Information Analysis of Rail Track for Predictive Maintenance

R B FAIZ , S.SINGH
Department of Computer Science
Loughborough University
Leicestershire, LE11 3TU
GREAT BRITAIN
R.Faiz @lboro.ac.uk, S.Singh@lboro.ac.uk

Abstract: *T*rack defects are deviation of actual from theoretical values of the tracks geometrical characteristics. Track defects are macroscopic and geometric in nature and are exclusively the consequence of train traffic. [5]

Rail track maintenance in terms of track geometry and other modalities like rail profile, ultrasonic's etc has been typically based on use of reactive maintenance. In case of such reactive maintenance discrete exeecedence of track geometry parameter measurements are compared against a pre-set threshold such that if they exceed the threshold then reactive maintenance is required to be done. This is particularly so in cases when current practices rely on conservative, engineering, decision. Besides it will not inform staff regarding defects in rail track which can subsequently helps in predictive maintenance.

This paper focuses on variable and time based linear regression analysis of track geometry parameters which can lead to significant predictive maintenance of track geometry. The over all aim of this research paper is to propose a predictive maintenance frame work that would assist in predicting future changes in rail track geometry measurements. Such framework can evaluate and prioritise track geometry maintenance effort across network rail. It will cause alarms before the defects will actually happen. Such research will result in effective and efficient rail track maintenance management resulting in low operating cost better train transit times for rail industry [2].

Key-Words: Predictive Maintenance Management, Rail Track Geometry, CURV, Cant Def, Cross Level, Dipped Left, Gauge.

1. Introduction

The railway track system is an important part of the transportation infrastructure of a country, and plays a significant role in sustaining a healthy economy [10]. The annual investment of funds to construct and maintain a viable track system is enormous. Unfortunately the pressure on rail road to reduce operating costs usually result in cutting or eliminating investment in research because it often does not generate a short term return on investment.

One of the most important railway engineering tasks is effective and robust condition monitoring, as track degradation problems can have serious affect on the safety of train operations [11]. In order to determine an effective condition monitoring strategy it is necessary to analyze track geometry parameters.

Maintenance can be either corrective: fixing on failure or it can be preventive: predicting failures before they happen. It is often very difficult to predict all maintenance and thus in reactive maintenance, expert judgments are made on the basis of imperfect information and previous experiences with a relatively short-term view of the future impacts on future maintenance.

In contrast to reactive maintenance predictive maintenance avoids excessive cost normally incurred by corrective maintenance. Besides it helps preventing defective track components and ensures that they carry out their intended functions throughout their service life. [3]

There are two key approaches to preventive maintenance. One is Time Directed maintenance in which time directed tasks are performed to prevent defects. Other type of maintenance is Condition-Based Maintenance which is also known as on-condition maintenance or condition-directed maintenance or predictive maintenance. It is designed to detect the start of a failure in conditions where either failure prevention is not feasible or how it can be achieved is not yet known. Condition maintenance is based on periodic inspection of rail track parameters thus helping in determining the true condition of rail track in time.

In rail industry, there is a widespread belief that corrective maintenance is always less economical than preventive maintenance [4]. As a result, time-directed maintenance becomes the norm of preventive maintenance action, motivating the indiscriminate use of overhaul or preventive replacement procedures. This approach to preventive maintenance, firstly, wastes a lot of resources in doing unnecessary tasks which will not reduce defects in rail track and secondly it is potentially risky [4].

2. Track Geometry

Track geometry is the study and analysis of the spatial position of rail track. X-axis defines the distance along the track towards the direction of the travel. Y defines the axis parallel to the running surface and Z defines the axis perpendicular to the running track

Track geometry has ballasts, sleepers, rail, and clips etc. Now track geometry can deteriorate because of frequent passage of heavy traffic, climate changes (weather), variations in soil conditions and geotechnical movements. Each track is composed of two types of structures:

The interaction between track components under a moving wheel load causes a large impact load, which increases with increasing track irregularity and train speed. This is because impact load increases with an increase in the size of the gap underneath the sleepers. The impact load increases the stresses on the ballast which, as a result, increases ballast settlement and ultimately results in a larger gap underneath the sleepers. Thus, degradation of track geometry tends to get faster. One the most effective way of restoring a track which has lost his geometry is by tamping. However, this may also result in ballast break downs.

