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LICENTIATE THESIS

A Study of the Track Degradation Process Related to Changes in Railway Traffic

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PREFACE

Several ideas have been thought in the area of railway technology. These include thought both by elderly men in grey hair and by youngsters with little or no experience but with a fresh and unrestricted mind. This is a statement based on observations at several railway conferences worldwide. It might seem impolite but is not intended to offend no one. Instead it is meant to be a compliment to a transport technology with its roots in the 17th century (see appendix A) that is still unparalleled in many ways and that has been continuously improved by a lot of enthusiastic people through several generations. This mode of transport is characterised by extremely low energy consumption, low environmental impact, capability to carry extreme loads and it has a good safety ranking for passenger transports. In spite of all these advantages there still remains a lot to enhance concerning its effectiveness and efficiency to make it competitive to other modes of transport.

This licentiate thesis presents new ideas related to railway maintenance. The conclusions and the new ideas are based on literature studies, empirical experience from field data and also tests performed during investigations and consequence studies for Banverket (Swedish National Rail Administration) during the time period 1995-2004.

The research work has been carried out under the auspices of Luleå Railway Research Centre (JvtC), a centre focussed on making railway maintenance effective and efficient.

- Citate -

"The time will come when people will travel in stages moved by steam engines from one city to another, almost as fast as birds can fly, 15 or 20 miles an hour.... A carriage will start from Washington in the morning, the passengers will breakfast at Baltimore, dine at Philadelphia, and sup in New York the same day.... Engines will drive boats 10 or 12 miles an hour, and there will be hundreds of steamers running on the Mississippi, as predicted years ago."

- Oliver Evans, 1800 -

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Another person of great importance is Ms Ulla Espling, Luleå Railway Research Centre who with her great enthusiasm and knowledge has inspired to this research. I also want to thank my colleagues at the Division of Operation and Maintenance Engineering for the creative discussions during the course of this research work.

Last but not least I want to express my gratitude to my beloved wife Inger and my dear children Sara and Linnea for their patience and understanding during my late evening work at home.

Luleå December, 2004

Dan Larsson

ABSTRACT

This licentiate thesis presents the results of a research project concerning railroad maintenance. After acquiring the state-of-the-art knowledge in relevant areas a prediction model for railroad track degradation has been developed. The model is named DeCoTrack (Degradation Cost Of Track). The research study has been performed in a close collaboration with track experts at Banverket.

The model simulates changes in degradation rate of the track due to changes in traffic characteristics. The inputs include for example parameters such as axle load, annual tonnage, speed, the mix of vehicle types and vehicle maintenance conditions. Outputs from the model are both track life length and the estimated degradation cost. When developing the model, results from research studies reported mainly from Europe and North America were combined with classical mechanical engineering theories, and empirical data from the last 20 years of railway transports in Sweden. By establishing compatible interfaces between the different input sources, information became easy to adapt to the model which was gradually implemented into an easy-to-use software.

The model DeCoTrack has been verified mainly based on an extensive literature survey trying to find other comparable models and to relate their output to that from DeCoTrack. Out of 900 abstracts, 40 research works were found of interest and studied in detail. They led to three existing models:

- TMPM/ITDM – Track Maintenance Planning Model / Integrated Track Degradation Model
- TRACS – Total Right of Way Analysis and Costing System
- The Damage Exponent Heavy Axle Load Analysis

These models turned out to be more complex than DeCoTrack and therefore it is more difficult to implement and use these models in real situations. In addition these models are also mainly focused on the modelling of uniform freight traffic while DeCoTrack can model and describe the track degradation due to mixed traffic. A direct comparison of outputs from these models has been done on traffic data where quantitative data were available. The correlations between outputs from DeCoTrack and the above mentioned models were good.

A search for more external research work on freight traffic leads undoubtedly to U.S. and the AAR/TTC test centre in Colorado. All of the three models above refer in some way to data from that centre. When it comes to high-speed passenger traffic and related maintenance issues, the major sources of knowledge can be found in Germany, France and Japan.

Future research is suggested to concentrate on vehicle classification. The domestic situation in Sweden with deregulation in traffic and mixed traffic on same routes highly prioritise such a decision. From an international perspective, that effort might bring a useful complement to the other models. They are focused on uniform freight traffic.

Key words: *Track degradation, Railway traffic characteristics, maintenance costs, prediction model, axle load*

SAMMANFATTNING

Denna licentiatavhandling presenterar resultaten av ett forskningsprojekt om järnvägsunderhåll. Sedan aktuella kunskaper om relevanta områden inhämtats, har en modell för att förutsäga slitage av järnvägsspår utvecklats. Modellen benämns DeCoTrack (Degradation Cost Of Track). Forskningen har utförts i nära samarbete med spårtekniska experter vid Banverket.

Modellen simulerar hur spårets nedbrytning förändras med förändringar i tågtrafiken. Indata innefattar t ex parametrar såsom axellast, årligt tonnage, hastighet, blandning av fordonstyper och fordonens underhållskondition. Utdata från modellen är både spårlivslängd och den beräknade nedbrytningskostnaden. När modellen utvecklades, kombinerades resultat av studier i huvudsak utförda i Europa och Nordamerika med klassiska maskintekniska teorier och empiriska data från de senaste 20 årens järnvägstrafik i Sverige. Genom att utforma kompatibla gränssnitt mellan de olika indatakällorna gjordes informationen lätt att anpassa till modellen, som gradvis implementerades i en lättanvänd programvara.

Modellen DeCoTrack har främst verifierats genom en omfattande litteraturundersökning i syfte att hitta andra jämförbara modeller och att relatera deras utdata till DeCoTracks. Av 900 abstracts, befanns 40 arbeten vara av intresse och studerades ingående. De resulterade i tre befintliga modeller:

- TMPM/ITDM – Track Maintenance Planning Model / Integrated Track Degradation Model
- TRACS – Total Right of Way Analysis and Costing System
- The Damage Exponent Heavy Axle Load Analysis

Dessa modeller visade sig vara mera komplexa än DeCoTrack och det är därför svårare att implementera och använda dem i verkliga situationer. Dessutom är dessa modeller i huvudsak fokuserade på modellering av enhetlig godstrafik, medan DeCoTrack kan modellera och beskriva spårnedbrytning orsakat av blandad trafik. En direkt jämförelse av utdata från dessa modeller har utförts på trafikdata där kvantitativa data fanns tillgängliga. Korrelationerna mellan utdata från DeCoTrack och ovannämnda modeller var god.

Sökande efter fler externa studier av godstrafik leder utan tvekan till USA och the AAR/TTC testcentrum i Colorado. Alla de tre ovannämnda modellerna refererar på ett eller annat sätt till data från detta centrum. När det gäller underhållsfrågor relaterade till snabbtåg och höghastighetståg så återfinns de främsta kunskapskällorna i Tyskland, Frankrike och Japan.

Framtida forskning föreslås bli koncentrerad på fordonsklassificering. Den inhemska situationen i Sverige med avreglering av trafiken och blandad trafik på samma linjer ger hög prioritet ät ett sådant beslut. I ett internationellt perspektiv kan denna insats bli till ett användbart komplement till de andra modellerna. De är fokuserade på enhetlig godstrafik.

