Project no. TIP5-CT-2006-031415O

INNOTRACK

Integrated Project (IP)

Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

D1.3.2 The state of the art of the simulation of vehicle track interaction as a method for determining track degradation rates

Part One – Strategic Models

Due date of deliverable: 31 August 2008

Actual submission date: 2 October 2008

Start date of project: 1 September 2006 Duration: 36 months

Organisation name of lead contractor for this deliverable: Network Rail

Revision [draft v1]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of Contents

Executive Summary

In order to assess the life cycle cost benefit of innovation it is necessary to determine the influence that the change will have on the operational life of all the track components, the change in maintenance requirements and track availability.

A change to a component of a switch designed to improve reliability may be assessed from accelerated laboratory tests and high resolution numerical models without the need to consider the other aspects of the route. When a change of rail or track support is considered necessary to improve LCC, or as a response to more severe traffic conditions it may be necessary to consider the impact of the change on an entire route as the benefit is unlikely to be the same over long distances that have different track characteristics. As the renewed track may have a life of forty years or more, the development of tools to assist in the determination of the whole life costs of changes in track and traffic for strategic decision making has become a technical priority. Models for this type of calculation are necessarily of lower resolution in order to allow for the wide variation in conditions on a route basis. The lower resolution should not reduce the validity of a decision to change track components or maintenance processes. The model may be based on experience of degradation rates of components under different conditions or include the output of vehicle dynamics software that simulates the response of specific vehicle types to the different track characteristics along the route.

This report (Part 1) examines six tools, one each from Sweden, Australia and Japan, two from the USA and one from Great Britain, which have been developed to assist with the strategic decision making process. The British model, the Vehicle-Track Interaction Strategic Model (VTISM), is then examined in more detail and possible areas for improvement suggested.

VITSM predicts vertical track geometry degradation. The equations used to predict vertical track degradation are adequate. One limitation of VTISM is it is built around Network Rail’s track geometry and vehicle databases. This makes it difficult to apply the track degradation model to a route not included in Network Rail’s system. It is also difficult to modify route characteristics, such as line speed.

Several vertical track degradation models have been developed with the goal of optimising track maintenance. The two approaches use mechanistic equations or trending analysis on historical data for a specified route. The mechanistic model could be applied to a variety of scenarios, but had to be calibrated to actual track data. The trending analysis approach was limited to the specific track route. This approach made it difficult to predict the effects of changing vehicle characteristic (axle load, speed, yaw stiffness) or track characteristic (sleepers or rails).

There has not been a lot of development in the area of lateral degradation models.

Due to lack of a prediction model for lateral track geometry degradation in VTISM, it is recommended that efforts should be made to develop such a model.

The relationship or algorithms between track geometry degradation, wheel/rail forces, track strength and tonnage should also include constants that will allow the calibration of the model to local conditions and adjustment of model predictions by actual historic track geometry degradation results for any specific route.

1. Introduction

In order to assess the life cycle cost benefit of innovation it is necessary to determine the influence that the change will have on the operational life of all the track components, the change in maintenance requirements and track availability.

A change to a component of a switch designed to improve reliability may be assessed from accelerated laboratory tests and high resolution numerical models without the need to consider the other aspects of the route. When a change of rail or track support is considered necessary to improve LCC, or as a response to more severe traffic conditions it may be necessary to consider the impact of the change on an entire route as the benefit is unlikely to be the same over long distances that have different track characteristics. As the renewed track may have a life of forty years or more, the development of tools to assist in the determination of the whole life costs of changes in track and traffic for strategic decision making has become a technical priority. Models for this type of calculation are necessarily of lower resolution in order to allow for the wide variation in conditions on a route basis. The lower resolution should not reduce the validity of a decision to change track components or maintenance processes. The model may be based on experience of degradation rates of components under different conditions or include the output of vehicle dynamics software that simulates the response of specific vehicle types to the different track characteristics along the route.

This report (Part 1) examines six tools, one each from Sweden, Australia and Japan, two from the USA and one from Great Britain, which have been developed to assist with the strategic decision making process. The British model, the Vehicle-Track Interaction Strategic Model (VTISM), is then examined in more detail and possible areas for improvement suggested.

