2) of Q value below maintenance (tamping) limit.

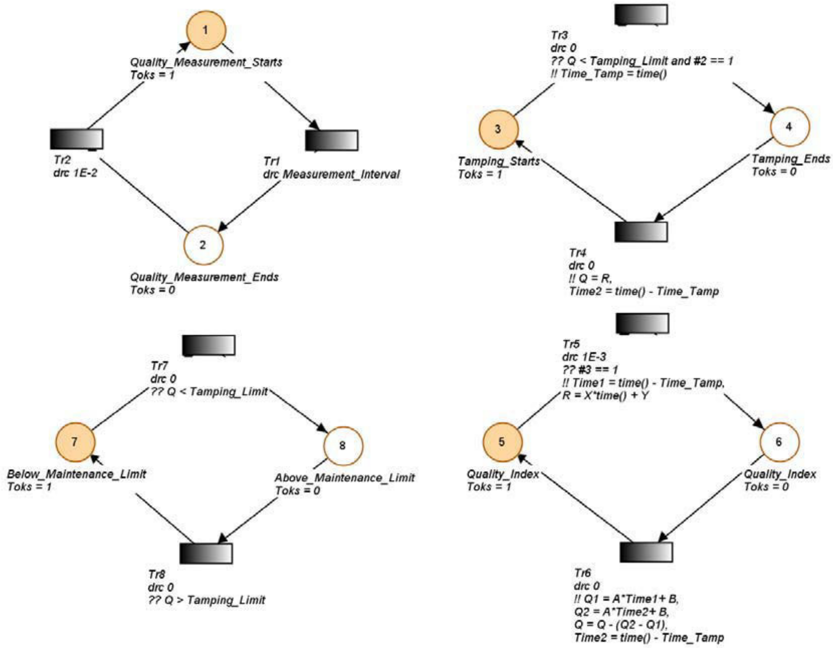

Figure 6: Petri-Net model for determination of probability of track quality index exceeding maintenance limit

Table 4: Description of places and transitions of Petri-net model for track quality

Places	Transitions
1: Start of measurement, 2: End of measurement	Tr1fires at each measurement interval. Tr2 fires when the measurement is over
3: Start of tamping, 4: End of tamping	Tr3 fires when Q value is below tamping limit and it is detected by the measuring wagon. Tr4 fires when the tamping is over.
5 & 6 : Act as counter for quality index	Firing of Tr5 and Tr6 calculate the track quality index at any given point of time.
7: Q value below maintenance limit, 8: Q value above maintenance limit	Tr7 fires when Q value falls below maintennace (tamping) limit and tamping is yet to be carried out. Tr8 fires when tamping is done and Q value is above maintenance limit.

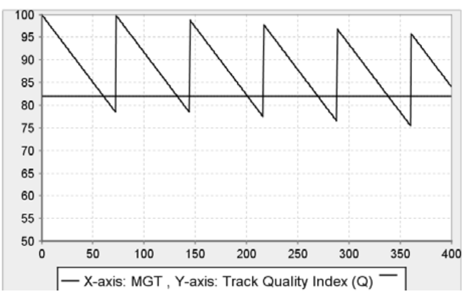

Figure 7: Q- value vs. MGT

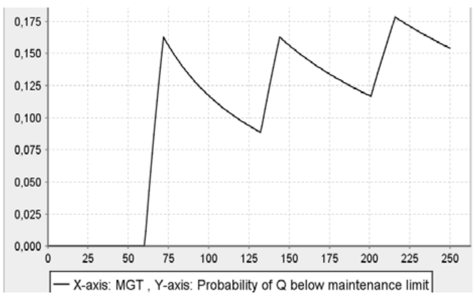

Figure 8: Probability of Q value below maintenance limit vs. MGT

It can be seen in Fig. 8 that as soon as the tamping is done on track, the probability decreases and hence the safety performance increases. However the overall probability increases with time; Fig. 9 illustrates the change in probability of Q value below maintenance limit with change in measurement interval for MGT 250 to 300. The mean value of the probability was considered. With increase in measurement frequency, infrastructure manager can estimate the additional maintenance investment.

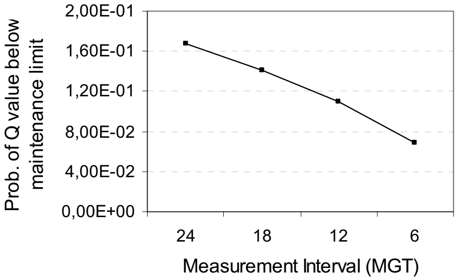

Figure 9: Change in probability of Q value below maintenance limit with change in measurement interval for MGT 250-300

3. DISCUSSION AND CONCLUSION

The safety performance of the railway track is compromised by derailments. Derailments take place due to faults on the track and/or due to bad vehicle dynamics. In these paper derailments due to undetected rail breaks and poor track quality have been described. However, derailments can also occur due to track buckling. Track buckling happens when the thermal stress in the track exceeds the track lateral resistance. Lateral resistance of the track changes due to maintenance work on the track. After each maintenance action, if the track lateral resistance is not restored to the original value, buckling may take place. The probability of buckling was not considered in this paper because probability of buckling depends on the quality of maintenance work rather than maintenance frequency. The Probabilities obtained in this paper can be used as safety indicators for the track. It has been shown in the paper that how frequency of track inspections and track quality measurements affect the probabilities. Reductions of these probabilities reduce the risk of derailment. This model will help the infrastructure managers to estimate additional maintenance investment to increase safety performance of the track to a desired level.

References

[1] Kumar, S., **Reliability Analysis and Cost Modelling of Degrading Systems**, PhD Thesis, Luleå University of Technology, Luleå, Sweden, ISSN: 1402-1544

[2] Zhao, J., Chan, A. H. C. and Stirling, A. B., **Risk Analysis of Derailment Induced by Rail Breaks − a Probabilistic Approach**, Annual Reliability and Maintainability Symposium, 2006, pp.486-491

[3] Cannon, D. F. *et al.*, **Rail Defects: An Overview**, International Journal of Fatigue & Fracture engineering Materials & Structures, Vol. 26, October 2003, pp. 865-886

[4] Vatn, J., Podfillini, Z. E. and Svee, H., **A Risk Based Approach to Determine Type of Ultrasonic Inspection and Frequencies in Railway Applications**, the World Congress on Railway Research, 2003, Edinburgh, UK

[5] Lindahl, M. **Track Geometry for High-speed Railways**, TRITA – FKT Report, Royal Institute of Technology, Stockholm, Sweden, ISSN: 1103: 470X