Nyckelord: *Järnväg, spårnedbrytning, ändrad trafik, blandad trafik, underhålls-kostnader, modell för förutsägelse, axellast.*

CONTENT

DEFINITIONS AND ACRONYMS

AAR	Association of American Railroads
Burlington Northern	Burlington Northern Railroad, a large American railroad company
CN	Canadian National, a Canadian railroad company
Corrective maintenance	Maintenance performed after a failure has occurred
Creep of the rails	An unwanted slip of the rail in the fastenings
CWR	Continuous Welded Rail
DeCoTrack	Degradation Cost of Track. The name of the developed model.
EUAC	Terminology in the model TRACS. Total costs of maintenance on the line distributed over several years
Freight charges	A fee paid by the operator to the track owner for using the track
Hambo	A manufacturer and type of rail fastenings
Hey-Back	A manufacturer and type of rail fastenings
IHHA	International Heavy Haul Association
ITDM/	Integrated Track Degradation Model, an Australian model
Jointed rails	Rail connected with bolts
KTH	Royal Institute of Technology
LCC	Life Cycle Cost.
LTU	Luleå University of Technology
MGT	Million Gross Tons, the total tonnage transported (U.S. Tons)
MIT	Massachusetts Institute of Technology
ORE	Office for Research and Experiments of the International Union of Railways
Pandrol	A manufacturer and type of rail fastenings
Predictive maintenance.	Maintenance performed to prevent failures
Quasi-static forces	Temporary forces acting for example during train passes through a curve
Rail grinding	Removal of thin metal surface layer on rails
ROI	Return On Investment.
SLEEPER	A timber or concrete cross-member, supporting the rails of railway tracks
Subgrade	The material in track deep below rail surface
Superelevation	The inclination of the rails in curves that makes the train tilt towards curve centre.
Superstructure	The material and components in track close to rail surface
Tamping	Vibrating the ballast to get a higher packing density and track stability
Ties	Sleeper (Am. English)

TM$	Track Management System, A maintenance prediction model developed for Burlington Northern
TMPM	Track Maintenance Planning Model, an Australian model
Track degradation	Slow deterioration of the track due to age and traffic
Track gauge	The distance between left and right rail
Track settlement	Disturbances to the track alignment
TRACS	Total Right of Way Analysis, a model name
Traffic characteristics	Traffic parameters such as vehicle mix, axle loads, speeds, annual tonnages, vehicle maintenance conditions etc.
TTC	Technology Test Center
Turnouts	A device that moves rails laterally to permit the movement of a vehicle or train from one track to another
Vertical track alignment	The vertical rail evenness

1 INTRODUCTION AND BACKGROUND

The railway is a branch that is very expensive to construct but it has a long life and low operating costs. Therefore, the asset value is very high which also leads to the statement that maintenance efforts might be of high value. By doing small changes in the maintenance strategy, the asset life length might be extended with for example 10% giving a large ROI. In Sweden, a 10 km track segment can typically cost 200 Mkr to renew and a 10% extended life will then save at least 20 Mkr neglecting interest effects. Comparing railways with other civil engineering project with high investments in the initial phase, it is obvious that maintenance plays a crucial role in the long time cost effectiveness. This can be illustrated as in Figure 1.1.

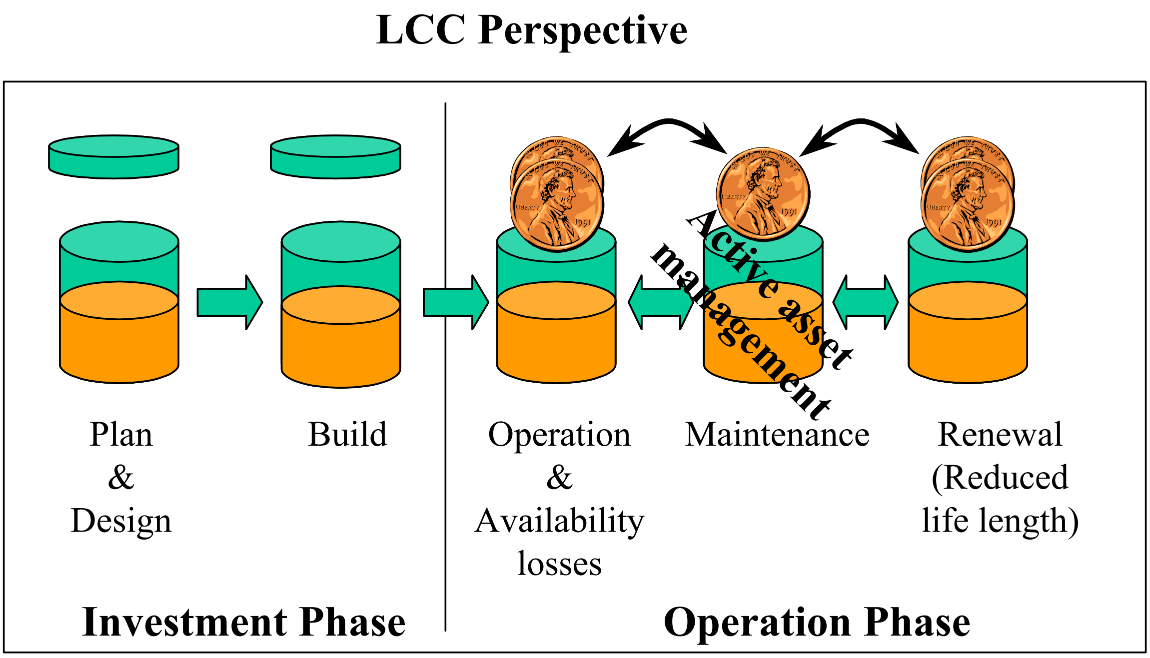

Figure 1.1: Railway maintenance represented in a LCC perspective. In the operation phase, maintenance is the major tool to use when optimising system overall costs.

All the containers represent cost deposits. After an initial investment phase, all money has gone into asset values that will be managed under the operational phase. By an active control of the maintenance the money flows between containers related to operation, maintenance and renewal. As railway technology requires to keep the track and the vehicles in adequate condition the maintenance itself represent a strongly costs intensive activity.

1.1 Overview of the Swedish Railway Sector

The Swedish railway network consists of 11000 km of track starting from the very north with arctic climate and curving track down to the very south with more straight lines in topographically flat country. The track construction, climate, topography, curvature and annual traffic load varies considerably throughout the Swedish network, as given in Figure 1.2. Most of the lines are single tracks and take care of both freight and passenger traffic. On these lines, Banverket, the Swedish National Rail Administration, acts as the primary infrastructure owner while several independent operators are running the traffic.