A second report (Part 2) will review higher resolution tools from a range of sources including those used within the InnoTrack project. The subject of model calibration and validation will also be discussed in Part 2.

2. State of the art literature review

A literature review was conducted to determine the state of the art of strategic track degradation models.

2.1 DECOTRACK[1]

The main focus of the Degradation Cost of Track (DeCoTrack) model developed by Luleå University of Technology and Banverket is to estimate the changes in maintenance and track degradation rate due to traffic change. DeCoTrack simulates changes in traffic parameters such as axle loads, annual tonnage, speed, mix of vehicle types and vehicle maintenance conditions. The outputs from this model are both track degradation rates and costs.

DeCoTrack is currently designed to simulate degradation of the sleeper, rails and ballast. The model has the rail degradation as base in the analysis. Rail degradation is generated by two mechanisms: wear and fatigue. The model describes the two mechanisms in parallel. Wear and fatigue are influenced by curvature. Rail life in higher curvature track is dominated by the wear mechanism. In tangent track the dominating degradation mechanism is rail fatigue. In the model, track settlement has the same type of relationship to axle load and tonnage as rail fatigue.

The rail fatigue and track settlement are dependent on the force amplitudes of the passing wheel set. The load from a wheel set is described by:

Total axle load = Static axle load + Quasi Static load (axle load in curves) + Dynamic axle load (unsprung mass and surface roughness)

A degradation index is calculated for both track conditions and vehicle data. Fatigue generated by each vehicle passing over a track segment is calculated and added together to give an annual total fatigue degradation index.

Rail wear is calculated in parallel with rail fatigue. Rail wear is correlated to curvature, vehicle steering performance and lubrication.

DeCoTrack develops an economic projection by a linear conversion between technical life and annual traffic-related maintenance costs.

The following are not included in DeCoTrack:

Effects of preventative maintenance (grinding)
Cost for turnouts degradation
Does not use incremental time stepping

2.2 Track Residual Deflection Analysis (TREDA)[2,3]

The Track Residual Deflection Analysis (TREDA) model was developed under Federal Railroad Administration (FRA) sponsorship to quantify lateral track shift (i.e., misalignment growth). The information was provided in an unpublished report, and the model has limited validation.

Track shift is defined as the permanent lateral distortion of a track segment which can occur under vehicle passes due to resulting lateral loads. The generalised TREDA model accounts for the following parameters to quantify track shift.

Sleeper type – Wood and concrete sleepers can be modelled using the program.

Unloaded sleeper lateral resistance

Sleeper-ballast friction coefficient as a function of vertical load

Sleeper-ballast hysteresis under cyclic load

Rail section properties

Rail temperature differences from the stress-free temperature Track curvature – User input parameter in degrees. The program converts degrees of curvature to chord length of 100ft (30.5m).

Initial misalignments – The model simulates this parameter with the assumption that the misalignment occurs in the middle of the track and is represented by misalignment amplitude at the centre, and the half length of the amplitude.

Axle vertical and lateral loads

Single or multiple axle vertical loads

Net axle lateral loads at single or multiple axles

Net axle loads varying over a finite wavelength

Vertical foundation modulus

The model will predict lateral track shift due to moving loads in the form of cumulative deflection of the track under a given number of passes. The output is in the form of residual deflection versus the number of axle passes, and the total deflection at the end of last pass as a function of distance along the track. Limited validation of results has been performed for tangent track with no initial misalignment and no thermal force.

2.3 Integrated Track Degradation Model (ITDM)[4]

The Integrated Track Degradation Model (ITDM) was developed by Queensland University of Technology, Australia to predict track behaviour and degradation. The model uses a mechanistic approach for its inter-related deterioration sub models: Rail Sub-Model, Sleeper Sub-Model, and Ballast and Subgrade Sub-Model. An entire track system or individual component degradation can be modelled. The degradation is calculated for cycles determined by tonnage and time.

Rail Sub-Model – Currently ITDM only analyzes degradation through rail wear. It is assumed that rail grinding removes most of the defects. The interactive relationship between grinding and rail fatigue has not yet been established, so rail fatigue is not included in the model. Axle load and train speed are the major factors affecting rail wear.