Reasons for Rail track Deterioration: Common effects of trains on rail track which result in more frequent rail track deterioration thus resulting in maintenance of track are:

1. The number of trains passing through as higher the number higher the rate of rail track deterioration would be.
2. A track may be subjected to heavy trains instead of light ones.
3. Speed has an important influence on track deterioration as high speed tilt trains are worse than average speed trains.
4. Better rail profile (stronger steels) gives less deterioration than rail profiles (weaker steels).
5. Track laid on blast deteriorates faster than slab track.
6. Stability of the track is dependent on type of soil it is laid on.
7. Thicker and cleaner ballast layer is better than thinner and dirtier blast layer.
8. Rate of deterioration of curved track is faster than tangent track.
9. Track deterioration can also be prevented by better drainage.

2.1. Track geometry parameters

Track geometry is fundamental for the safe passage of vehicles. Failing to be so, in which case, may result in disastrous consequences.
Rail defects are the most critical defects that affect the safety of train operations. Rest of the defects which are non critical are may occur in the rail but do not affect the structural integrity of the rail or the safety of the trains operating over the defect.

Degradation in track geometry due to frequent passage of heavy rail traffic, effects of Climate changes Like for instance flooding, extreme cold etc, variations in soil conditions and Geotechnical movements will cause the track to move away from the design geometry in both the vertical and horizontal planes and this deterioration away from the design can cause discomfort for passengers and eventually become unsafe for the passage of trains. To ensure the track can be repaired in good time, the deterioration must be detected and the worst areas prioritised so that engineers can maintain the track based on an urgency basis.

DIPPEDLEFT: Fish plate is a joint that is used to join two rails together longitudinally. These longitudinal rails may be joined together by a fish plate. When the joint wears out it dips on inner sides as shown in the diagram 1. It can happen on either rail left (dipped left) or right (dipped right**)**. Series of dips at regular intervals in one or both rails of track can also cause derailment.

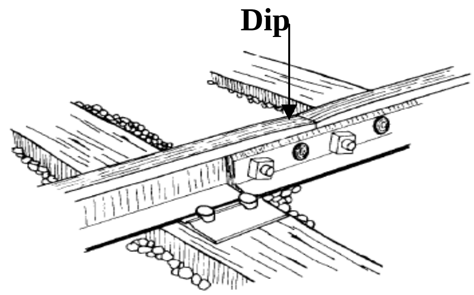

Figure 1 [3]

CURV: A track can be either of three types: tangents, curves, and spirals. A tangent track refers to straight track (As shown in Figure 2) and a curve track refers to a track with measurable curvature (As shown in Figure 2).

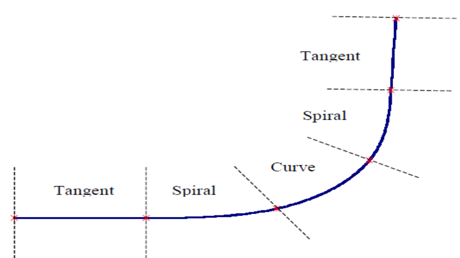

Figure 2 [3]

Track curves are typically identified by degrees. As explained in Figure 2, a one-degree curve is defined as a curved section of the track with a radius such that a 100-ft cord corresponds to a one-degree arc

The term spiral track refers to the section of the track that acts as a smooth transition between tangents and curves (As shown in Figure 2).

So curvature (CURV) is the spatial rate of turn in the horizontal plane of the track. It can be measured by measuring the distance between centres of string to the centre of rail in a curve or it can even be calculated by radius formula.

CANTDEF: As most trains cannot lean (or tilt) into curves to counteract the centrifugal (G) force, the track is canted (one rail raised above the other) into the curve so that the forces are at equilibrium at the maximum line speed. This parameter calculates whether the cant is sufficient to ensure the comfort of passengers and safety of freight.