The Swedish railway network mainly consists of continuous welded rails (CWR) but jointed tracks are still in use. All tracks have standard gauge, 1435 mm. The main lines consist of UIC60 or BV50 rails and concrete or hardwood sleepers with elastic fastenings. The normal sleeper spacing is 650 mm for CWR tracks. Up north, on one part of the Heavy Haul railway for iron-ore traffic between Kiruna and Riksgränsen, the track consists of 50 kg/m rails, hardwood sleepers and 500 mm sleeper spacing. From Riksgränsen there is a 42 km track extension in Norway down to the Atlantic harbour in Narvik. This extension is named Ofotenbanan

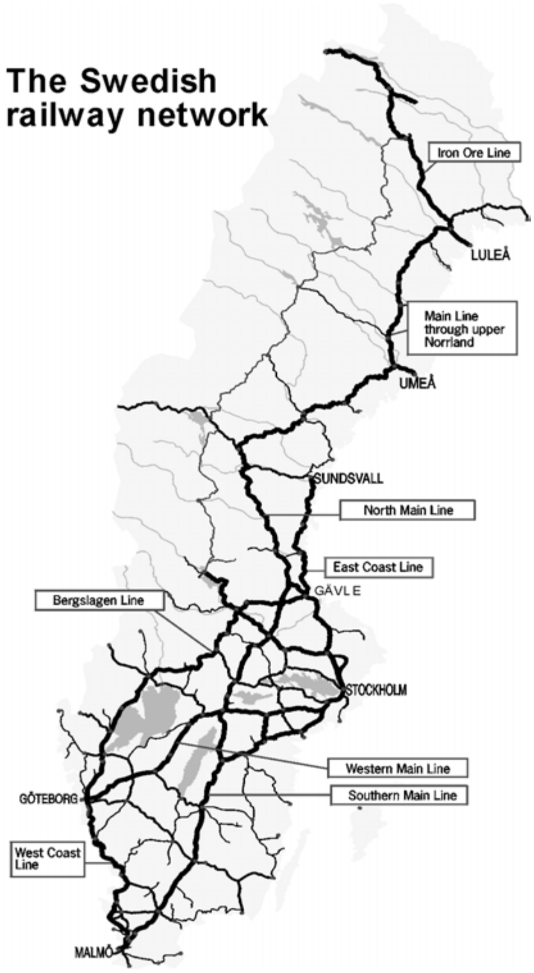

Figure 1.2: The Swedish Railway Network

1.2 Need for an Increased Axle Load

A deregulated railway market in Sweden started during the 90s to search for cost efficiency in all parts of the branch. First to request an increased axle load was the iron ore company LKAB in north Sweden. Since the 70s the iron ore trains had run with a

25 tonnes axle load on Malmbanan and now LKAB asked Banverket to increase that limit to 30 tonnes. LKAB had benchmarked with other iron ore companies and found that the rail transports was more expensive than transports performed by their main competitors. Costs related to transport time, available time on track, freight access charges, wagons, locomotives and engine drivers made a compelling demand to increase the axle load.

After that LKAB decided to initiate measures for an increase in axle load several other operators have followed. It is mostly operators that transport freight to/from paper mills and steel mills. As those kinds of transports are very heavy their need is strong. Sweden has a lot of such process industries contributing to our export income which makes the questions a national interest. Requirements from the industry were to get permission for 25 tonnes axle load on their lines by the end of 1999.

1.3 Consequence Studies on the Line Malmbanan

Banverket made a quick response to these request and launched several consequence studies to prepare for future decisions. First to study in 1995 was the expected consequences of an increased axle load on Malmbanan, the iron ore line in north Sweden. Several divisions at Luleå University of Technology became involved with research concerning the railway maintenance and its relation to changes in traffic. Also the Norwegian State Railways and LKAB participated in the research.

The research assessed the economical, technical and environmental consequences of allowing 30 tonne axle load on the existing tracks. The objectives were to increase the understanding of the effects of higher axle load on track degradation mechanisms, and determine a reliable cost estimation for future maintenance costs and track investments.

My part in the research was to participate in a team that searched for and gathered international knowledge in the area and also investigated and documented the current maintenance need on the superstructure on Malmbanan. It was in an early stage obvious that a confident evaluation of the current degradation of the track required long time studies due to the very slow degradation trend. Degradation of the track superstructure (rail, fastenings, sleepers and ballast) include failure mechanisms (especially fatigue) that might require 3-5 years of propagation before the underlying cause leads to any evident problem.

Fortunately, in the project, we could find maintenance history data on Malmbanan for a time span from 1979 to 1995 which turned out to be of great value. The international search for knowledge led us mainly to U.S. where heavy axle load freight traffic is studied at the AAR/TTC centre in Pueblo, Colorado. Other countries with major knowledge in heavy axle load transports turned out to be Canada, Brazil, South Africa, Australia, China and Russia. By visiting conferences held by IHHA (International Heavy Haul Association) in U.S. 1995, South Africa 1997 and Australia 2001 and by reading related articles a state-of-the-art awareness in heavy axle load maintenance was achieved. When mixing the international knowledge found with the field data from Malmbanan it seemed to correlate very well.

From the studies, LKAB concluded that an effective way of cutting transport costs would be to increase the axle load from 25 to 30 tonnes on the iron-ore line, Malmbanan & Ofotenbanen. The investigations also showed that the costs for upgrading the infrastructure was lower than expected as described by the project report [1].

It was concluded that the present track could be exposed to 30 tonnes axle load without a significant increase in track degradation. However this conclusion presupposed improved bogie design for wagons and locomotives, longer trains and reduction in the total number of wagons and locomotives. By technical analysis, mathematical models, practical experience and extensive research they estimated an expected increase in costs for track structure maintenance and renewal by 3%. However there is a certain amount of uncertainty in this estimation so the project group also calculated a confidence interval. In a worst case scenario the cost could increase 13% and in a best case scenario there could be a cost decrease of 4%.

The economical analysis of Malmbanan indicates that about 50% of the total cost for maintenance and renewal were related to traffic and 50% not related to traffic, such as signalling, electricity, snow-clearance etc. Costs for maintenance and renewal of rails, on some lines, account for more than 50% of the costs related to traffic. The results from the analysis have made it possible for the mining company LKAB to start up the 30 tonne traffic with new wagons and locomotives on the Malmbanan line in year 2001.

The 30 tonne project on Malmbanan became a precedent for increasing the axle load even on other lines in Sweden.

1.4 Consequence Studies on the Line Borlänge-Gothenburg

In 1996, after contacts between Banverket, freight operators and industries, Banverket decided to examine the possibilities to increase the axle load from 22.5 tonnes to 25 tonnes on some other lines besides Malmbanan. Banverket therefore launched the 25 tonne project on the line Borlänge - Gothenburg, which was split into four main packages: track, subgrade, bridges, and extended loading gauge.

With the achieved knowledge in the 30 tonne axle load study, I was asked to participate in this 25 tonne project and in its "Track" subproject. The subproject was divided into several parts:

- Economical analysis of existing costs
- Technical analysis of existing status
- Experiences and literature study
- Model for Track degradation costs
- Track construction

The purpose of the "Track" subproject was to investigate the technical and economical consequences for the track maintenance and renewal costs when increasing the axle load from 22.5 tonne to 25 tonne and increasing the weight/m from 60 to 80 kN/m.

The consequences of mixed traffic, freight traffic and passenger traffic in normal and high speed was to be particularly observed. Results from the consequence study of 30 tonne axle load on Malmbanan had produced a lot of information and had proved to be a valuable reference for different studies in track degradation, especially concerning rail wear in curves and rail fatigue. Even though the experiences and knowledge from Malmbanan gave us a lot of information the traffic conditions on that line differs a lot from the actual 25 tonnes traffic on main lines. Almost 100% of the tonnage on Malmbanan consists of iron-ore trains with very few passenger trains and other freight trains, and the speed is limited to 50 km/h for the old iron-ore wagons. The main lines for 25 tonne traffic will serve several types of freight wagons up to 100 km/h, several types of passenger traffic and also high speed traffic at 200 km/h. This means that there is a large mix of vehicles with different running characteristics, speeds and axle loads running on the same line.