Sleeper Sub-Model – Timber sleepers are assumed to fail by spike killing, plate cutting, and decay. Stress conditions in a timber sleeper are correlated with sleeper life. In the model all wheel loads are classified and standardised. The assumption is that each standardised wheel loading cycle causes an equal amount of sleeper damage. Therefore the total sleeper replacement in a section of track for a given period is proportional to the total wheel loading cycles. Analysis of sleeper degradation is independent of historical data and length of track, because the model relates sleeper degradation with applied loads.

Ballast and Subgrade Sub-Model – Track modulus is the key parameter in predicting track degradation. Subgrade stiffness and ballast depth have the most effect on track roughness.

ITDM integrates various types of track component degradation. The effect of the deterioration of one component on the other is reflected by changes in the dynamic force on the rails.

2.4 Transition Process Model[5]

The Transition Process Model was developed in Japan to determine an optimal tamping schedule for the Japanese railway network. The modelling was undertaken in three parts:

1. Predicting track degradation – Degradation Model
2. Predicting required maintenance operations – Restoration Model
3. Planning an optimal maintenance schedule - Optimal Track Maintenance Scheduling Model

The degradation model applies an exponential smoothing function to historical data for lengths of track known as “lots”. A lot is a track section 100 m in length and a division for a tamping unit. The model predicts the growth of the standard deviation of surface irregularities over time.

The restoration model predicts the tamping maintenance effects on surface irregularities. The actual data for a given lot is reviewed. A comparison between pre and post tamping measurements is done. A linear regression and a 95% confidence interval are used to determine the relationship. This equation is applied to all lots. The model assumes that the effect of maintenance is constant across all segments of track.

The optimal track maintenance model’s goal is to optimise the operation of the tamper. The output from the degradation model and the restoration model are used. The model uses the data to determine which lot has the highest degradation rate and requires the most maintenance (restorations). The tamper schedule is then optimised to maintain the track in the best condition possible with the available resources.

In summary, the model is based mainly on trending analysis of short segments (100m lots) of track. It uses historical data to predict future degradation, and maintenance requirement. This information is then used to optimise the maintenance schedule against the resource level available.

2.5 Railway Track Life-Cycle Model (RTLMTM)[6]

The Railway Track Life-Cycle Model (RTLM) was developed under the Association of American Railroads' Research Program. RTLM predicts rail wear rate, rail defect growth rate, wooden sleeper degradation, turnout degradation, ballast degradation, and track roughness growth. Maintenance costs are calculated based on degradation rates, maintenance policies, replacement costs, and interest rates.

In RTLM, degradation calculations are based on the mechanistic models derived from theoretical or experimental results. Each degradation model has coefficients that allow for calibration against field data.

Track roughness is calculated from cumulative permanent deformation of ballast, subballast, and subgrade layers under repeated axle loads.

Ballast life is calculated based on ballast fouling from breakdown due to traffic and tamping, and from other sources such as wet spots (mud pumping).

Wooden sleeper degradation is calculated in terms of plate cutting and spike kill damage due to traffic, and decay due to weather.

Rail wear rate is calculated from the product of wheel/rail tangential forces and creepage.

Rail defect rate is derived from metal fatigue equations and Weibull distribution.

The program allows users to build different track segments. Each track segment may contain different rail, sleepers, fasteners, ballast types, and train service. The calculation can be performed for one segment or many. The output is given for each individual segment or the entire track based on weighted averages of the individual segments.

2.6 VTISM[7,8]

The Vehicle Track Interaction Strategic Model (VTISM) was developed on behalf of Network Rail and the Rail Safety and Standards Board for use by the British railway industry in strategic asset management. It combines outputs from the following models to optimise maintenance and renewal strategies taking into account vehicle and track characteristics.

The vehicle dynamics modelling package VAMPIRE simulates the dynamic load environment for a given vehicle and track characteristics.

The Whole Life Rail Model (WLRM) uses the output loads from the Vampire simulation to predict the probability of formation of RCF and side wear.

The Track Strategic Planning Application (T-SPA) software predicts the impact of different renewal, maintenance, and train operations on the condition and performance of the track for a given time period. The track geometry degradation models reside within T-SPA.