The difference between levels of two rails in a curve is called as track cant (which is same as super elevation) and is arranged to compensate lateral part of acceleration. A cant angle arises where cant is rearranged. Maximum value of cant is set with respect to stationary conditions and slowly running trains so as to avoid passenger discomfort at stand still or low speed and risk of derailment of freight trains. It is than desirable to have cant deficiency some amount of uncompensated lateral acceleration remains in the track plane. So in other words cant deficiency is the difference between equilibrium cant and the actual cant. [7]

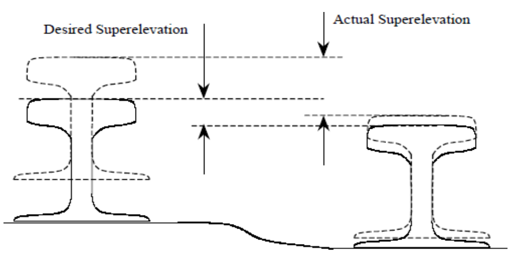

Figure 3 [3]

Cross Level: Cross Level is the difference in elevation between the top surfaces of the two rails measured at right angles to the track as explained in figure 4. On curves cross level is often referred to as 'cant' or 'super elevation'. On curves the track will have a designed cross level to counteract the g forces involved in a train changing direction at speed.

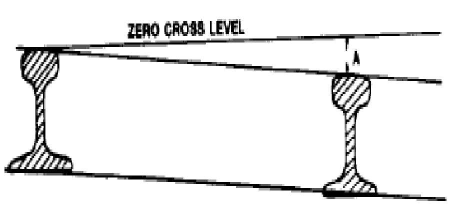

Figure 4

So the cross level, not to be confused with the super elevation, is the amount of vertical deviation between the left and right rail from their intended distance or it is the intended increase in elevation of the outer rail above the inner rail in curve. The intended distance refers to the amount of super elevation. For instance, if the super elevation is zero, then any difference between the elevation of the left and right rail is the cross level.

If the super elevation, however, is a positive, for example, then the cross level is the deviation from this super elevation. A positive cross level refers to the case when the left rail is above the right rail, and a negative cross level refers to an instance when the left rail is below the right rail. [8]

Super elevation is the amount of elevation that the outer rail in a curve is raised above in comparison to the inner rail. This is being done to compensate centrifugal forces that the vehicle will experience when travelling through a curve for that reason the outer rail may be raised, or super-elevated so as to tip the train inward. Now super elevation can either be positive super elevation: when the left rail is raised above the right rail or a negative super elevation when the right rail is raised above the left rail (as explained in fig 3).

Track Gauge: Gauge is the distance between the two rails, measured at right angles to the rails in a plane below the top surface of the rail head. Gauge can also be defined as the lateral deviation of the width or distance between the rails or it is the lateral deviation of the track from its nominal gauge.

Therefore, the term gauge, when discussing track geometry, will refer to the deviation of the track from its nominal gauge. A widening of the gauge corresponds to a positive deviation, while a negative deviation corresponds to a narrowing of the gauge.

So according to Figure 6 the Gauge deviation can be computed subtracting nominal deviation from actual deviation.

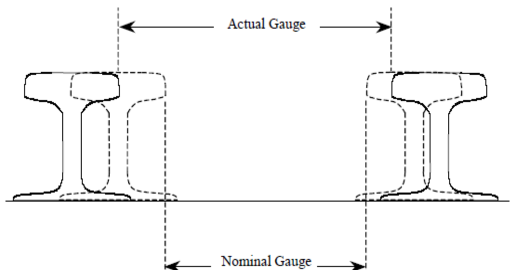

Figure 5 [3]

3. Existing Track Condition Monitoring

Deprivation in track can either due to heavy rail traffic or effects of Climate changes including flooding, extreme cold etc accompanied by variations in soil conditions and Geotechnical movements will cause the track to move away from the design geometry in both the vertical and horizontal planes. This deterioration moves the track away from the standard design can cause discomfort for passengers and eventually become unsafe for the passage of trains.