The limited time schedule forced Banverket to work very fast with this investigation. Extensive investigations were carried out by Banverket in the following areas; field inspections of track, subgrade, culverts and bridges, calculations of geotechnical stability and calculations of carrying capacity of bridges. It was concluded that the current superstructure would withstand the higher axle load. Maximum speed for 25 tonne trains was set to 90 km/h on UIC60 rail, 80 km/h on BV50 rail and 70 km/h on BV50 rail with wooden sleepers. On some sections on the line, reinforcement was made on the subgrade and bridges. New bridges also replaced a few older bridges. Finally, at the end of 1999, Banverket could allow 25 tonne trains on the line between Borlänge and Gothenburg. The investigation is fully documented in a report [2].

The economical and technical analysis for the lines between Borlänge and Gothenburg indicated similarities with the experiences for Malmbanan. Costs for maintenance and renewal of rails sometimes made up more than 50% of the traffic related maintenance costs. It showed that a model for predicting track degradation costs should focus on rails.

1.5 The Need of a Track Degradation Model

In this second consequence study on the line Borlänge-Gothenburg with its very mixed traffic it became difficult to separate track degradations effect related to the freight traffic. If effects of an increased axle load on freight trains was to be found then such a separation seemed necessary so the separated part could be evaluated regardless of other traffic on the same line. This was an obvious problem that led to the research question (presented later in chapter 2.1): Could it be possible to develop a simulation model for track degradation that gathered existing research knowledge combined with empirical data from the 30 tonne axle load study on Malmbanan?

With the acceptance from Banverket regarding financing an early embryo to such a model was developed in 1998. In collaboration with track experts at Banverket, a framework for the model was defined. It was expected to help in prediction of economic effects due to changes in traffic and it should be based on technical and economical parameters for track degradation where output would be in economic terms. The early model was presented at the IHHA conference in Brisbane 2001 [3].

In the beginning, the model aimed at simulating and predicting effects on track degradation costs due to changes in traffic, mainly an increase of axle loads from 22.5 to 25 tonnes. This is a complex question, especially in Sweden, where traffic on most lines is a mixture of passenger- and freight trains and where deregulations of operators and of maintenance contractors have been made. An effect thereof is that a lot of historical economic data become worthless. Also, as operators want to reduce their costs, a tendency to introduce low-cost rolling stock is obvious which might reduce the steering performance and increase the resulting track degradation. A differentiated freight charging policy related to car performance could prevent such an evolution. A future use of the model might then be to help in calculating the proper rates related to car performance.

2 THE RESEARCH FRAMEWORK

2.1 Research Questions

The present operators are demanding and asking for permission to run a large mix of wagons, maybe in the future also to a differentiated freight charge. To deal with such demands an applied model for prediction of track degradation is required. As rail deterioration is ranked as the primary cost factor, it has to be considered by the proposed model together with other factors such as track lining. The research questions are therefore:

- Can existing research results and experiences worldwide be used to predict changes in track degradation costs due to changes in traffic?
- Are the international research results applicable to and useful for Swedish conditions?
- Are there any shortcomings in today's knowledge of predicting track maintenance?

2.2 Research Objectives

Based on the research questions there are some measurable goals to state:

- Develop a track degradation model for mixed traffic based on state-of-the-art knowledge
- Verify the model
- Implementation of the model into an easy-to-use software

2.3 Scope and Limitations

The research questions are focused on effects of changes in traffic. To make the research work relevant and applicable in real situation, the study includes:

- Search for a model that can separate effects of different vehicles types in parallel on the same track (mixed traffic).
- A possibility to simulate effects of axle load, speed, vehicle design and vehicle maintenance conditions for each vehicle type separately.
- A possibility to describe geometry of the studied track segment.
- A possibility to enter some degradation characteristics of the current track (field observations)

- A possibility to calculate some economical key values related to the track degradation.

To reduce the complexity there are also some necessary limitations. They are to exclude effects of:

- Changes in maintenance strategies, the amount of corrective versus predictive maintenance.
- Changes in maintenance organisation and outsourcing.
- Changes in maintenance tasks such as rail grinding and techniques for track renewal.
- Changes in component data such as rail steel quality. Component mix is supposed to be as is.
- Changes in asset valuation and accounting principles.

3 RESEARCH METHODOLOGY

Adapting theory into practice is not always so easy. In this research project several steps were to be taken and both inductive and deductive approaches seemed appropriate. Their definitions are:

> **Induction**
> "a process whereby from sensible singulars, perceived by the senses, one arrives at universal concepts and principles held by the intellect. Thus, from the sense experience of even a single yellow tulip, the intellect grasps that it is a special kind, a kind found in every single tulip. The person proves not only that he sees the tulip but also that he knows what kind of thing the tulip is by the following. He is able to point out all the others of the same kind. If the individual did not know the essence or whatness existing in each tulip, he could not group them together.", [4]
>
> **Deduction**
> "the human process of going from one thing to another, i.e., of moving from the known to the unknown ... Utilising what he knows, the human being is able to move to what he doesn't see directly. In other words, the rational person by means of what he already knows, is able to go beyond his immediate perception and solve very obscure problems. This is the nature of the reasoning process: to go from the known to the unknown.", [5]

The early studies of empirical data from Malmbanan needed surely an inductive approach trying to find relationship between the observed parameters. Next step when it came to mixing different research material into a full frame model the approach had to be deductive.

I realised that research projects mostly are very deep and very narrow in their content and focus. That makes their results difficult to use in modelling of broad banded implementations such as maintenance. However, after some weeks of studies of different research articles the first two research questions seemed to have a positive answer and an idea to approach for a model was formed. It can be described in the following steps:

1. Helicopter view. This model work has to focus on overall functionality enabling simulation of large scale effects on maintenance during long time periods.
2. Puzzle definition: Every research input has to be defined with function and its input/output interface. Such a definition can then be a piece placed into a jigsaw puzzle representing the overall model.
3. Missing pieces in step 2 is to be formed by either further empirical models or classic mechanical engineering theory.

4. Missing pieces in 3 also give automatic framework for future research including research question, the requested function and input/output definitions

Given the conditions as described in section 2.1, the early work of developing a model resulted in a maintenance prediction puzzle described in Figure 3.1. The blocks interact and form the total cost frame for maintaining track function. Every piece of the puzzle was to be described in terms of its interface to the other pieces. To simplify the task, maintenance activities were assumed to be unchanged, thereby not dealing with any effects of changes in preventive maintenance. The next step was to search for algorithms describing the other pieces and their interfaces.