2.6.1 T-SPA

T-SPA is a decision support tool used to provide analysis of track renewal and maintenance options, related to condition and performance of the track. The asset behaviour relationships are the core of T-SPA. The relationships are used in two main ways:

They provide short and long term forecasts of key track indicators under different renewal, maintenance and traffic scenarios.

They allow different renewal and maintenance strategies to be tested, calculating parameters to which replacement criteria and maintenance thresholds can be applied.

Several models are used to predict the degradation of track components due to traffic volume, vehicle types, and the age and condition of components. There are five categories of models:

Service Life Relationships

Rail defect

Rail breaks

Track geometry and ballast life

Level 2 exceedences

T-SPA requires three main sources of user specified inputs: train service data, maintenance regimes, and renewal criteria. The other data used in calculations are stored in databases linked to the model.

The volume, type and speed of traffic are major causes of degradation. The train service pattern can either be held constant or projected traffic growth can be modelled. It is also important to know the traffic volume in order to determine the impact of poor track conditions that require imposition of temporary speed restrictions on services (i.e. delay penalties).

T-SPA's definition of the maintenance cycle relates only to tamping and stoneblowing. Rail grinding is not included. Track geometry thresholds are specified by the user to determine when maintenance is invoked. A constant maintenance interval can also be specified.

Renewals can be specified when a calculated parameter reaches a specified limit. Different renewal scenarios can be modelled to determine what will provide the maximum benefit in terms of safety and train delay mitigation. T-SPA is also useful in establishing the priorities for renewal applications.

T-SPA calculations represent renewals, maintenance and train service scenarios. There are several outputs that need to be considered to determine the effectiveness and affordability of the scenario. The output may be classified into four categories: demographics, condition, performance, and investment.

The demographic outputs from T-SPA are age and residual life of assets for each segment.

The condition outputs for rail are number of defects removed and the number of rail breaks. Track geometry condition outputs are short wave (35m) vertical standard deviations, and the number of level 2 exceedences. There is no sleeper degradation model in T-SPA. Renewal of sleepers is based mainly on the age and accumulated tonnage.

Performance outputs mainly relate to track condition. This includes rail defects, breaks, RCF damage, track geometry, sleeper age, and ballast condition.

Investment outputs are the volume of renewals and maintenance activities and the associated costs.

2.6.2 Track Geometry and Ballast Life

The focus of this task is on the track geometry and ballast life models. Figure 1 is an overview of the geometry model and its relationship between the inputs and outputs. In the model track geometry is evaluated every 200m.

Track geometry deteriorates through two mechanisms: the effect of dynamic forces, and the condition of the ballast. These mechanisms are described by the interaction of the force model and the ballast model.

The force model is applied to individual track sections defined by user and calculates the mean forces experienced by the track due track and vehicle properties. The data for the selected track section is read into T-SPA from Network Rail's vehicle and track databases. The data is used to define the current asset condition and the degradation is calculated in monthly intervals for a specified time period. The degradation is quantified by the change in standard deviation.

The three types of forces calculated in T-SPA are the following:

Ride force due to vehicle body bounce – The ride force depends on the average standard deviation for the track section, the speed of the vehicle and its ride characteristics, the impact of previous maintenance operations, and the axle load.

General P2 forces arising from the unsprung mass of vehicle axles acting on a rough track surface - The calculation of the P2 forces depends on both vehicle and track properties. The track properties are defined by the track stiffness, track damping, rail characteristics, sleeper spacing.

P2 forces arising from the unsprung mass of vehicle axles acting on individual track dips - Track dips can be a result of welds or joints.

The contribution of each of the forces to the degradation rate is:

$$\mathbf{SDTotal = \sqrt{}(SDTrackdips^2 + SDUnsprungMass^2 + SDTotRideForce^2)}$$

The ballast condition depends on the fraction of available ballast voids which has been filled by fines. The model evaluates fines generated from the following:

Environmental fines - Contaminates from the surrounding atmosphere, i.e. dust, wind blown particulate

General traffic fines - Created through the breakdown of ballast under traffic.

Wagon fines - Material dropped from passing vehicles.

Maintenance fines - Generated from maintenance activities such as tamping.

The accumulation of fines in the available voids contributes to the increase of geometry degradation. The ballast model predicts the rate at which the available voids are filled with fines.