Track maintenance can range from isolated spot defects to complete relaying and replacement of track bed. One of the most challenging tasks, in recording track design, is to measure how much a track has moved from its original design. When the track condition is close to its minimum quality standard of network rail it gets closer to derailment which may result in higher repairing and maintenance costs.

In network rail, track condition can be monitored by either standard deviation or discrete execedence. Discrete execedence involves situations where there are large track movements over small distances can jeopardise the safety of track. To answer these situations track engineers have two levels of exceedence. Level 1 includes Twist, Tops, Alignment and Gauge. When exceedence in any one of these is observed unambiguous actions are taken Like for instance “Close the line” or if the exceedence is serious than “Repair it with in 36 hours”. Where as in level 2 positions of the exceedence are marked by paint. [6]

Some discrete exceedances require an emergency speed restriction to be imposed to reduce the risk of derailment and ensure passenger comfort. One of the side effects of this is the delay caused to trains traversing the area. In the UK the cost of a speed restriction ranges from around $90 (£40) to over $460 (£200+) per-minute-per-train depending upon the type of route and is paid to affected parties by the organisation causing the delay. [6]

By far one of the biggest cause of train delays is infrastructure problems, so Rail companies pay a great deal of money to train operators each year. Most of the very large costs are related to speed restrictions imposed to ensure the safe passage of trains over poor quality track or damaged rails.

4. Experimental Design

The aim of this research paper is to propose a predictive maintenance frame work that would assist in predicting future changes in rail track geometry measurements. In total track geometry has number of variables in itself. This frame work only focuses on linear variables. Such a frame work will cause alarms before the defects will actually happen.

Linear Regression estimates the coefficients of the linear equation, involving one or more independent variables that best predict the value of the dependent variable [9]. For each value of the independent variable, the distribution of the dependent variable must be normal. The variance of the distribution of the dependent variable should be constant for all values of the independent variable.

The relationship between the dependent variable and each independent variable should be linear, and all observations should be independent.

The frame work is based on how well a linear variable can be predicted from other linear variables in track geometry. In order to make the frame work more robust and effective linear regression is divided in to two types. A variable based linear regression and time based time linear regression. In variable based linear regression each variable is predicted by other variables in all four base files of track geometry.

Another way to explore predictive maintenance is to look at variables in terms of their prediction error along the time. To do so each variable in last, fourth, base file was predicted from rest of the three, previous, base files. This time based linear regression helps in understanding individual variables behaviour along the time.

In time based regression all four base files needs to be aligned properly. Alignment of base files refers to the fact that they all should have exactly the same starting point. All four base files were aligned based on engineers line reference (ELR), Track ID, Miles and Yards.

All values in the table i.e. dependent variables, adjusted R square, prediction error have their mean as first value in the table and standard deviation as second value. Standard deviation is calculated so as to see how well mean values represent population, the less they deviate the better the mean represents the population

In regression table Adjusted R squared (attempts to correct R squared to more closely reflect the goodness of fit of the model in the population) helps you to determine which model is best or how well dependent variable can be well predicted by the independent variables. In regression, the R square coefficient of determination is a statistical measure of how well the regression line approximates the real data points. Higher the value of R squared the better the model is. An R square of 1.0 indicates that the regression line perfectly fits the data. Hence R square is a statistic that will give some information about the goodness of fit of a model. Where as, prediction error can be minimized by model accuracy. However, the less the prediction error the better the dependent variable can be predicted from rest of the set of independent variables. To make prediction error more comparable error is standardized. The conclusions drawn from the research are specific to rail data analysed.

4.1. Dipped Left

Fish plate is a joint that is used to join two rails together longitudinally. These longitudinal rails may be joined together by a fish plate. When the joint wears out it dips on inner sides as shown in the diagram 14. It can happen on either rail left (dipped left) or right (dipped right). Series of dips at regular intervals in one or both rails of track can also cause derailment.

a. The highest mean value of coefficient amongst all independent variable is dipped right 0.28 which means that if dipped right goes up by one mm then dipped left will go up (because of positive relationship between them) by 0.28 mm. Where as, rest of the variables have the lowest mean value of 0.00.
b. Mean of R square value is 0.13 which means that this dependent variable can be predicted with less confidence by the independent variables.
c. Mean of standardized prediction error is 0.16, which is very low. The standard deviation of standardized prediction error in all four base files is 0.09, which is very low. Thus mean of standardized prediction error is very good representation of population.
d. The model fit is perfect 0.13, so dipped left can be predicted with less confidence by rest of, independent variables, dipped right, cat_def, gauge, cross level, curv, TOPLS, TOPRS, TOPML, ALIGML, ALIGMS, TWIST1 and TWIST2. If the model fit is improved mean of standardized error can be further minimized.