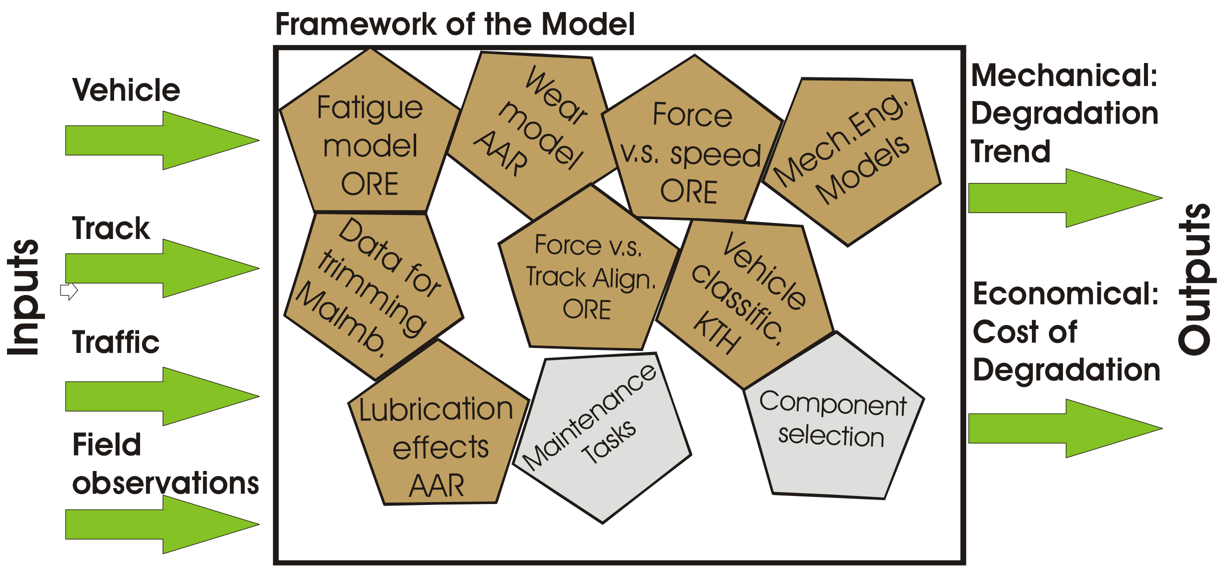

Figure 3.1: Model input block forms a maintenance prediction jigsaw puzzle. Light coloured pieces represent areas with low or missing content in the model.

4 DEVELOPMENT OF THE DECOTRACK MODEL

The early research and model work needed a suitable name. After some brainstorming sessions with my research colleagues at JvtC it was decided to name the model **DeCoTrack** as an abbreviation of **De**gradation **Co**st of **Track.** As described in chapter 3 the amount of research results found and the experiences from the consequence study on Malmbanan led to a positive answer on the first research question. As the results found that far also was close to the observations made on Malmbanan, it signalled a relevance for Swedish conditions and a yes to the second research question. These observations supported the statements:

- A model should be possible to develop.
- International research results are representative for Swedish conditions.

A model work was now about to begin.

4.1 Sources of Information

The thorough search for information led to several sources, which became the base for the model. Major contributions were found in:

- A Banverket report collection about the maintenance history of the iron ore line Malmbanan and the estimated consequences of increasing axle loads from 25 to 30 tonnes [1].
- ORE D161 European field studies during the 80's concerning 20 to 22.5 tonnes axle load increase on freight wagons and its effect on rail fatigue, rail geometry deterioration and costs [6]
- ORE D161.1 European field studies during the 80's concerning 20 to 22.5 tonnes axle load increase on freight wagons and its effect on rail fatigue, rail geometry deterioration and costs [7]
- ORE D141 European studies of the consequences during the early 80's concerning 20 to 22 tonnes axle load increase [8]
- ORE D173 A report about rolling contact fatigue and its relation to rail weight, wear and axle load. [9]
- A report from a Scandinavian co-operative study among the rail administrations. The study was about wheel-rail wear. [10]
- An article discussing the use of life prediction models as a tool in maintenance planning [11]
- A report from Royal Institute of Technology (KTH) ranking steering performance on different wagons and locomotives used in Sweden [12]
- An article presenting wear test results from the AAR test centre in Colorado, USA. [13]

- A report from AAR discussing rail wear and the influence of rail lubrication [14]
- Experiences from Luleå University of Technology (LTU) concerning friction and wear models for rolling/sliding contacts
- Standard mechanical dynamics literatures concerning loads and force distribution in curves

4.2 Introduction to the Model

An early version of the track maintenance prediction model was presented in [3]. It was based on research results worldwide during the 80’s and 90’s, especially empirical studies made by ORE in Europe [6] - [8]. With focus on rail wear and rail fatigue, the model estimated current and future degradation rates and converted it to economic terms. Other cost-consuming parameters such as track settlement, ballast and track reinvestment was expected to change linearly with one of the rail wear/fatigue parameters, whatever largest. Later work has refined the model with cost terms added that are proportional to the transported tonnage only and not to any vehicle parameters such as axle load, steering performance or speed.
The current degradation model is designed to simulate degradation of the super-structure (sleeper and upwards) and the ballast. As rail represent the top single cost consumer, the model still has rail degradation as a base in the analysis. Rail degradation is supposed to be generated by two mechanisms:

- Wear
- Fatigue

These mechanisms vary in strength depending on where on track the study is performed. Track curvature has a major influence with the following relationships to degradation:

- Narrow curves implies wear (ahead of fatigue)
- Tangent track implies fatigue (ahead of wear).

Expressed in a plot, it will look like Figure 4.1.

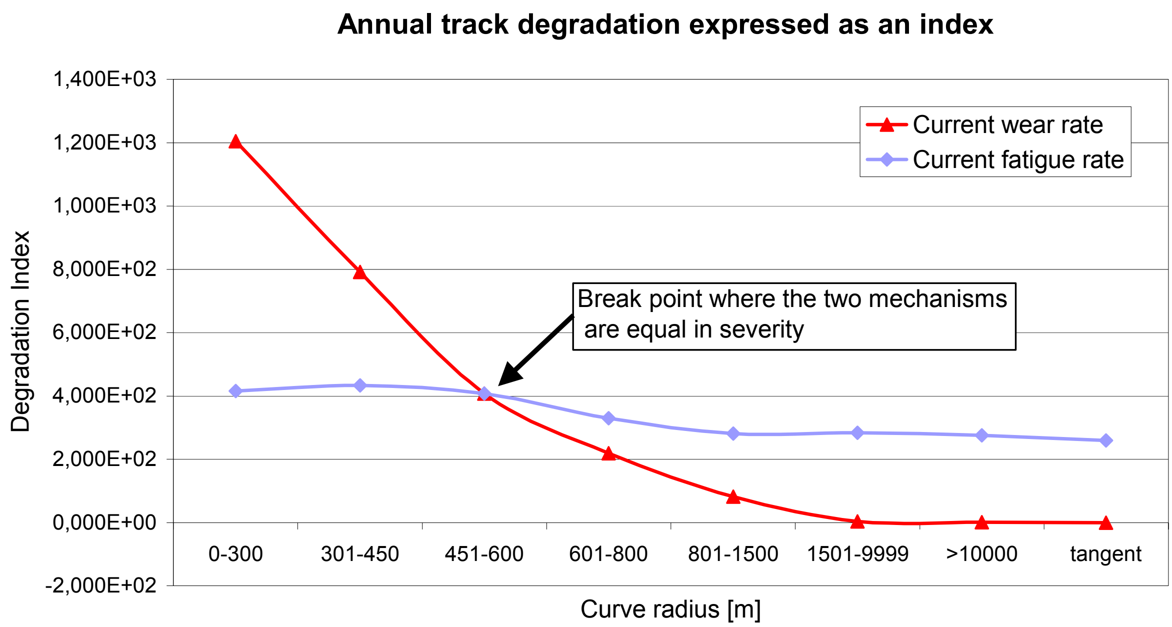

Figure 4.1: Wear and fatigue mechanisms as a function of curve radii. The degradation index corresponds to a relative degradation rate.