Calculating the standard deviation for every track section at every time point would be excessive. An empirical function is fitted through several points of the calculated geometry.

$$\mathbf{SDTotal = k\ exp\ (at^b)}$$

The coefficients a, b, and k are determined from the 3 point fit to SD total calculated at t=0.5, 1, and 2. This function allows the known geometry and the deterioration rate of the track section to set the initial ballast condition factor. A local calibration constant allows for characteristics of the track section behaviour not accounted for by the theoretical model to be incorporated into the results. This approach allows the theoretical model to be integrated with recent field conditions of the track section. The geometry degradation equations can be found in the appendix.

2.6.3 Maintenance Model

As the ballast becomes clogged with fines or when the deterioration rate exceeds the maintenance criteria a maintenance cycle is triggered. Maintenance cycles are modelled in T-SPA. The following summarises the main features of the model:

Maintenance is treated similarly to renewals; it is triggered by user-defined criteria and subject to budget restrictions.

The model moves forward in monthly intervals. Maintenance actions are considered monthly, but renewals are considered annually.

Maintenance or renewals are considered on the basis of the track conditions from the previous period.

Scheduled maintenance actions take place at the end of the time period.

Renewals are scheduled for the year ahead. The month in which they occur is random (based on a random number generator with a seed of the track ID and year).

The track quality limit to be applied for a track section is relaxed if maintenance cannot retain the track quality within the current limit. This will continue until either the worst track quality limit is reached or the ballast is renewed.

Stoneblowing is generally applied when tamping can no longer keep the track quality in the satisfactory band. The criteria for this action can also be set by the user