Variable Based Regression Table 1

In Dependent Variables	Mean and Standard Deviation of **Dependent Variables**			
	DIPPED_ LEFT	CANT_D EF	CROSS LEVEL	CURV
DIPPED LEFT		.00 .00	-.21 .56	-.01 .00
DIPPED RIGHT	.28 .07	-.01 .00	-.02 .02	.06 .00
CANTDE F	.00 .00		-.45 .01	3.3 .13
GAUGE	-.00 .00	-.09 .00	.07 .94	.38 .01
CROSS LEVEL	.00 .00	-.52 .04		3.05 .08
CURV	-.00 .00	.20 .01	.28 .01	
TOPLS	.01 .01	.00 .00	.07 .24	.00 .00
TOPRS	-.00 .01	.00 .00	-.05 .22	-.00 .00
TOPML	-.00 .00	.00 .00	-.00 .00	.00 .01
ALIGML	.00 .00	.00 .00	-.02 .20	-.02 .06
ALIGMS	-.00 .01	-.00 .00	-.12 .40	-.08 .19
TWIST2	.00 .00	.00 .00	.10 .16	-.01 .00
TWIST 1	.00 .01	.00 .00	-.18 .04	.00 .00
Adjusted R Square	.13 .15	.86 .02	.73 .45	.97 .00
Mean and Standard Deviation of **Predictive Error**	0.16 0.09	0.60 0.58	0.61 0.46	0.42 0.45

4.2. Cant_Def

As most trains can not lean (or tilt) into curves to counteract the centrifugal (G) force, the track is canted (one rail raised above the other) into the curve so that the forces are at equilibrium at the maximum line speed. The difference between levels of two rails in a curve is called as track cant (which is same as super elevation) and is arranged to compensate lateral part of acceleration.

a. The highest mean value of coefficient amongst all independent variable is dipped right -0.52 which means that if cross level goes up by one mm then cant_def will go down (because of negative relationship between them) by 0.28 mm. Where as, the lowest mean is -0.52 of cross level.
b. Mean of R square value is 0.86 which means that this dependent variable can be almost perfectly predicted by the independent variables.
c. Mean of standardized prediction error is 0.60, which is medium. The standard deviation of standardized prediction error in all four base files is 0.58, which is low. Thus mean of standardized prediction error is a good representation of population.
d. The model fit is perfect 0.86, so cat_def can be almost perfectly predicted by rest of independent variables; dipped left, dipped right, gauge, cross level, curv, TOPLS, TOPRS, TOPML, ALIGML, ALIGMS, TWIST1 and TWIST2. As the model fitness is almost perfect so it is difficult to further improve mean of standardized prediction error.

4.3. Cross Level

Cross Level is the difference in elevation between the top surfaces of the two rails measured at right angles to the track.

a. The highest mean value of coefficient amongst all independent variable is curv 0.28 which means that if curv goes up by one mm then cross level will go up (because of positive relationship between them) by 0.28 mm. Where as, rest of the variables; cant_def has the lowest mean value of -0.45.

b. Mean of R square value is 0.73 which means that this dependent variable can be almost perfectly predicted by the independent variables.
c. Mean of standardized prediction error is 0.61, which is medium. The standard deviation of standardized prediction error in all four base files is 0.46, which is low. Thus mean of standardized prediction error is a good representation of population.
d. The model fit is perfect 0.73, so cross level can be almost perfectly predicted by rest of independent variables; dipped left, dipped right, gauge, cant_def, curv, TOPLS, TOPRS, TOPML, ALIGML, ALIGMS, TWIST1 and TWIST2. As the model fitness is almost perfect so it is difficult to further improve mean of standardized prediction error.