The model does not superimpose the two deterioration mechanisms but instead describes them to work in parallel. It is shown how wear and fatigue are influenced by curvature and that narrow curve track will make wear the major factor to limited rail life. For every point studied, the upper graph gives rail its life limit. Vehicle and track data as well as the annual tonnage on the line influence both curves. A similar approach is presented by A. Zarembski [11]. The rail degradation is governed by wear on track with short life length while it is governed by fatigue on rail with long life.
The model uses the rail degradation equations on part of other track components as well. This approach is supported by the results in ORE D161 rp3 [6] showing that Track settlement has same relation to axle load and tonnage as rail fatigue. The following equation is presented:

(1) $E = k * T^{\alpha} * P^{\beta}$

where

E=	A track degradation index
k=	Constant related to a specific track
T=	Total accumulated tonnage since the track was new
P=	Axle load

The exponents α and β are suggested to be:

Rail, internal fatigue and welds:	α=1	β=3
Rail, surface defects:	α=3	β=3.5
Other components in superstructure:	α=3	β=3
Track settlement:	α=1	β=3

From studies of reports D141, D161.1 and D161 it is obvious that a large uncertainty is present when it comes to estimation of the factor α that vary between 1-3. This uncertainty has led to that a straight tonnage dependency is used when calculating costs for rail replacement and for costs not separately defined.
In this perspective, it seems legal to make some simplifying assumptions. The degradation rate of the track is described by two separate equations: Rail, track settlement, turnouts and ties are assumed to degrade at a similar rate and with a relation to both axle load and tonnage hauled. Ballast, rail replacement, investment, inspections and other track components are supposed to be tonnage but not axle load dependent.

4.3 The Fatigue Mechanism

Fatigue of rail and settlement of track are strongly dependent of the force amplitudes excited by a passing wheel set. The loads from a single pair of wheels can be divided into three components:

(2) $P_{tot} = P_{static} + P_{kvasistatic} + P_{dynamic}$

where

P_{tot}= Total axle load [ton]
P_{static}= Static axle load [ton]
$P_{kvasistatic}$= Quasi-static add to axle load in curves due to centripetal acceleration and the superelevation [ton]
$P_{dynamic}$= Dynamic add to axle load due to unspringed masses and roughness of wheel and track [ton]

The quasi-static load is calculated by common formulas handling curve radius, train speed, centre of mass and the superelevation. The dynamic add is calculated by a formula from ORE D161.1 rp4 [7] declaring:

(3) $P_{dynamic} = 1.201+0.060A+0.051*(V-50)*(S-0.5)$ [ton]

where

$P_{dynamic}$= Dynamic add to axle load [ton]
A= Static axle load 5-22.5 ton [ton]
V= Train speed 50-120 [km/h]
S= Vertical track alignment, $\sigma_{BMS,}$ standard deviation 0.5-3 [mm]

Based on formula (1) a modified equation is formed including curve radius and number of passing axles

(4) $$e_u(r) = k_u * \sum_{f=vehicle} (k_{uf} * Ptot_f^3(r) * n_f)$$

where

e_u = Degradation index due to fatigue as a function of curve radius

k_u = Coefficient adjusting the output to the studied track segment

k_{uf} = Coefficient weighing each vehicles ability to generate fatigue. It is a relative classification based on empirical data on the dynamic adds to axle load. Data is given from studies at KTH [12].

$Ptot_f$ = Total axle load for each vehicle type expressed as a function of curve radius where effects of load projection due speed, centre of mass and superelevation is included.

n_f = Number of axle passes per year for each vehicle type.

The calculation of k_{uf} is simple. A relative classification is done by using formula (5):

(5) $$k_{uf} = \frac{\text{Dynamic axle load of vehicle f}}{\text{Dynamic axle load of reference vehicle}}$$

In Figure 4.2 some data from the calculation is presented where a 4-axle freight car has been set to 1,00 as a reference. An explanation of k_{sf} is given in the section about the wear mechanism.

	Vehicle constant	
Vehicle type	k_{sf} wear	k_{uf} fatigue
X2 locomotive	3,6	1,14
X2 passenger car	2,9	0,94
RC locomotive (passenger)	7,3	1,43
Passenger car	7,3	0,88
X10A	1,4	1,03
X10B	1,4	1,03
RC locomotive (freight)	7,3	0,91
Freight car (2 axles)	3,6	1,29
Freight car (4 axles)	3,6	1

Figure 4.2: Classification of vehicles showing their ability to cause wear and fatigue on track

The model described above will include both track data and vehicle data. Every vehicle on track is calculated where after all results are added to give the annual total fatigue degradation index.

4.4 The Wear Mechanism

In parallel to the case of fatigue, the model includes an estimation of rail wear. It is strongly influenced by curve radius, vehicle steering performance and the amount of lubrication. In narrow curves with poor lubrication this mechanism will exceed all the degradations due to fatigue. The most common wear model among researchers states that rail wear at a given point of the track is proportional to the energy loss due to friction. The energy loss is proportional to the hauled tonnage and will not be changed with axle load. We have added the quasi-static additional load in curves, an empirical formula for the effect of lubrication and a vehicle classification wear coefficient, which lead to the following equation:

(6) $$e_s(r) = k_s * f(\mu) * F(r) * \sum_{f = \text{vehicle}} (k_{sf} * P_f(r) * n_f)$$

where:

e_s = Wear index in track as a function of curve radius r

k_s = Coefficient adjusting the output to the studied track segment.

$f(\mu)$ = A function relating wear to the friction coefficient, further described in text below.

$f(r)$ = A function relating wear to curve radius, further described in text below.

k_{sf} = Coefficient weighing each vehicles ability to generate wear. It is a relative classification based on simulated data on the friction energy dissipation of different vehicles. Data is given from studies at KTH [12].

$P_{f(}(r)$ = Axle load including both static and quasi-static load in a given curve radius.

n_f= Number of axle passes per year for each vehicle type.

The function $f(\mu)$ has been calculated from a curve regression of data in an AAR report [14]. This gives:

(7) $$f(\mu) = 6{,}0112 * \mu_{meas}^2 + 0{,}4267 * \mu_{meas} - 0{,}1322$$

where

μ_{meas} = The measured friction coefficient on rail

This equation is valid for friction coefficients in the range $0.1<\mu<0.4$ and it scales the output from 1.00 at μ=0.4 down to approximately 1/15 at μ=0.1. This corresponds to the actual effects on wear due to a change in lubrication. Results refer to measurements made at the test facility AAR/TTC in Colorado, US.

The other function F(r) has been formed based on field measurements of wear in different curve radii. The lubrication plays a crucial role, Figure 4.3. We have chosen to use the Swedish reference dry wear based on a lot of field measurements during the 80's. The wear was then measured on several curves, track components and with varying traffic mix.