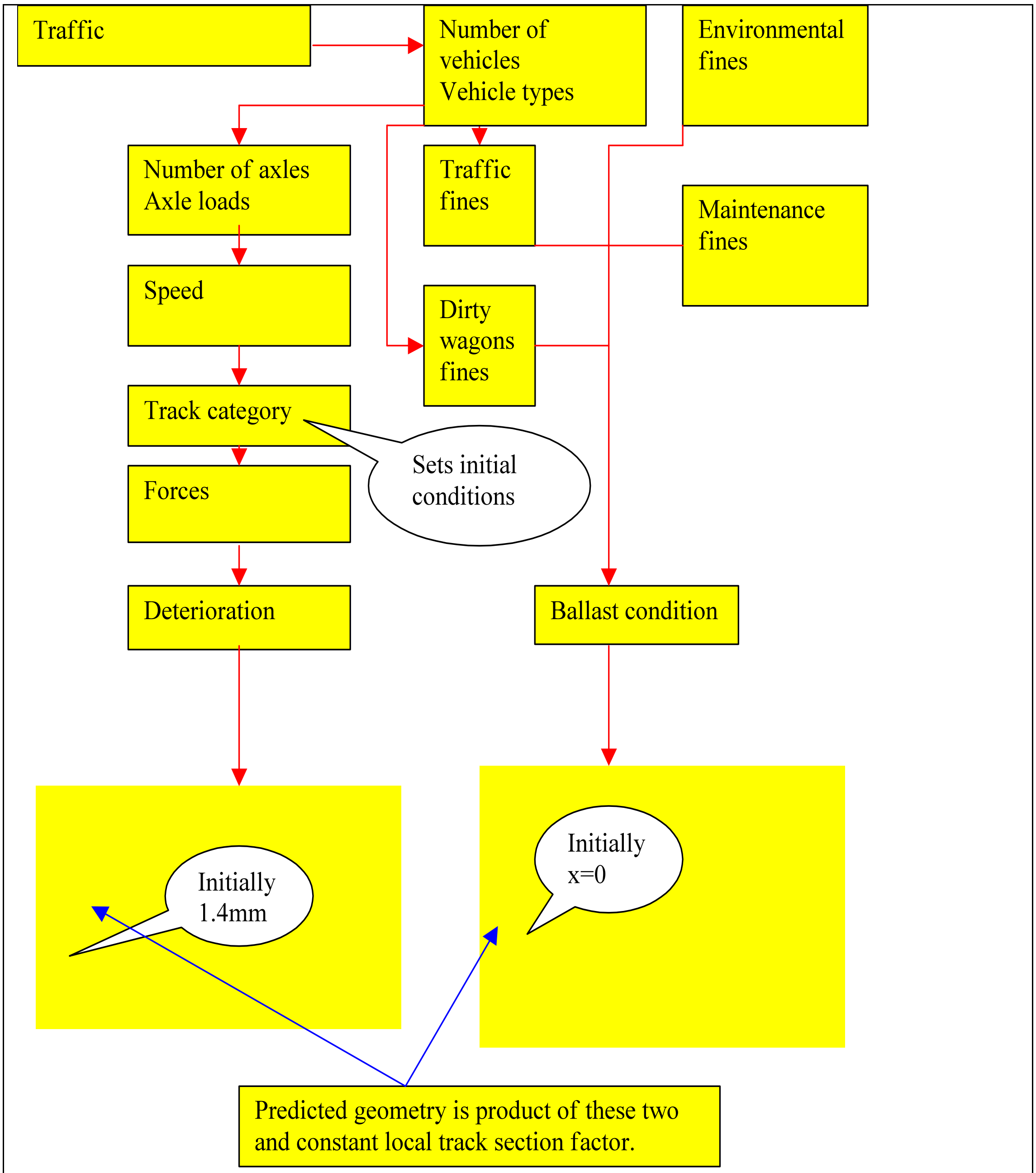

Figure 1: Schematic of geometry model

This shows how the various factors combine to predict the future geometry of a newly laid track section on high-speed track. Maintenance, such as tamping, is not shown in this diagram but would be applied in practice to keep the geometry under a prescribed limit. This is discussed separately. Time is essentially going from left to right in the two graphs so that the traffic drives SDTotal higher and BCF also increases. The final vertical geometry prediction is the product of these two and a constant local track section factor

2.6.4 Summary

VITSM predicts vertical geometry degradation. It uses the measure of standard deviation of the position of the top of one rail surface measured from its ideal position over 200m segments with a 35m low pass filter to quantify the track geometry. Upon review of the methodology, the equations used in T-SPA to predict vertical track degradation are considered to be adequate, if the local calibration constant is indeed used to represent the effect of subgrade/formation on track geometry degradation. One limitation of VTISM is that it is built around Network Rail's track geometry and vehicle databases. This makes it difficult to apply the track degradation model to a route not included in Network Rail's system. It is also difficult to modify route characteristics, such as line speed.

The residual ballast life is currently calculated from the service life and age of ballast. It does not take into account the ballast condition and the rate at which the voids are filled with fines. This is an area that may be improved upon.

Because VTISM does not have a lateral track geometry degradation model, a further area for improvement would be the development of such a model for predicting lateral track geometry as a result of traffic volume, lateral wheel/rail forces and track condition.

3. Conclusion

VITSM predicts vertical track geometry degradation. It uses the measure of standard deviation of the position of the top of one rail surface measured from its ideal position over 200m segments with a 35m low pass filter to quantify the track geometry. The equations used to predict vertical track degradation are adequate. One limitation of VTISM is it is built around Network Rail's track geometry and vehicle databases. This makes it difficult to apply the track degradation model to a route not included in Network Rail's system. It is also difficult to modify route characteristics, such as line speed.

Several vertical track degradation models have been developed with the goal of optimising track maintenance. The two approaches were using mechanistic equations or trending analysis on historical data for specified route. The mechanistic model could be applied to a variety of scenarios, but had to be calibrated to actual track data. The trending analysis approach was limited to the specific track route. This approach made it difficult to predict the effects of changing vehicle characteristic (axle load, speed, yaw stiffness) or track characteristic (sleepers or rails).

There has not been a lot of development in the area of lateral degradation models.

Due to lack of a prediction model for lateral track geometry degradation in VTISM, it is recommended that efforts should be made to develop such a model. The approach to developing a model would be similar to the one used in predicting vertical track geometry degradation. Prediction of misalignment growth should take into accounts lateral wheel loads applied to the track, track condition, and traffic characteristics.

The relationship or algorithms between track geometry degradation, wheel/rail forces, track strength and tonnage should also include constants that will allow the calibration of the model to local conditions and adjustment of model predictions by actual historic track geometry degradation results for any specific route.