4.4. CURV

Curvature (CURV) is the spatial rate of turn in the horizontal plane of track.

a. The highest mean value of coefficient amongst all independent variable is cant_def 3.3 which means that if cant_def goes up by one mm then curv will go up (because of positive relationship between them) by 3.3 mm. Where as, rest of the variables; ALIGMS has the lowest mean value of -0.08.
b. Mean of R square value is 0.97 which means that this dependent variable can be almost perfectly predicted by the independent variables.
c. Mean of standardized prediction error is 0.42, which is medium. The standard deviation of standardized prediction error in all four base files is 0.45, which is low. Thus mean of standardized prediction error is a good representation of population.
d. The model fit is perfect 0.97, so curv can be almost perfectly predicted by rest of independent variables; dipped left, dipped right, gauge, cant_def, cross level, TOPLS, TOPRS, TOPML, ALIGML, ALIGMS, TWIST1 and TWIST2. As the model fitness is almost perfect so it is difficult to further improve mean of standardized prediction error.

5. Track Geometry Time Based Linear Regression

5.1. Cross Level

Cross Level is the difference in elevation between the top surfaces of the two rails measured at right angles to the track.

a. The highest mean value of coefficient amongst three independent variables is from third base file which is 0.70. This means that if cross level of third base file goes up by one mm then the dependent cross level will go up (because of positive relationship between them) by 0.70 mm. Where as, the lowest values is 0.03 in first base file.
b. R square value is 0.99 which means that this dependent variable can be perfectly predicted by the dependent variables.
c. Mean of standardized prediction error is 0.12, which is lowest. The standard deviation of standardized prediction error in all four base files is 1.60, which is low. Thus mean of standardized prediction error is reasonably good representation of population.
d. The model fit is 0.99 which is nearly perfect, so dependent variable, cross level can be predicted with less confidence. As the model fitness is perfect so it is impossible to further improve mean of standardized prediction error.

Time Based Regression Table 2

Dependent Variables	Independent Variables			Adjusted R Square	Mean and Standard Deviation of **Predictive Error**
	1	2	3		
CROSS LEVEL _4	0.03	0.34	0.70	0.99	0.12 1.60
GAUGE _4	0.11	0.41	3.71	0.41	0.09 1.07
CURV_ 4	-0.28	1.24		0.94	0.05 3.59
CANTD EF_4	0.12	0.82		0.83	0.02 0.49

5.2. Gauge

Gauge is the distance between the two rails, measured at right angles to the rails in a plane below the top surface of the rail head. So according to Figure the Gauge deviation can be computed subtracting nominal deviation from actual deviation.

a. The highest mean value of coefficient amongst three independent variables is from third base file which is 3.71. This means that if gauge of third base file goes up by one mm then the dependent gauge will go up (because of positive relationship between them) by 3.71 mm. Where as, the lowest values is 0.11 in first base file.
b. R square value is 0.41 which means that this dependent variable can be predicted with some confidence by the dependent variables.
c. Mean of standardized prediction error is 0.09, which is lowest. The standard deviation of standardized prediction error in all four base files is 1.07, which is low. Thus mean of standardized prediction error is reasonably good representation of population.
d. The model fit is 0.41 which is very low so dependent variable; gauge can be predicted with less confidence. If the model fit is improved mean of standardized error can be further minimized.

5.3. CURV

Curvature (CURV) is the spatial rate of turn in the horizontal plane of track.

a. The highest mean value of coefficient amongst three independent variables is from third base file which is 1.24. This means that if curv of third base file goes up by one mm then the dependent curv will go up (because of positive relationship between them) by 1.24 mm. Where as, the lowest values is -0.28 in first base file.
b. R square value is 0.94 which means that this dependent variable can be almost perfectly predicted with by the dependent variables.
c. Mean of standardized prediction error is 0.05, which is lowest. The standard deviation of standardized prediction error in all four base files is 3.59, which is high. Thus mean of standardized prediction error is not a good representation of population.
d. The model fit is 0.94 which is almost perfect so dependent variable; curv can be almost perfectly predicted. As the model fitness is almost perfect so it is very difficult to further improve mean of standardized prediction error.