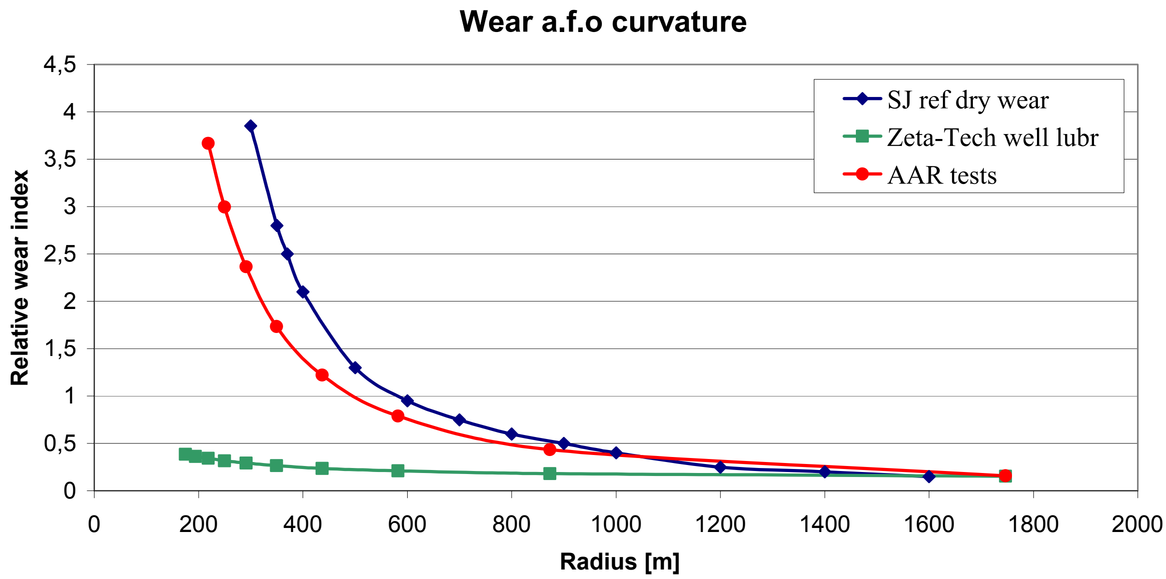

Figure 4.3: Wear index as a function of curvature.

By using curve regression the plot was approximately described in a logarithmic expression:

(8) $f(r)= 1/r^{1,9}$

The coefficient k_{sf} ranks each vehicles concerning wear generation. The coefficient is based on a formula for energy dissipation presented by E. Andersson and S. Stichel at KTH [12]. By using listed data for different vehicles and using the pre-selected curve radius r =800m some relative indexes k_{sf} are calculated. The formula used is:

(9) $$k_{sf} = \frac{\text{Friction energy loss in curve for vehicle f}}{\text{Friction energy loss in curve for reference vehicle}}$$

4.5 Field Observations

The models main focus is to estimate changes in maintenance and in the track degradation rate when the traffic is changed. Therefore it is tuned to reflect the current situation after which future changes of traffic are simulated. The tuning is made by a set of key parameters for the studied track section:

- A value of the curve radius, r (m), where wear exceed fatigue as the dominant rail degradation mechanism. This corresponds to the break point in Figure 4.1. This parameter sets the relative weighing between k_u and k_s in the described mechanisms.

- An estimated life length of track with the current traffic volume. It is expressed as accumulated tonnage (MGT) at a free selectable curve radius.
- Annual maintenance costs that are supposed to be independent of traffic volume, from now on labelled $\mathbf{C_{ob}}$.
- Annual maintenance costs that is supposed to be dependent of traffic volume and proportional to tonnage. Such areas include costs for track reinvestment, ballast, inspections, costs due to accidents/derailment and other unspecified track components, This cost is from now on labelled $\mathbf{C_T}$.
- Annual maintenance costs that is supposed to be dependent on traffic volume and especially influenced by both axle load and tonnage. Typical costs include rail replacement, rail maintenance, tamping, turnouts and ties. The factor is from now on labelled $\mathbf{C_{ax}}$.

When the key parameters are given, it is assumed that the current traffic has run unchanged for several years so that it can be expected to reflect the current maintenance volume. The key parameters are used for controlling the relative position between the plots in Figure 4.1 and to relate them to the actual rail life length. Entered maintenance costs makes it possible to convert mechanical data into economical data and to distribute costs along the studied track section based on the underlying mechanical mechanisms.

4.6 Economic Projection

The model converts mechanical degradation to economic terms by a linear conversion between technical life and annual traffic-related maintenance cost. In mathematical terms this is expressed as:

$$(10) \qquad C_{tr} = C_T(ref) * \frac{T}{T(ref)} + C_{ax}(ref) * \sum_{\substack{\text{curve} \\ \text{radius}}} L * \frac{\max(e_u, e_s)}{\max(e_u(ref), e_s(ref))}$$

where:

C_{tr} = Annual traffic-dependent maintenance cost
C_T = Annual maintenance cost, tonnage but not axle load dependent, for example track replacement costs
C_{ax} = Annual maintenance cost, both axle load and tonnage dependent
T = Annual tonnage
ref = Reference year, e.g. current situation
L = The normalised part [0-1] of total track length having a given curve radius interval
e_u = Degradation index due to fatigue and dynamic forces

es = Degradation index to wear

Formula (10) expresses that all costs are relative to current conditions and they are distributed along track according to the curvature. Noticeable is that the tonnage-dependent cost C_T includes track replacement although the technical life of track is governed by wear and/or fatigue mechanisms as described. Such a statement is based on estimates of the fact that track replacement cost not necessarily is proportional to time between replacements. The amount of work and the component volume might vary and any effects of asset values and interest are not included. The later in spite of the fact of a technical life reaching 40-50 years. Such considerations have to be taken when the reinvestment costs are distributed into annual track reinvestment amounts.
The total maintenance cost of track is calculated by the following formula:

(11) $$C_{tot} = C_{ob} + C_{tr}$$

where
C_{tot}= Total annual maintenance cost
C_{ob}= Annual maintenance cost, traffic independent
C_{tr}= Annual maintenance cost, traffic dependent (= $C_T + C_{ax}$)

4.7 Model Output

4.7.1 Output Showing Track Degradation

From the model a plot of annual track consumption ca be presented. The degradation, expressed as % of track life per year, is plotted against curve radius, Figure 4.4. A value of 5% means for example that the track is to be replaced after 20 years in service. The two plotted lines represent two traffic situations where “Current traffic mix” reflects 22,5 ton axle load trains and “Future traffic mix” reflects 25-ton axle load trains. All other parameters such as annual tonnage, track standard and vehicle type are assumed to be unchanged. The plots are based on the worst case in the wear/fatigue diagram in Figure 4.1. On tangent track it is rail fatigue that restricts the track life and in curves it is rail wear. Track degradation increases in the “Future traffic mix” scenario on all curve radius >600m due to the increased axle load while the degradation in curves is unchanged as wear is assumed to be proportional to the total (unchanged) tonnage. Detailed information of this example is given in Chapter 4.8.