5.4. Cant_Def

As most trains can not lean (or tilt) into curves to counteract the centrifugal (G) force, the track is canted (one rail raised above the other) into the curve so that the forces are at equilibrium at the maximum line speed. The difference between levels of two rails in a curve is called as track cant (which is same as super elevation) and is arranged to compensate lateral part of acceleration.

a. The highest mean value of coefficient amongst three independent variables is from third base file which is 0.82. This means that if cant_def of third base file goes up by one mm then the dependent cant_def will go up (because of positive relationship between them) by 0.82 mm. Where as, the lowest values is 0.12 in first base file.
b. R square value is 0.83 which means that this dependent variable can be almost perfectly predicted with by the dependent variables.
c. Mean of standardized prediction error is 0.02, which is lowest. The standard deviation of standardized prediction error in all four base files is 0.49, which is very. Thus mean of standardized prediction error is a reasonably good representation of population.
d. The model fit is 0.83 which is almost perfect so dependent variable; cant_def can be almost perfectly predicted. As the model fitness is almost perfect so it is very difficult to further improve mean of standardized prediction error.

6. Conclusion

Preventive maintenance management can be used to determine defects in rail track and prevent them happening in future. Such system can also help in identifying trends for effective and efficient preventive maintenance management. Unfortunately the pressure on rail road to reduce operating costs usually result in cutting or eliminating investment in research because it often does not generate a short term return on investment.

This paper focuses on linear regression analysis of track geometry parameters which leads to significant rail track maintenance productivity gains.

The predictive maintenance management frame work is based on how well a linear variable can be predicted from other linear variables in track geometry. In order to make the frame work more robust and effective linear regression is divided in to two types. A variable based linear regression and time based time linear regression.

The aim of research paper is to apply preventive maintenance management to track geometry evaluate and prioritise condition monitoring effort across network rail. Such research will result in effective and efficient maintenance management resulting in benefits like low operating cost, better train transit times for rail industry [2].

References:

[1] Leedham, R.C.; Nelson, S, “Wheel /rail profile studies”, Railroad Conference, Proceedings of the 1995 IEEE/ASME Joint, Page(s):159 – 162

[2] L. Ferreira.. and Murray, M, “Modelling Rail Track Deterioration and Maintenance: Current Practices and Future Needs”, 1997.

[3] Darris L. White, “Statistical Characterization of Vehicle and Track Interaction Using Rail Vehicle Response and Track Geometry Measurements”, Thesis submitted to the Faculty of Virginia Polytechnic Institute and State University, July 29, 1998

[4] J. woodhouse, “Asset management decision making”, June 2001.
[5] Alfelor R.M., Mc Neil S., (1994), ‘ Heuristic Algorithms for aggregating rail surface defect data’, ASCE, Journal of Transport Engineering, Vol. 120, No. 2.
[6] Naylor Zac, “Discussion on Track Geometry Recording”, April 2007.
[7] Martin Lindhal, “Track Geometry for high speed railways”, Railway Technology Department of Vehicle Engineering Royal Institute of technology, Stockholm 2001.
[8] Kenneth P. Kramp, “The Analysis and Creation of Track Irregularities Using TRAKVU”, Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University, June 30, 1998.
[9] D.G Cristina and C.D Corina, “ The principal components analysis – method to reduce the collinearity in multiple linear regression model; application in medical studies”, Proceedings of the 2nd WSEAS International Conference on Multivariate Analysis and its Application in Science and Engineering MAASE '09 Istanbul, Turkey, June 1,2009.
[10] V.Ungureanu, “On elimination of interior rail joints and the including of welded railway switches in continuous welded rail track”, Proceedings of the 11th WSEAS International Conference on Sustainability in Science Engineering, Volume 2, SSE May 27-29 2009.
[11] G. Lucaci, “Numerical Analysis of Rail-Subgrade System” , Proceedings of the 11th WSEAS International Conference on Sustainability in Science Engineering, Volume 1, SSE May 27-29 2009.