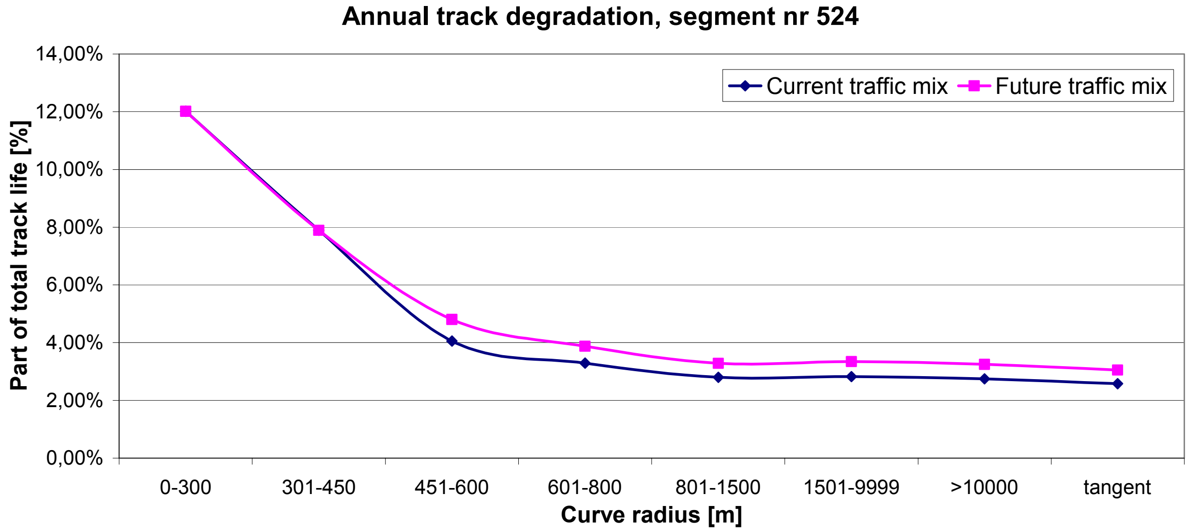

Figure 4.4: Annual track consumption expressed as % of total track life.

4.7.2 Output Showing Annual Track Degradation Cost

The model also can produce a plot, Figure 4.5, where the annual traffic dependent maintenance costs are distributed on the curve radii of a track section. The calculation is based on expressions (10)+(11) and the diagram reflects costs due to track degradation weighted with track length and with added traffic non-dependent costs and purely tonnage dependent costs. The shown example is based on same data as Figure 4.4. All freight tonnage is moved from 22,5 to 25 ton axle load. The total cost increase is +4,2%.

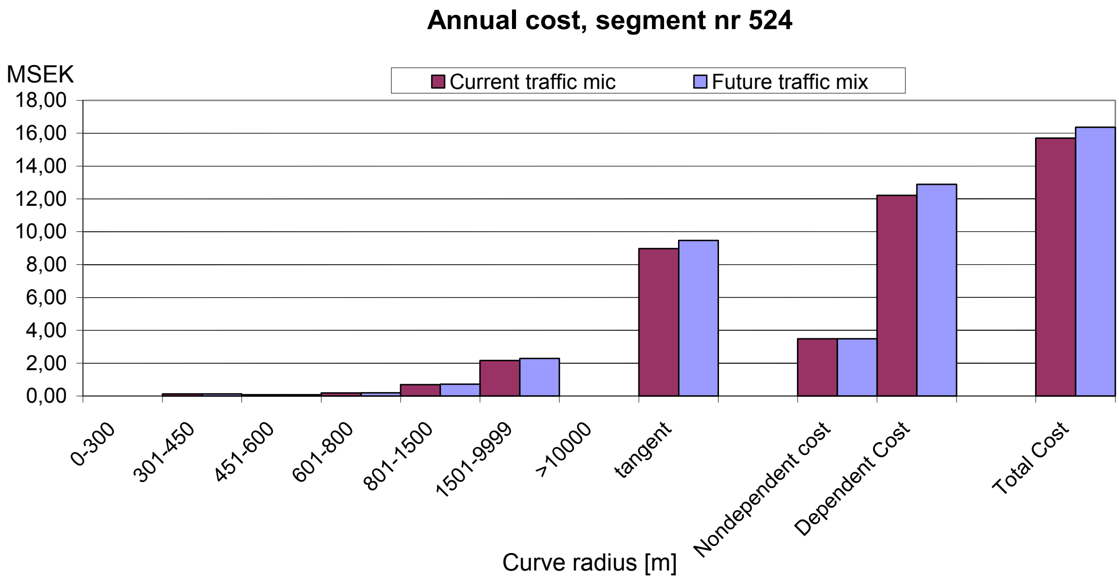

Figure 4.5: Annual degradation costs related to curve radius. An increase of +4,2% in total cost

4.8 A DeCoTrack Simulation Example

This chapter shows screen dumps from a DecoTrack simulation. The example is based on a track segment, nr 524, with a total length of approximately 54 km. The annual traffic is currently 2,1 MGT (million gross tons) of passenger trains and 9,1 MGT of freight trains with 22,5 ton axle load. In the future all freights are assumed to be carried on 25-ton axle load cars. All other parameters are expected to be unchanged. Figure 4.6 - Figure 4.12 represent the consecutive steps of the simulation. From Figure 4.12 the change in total costs can be read. In this case it is an increase of +4,2%.

Track data, segment nr 524

Parameter	Curve radius [m]								
	0-300	301-450	451-600	601-800	801-1500	501-1000	>10000	tangent	total
Track length [km]		0,360	0,290	0,760	3,009	9,460		40,363	54,242
Track vert. alignment [mm]	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	
Friction coefficient μ	0,400	0,400	0,400	0,400	0,400	0,400	0,400	0,400	
Super elevation h_a [mm]	150	150	140	130	100	40	25		

Annual maintenance cost, traffic nondependent [MSEK]	3,48
Annual maint. cost, rail+sleepers+turnout+tamping[MSEK]	3,7
Annual maint. cost, track replacement+others [MSEK]	8,52

Segment nr	524

Figure 4.6: Track data for the specified segment with a total length of 54,242 km.

Vehicle data, segment nr 524

	Ax. load	Vehicle classific.		Speed profile in different curve radii [km/h]								Mass
Vehicle type	[ton]	Wear	Fatigue	300	375	525	700	1150	5750	10000	tngnt	cntr [m]
X2-locomotive	18	3,6	1,14	100	110	130	140	140	140	140	140	1,6
X2 coach	13	2,9	0,94	100	110	130	140	140	140	140	140	2,1
RC passenger locomotive	19	7,3	1,43	85	95	110	120	140	140	140	140	2,5
Passenger coach std	12	7,3	0,88	85	95	110	120	140	140	140	140	3
X10A	13,5	1,4	1,03	85	95	110	120	140	140	140	140	2,9
X10B	13,5	1,4	1,03	85	95	110	120	140	140	140	140	2,9
RC freight locomotive	20	7,3	0,91	80	90	100	100	100	100	100	100	1,5
Freight car 2-axle 5 ton	5	5,1	1,29	80	90	100	100	100	100	100	100	2,2
Freight car 2-axle 10 ton	10	5,1	1,29	80	90	100	100	100	100	100	100	2,2
Freight car 2-axle 15 ton	15	5,1	1,29	80	90	100	100	100	100	100	100	2,2
Freight car 2-axle 20 ton	20	5,1	1,29	80	90	100	100	100	100	100	100	2,2
Freight car 2-axle 22,5 ton	22,5	5,1	1,29	80	90	100	100	100	100	100	100	2,2
Freight car 2-axle 25 ton	25	5,1	1,29	80	90	100	100	100	100	100	100	2,2
Freight car 4-axle 5 ton	5	3,6	1	80	90	100	100	100	100	100	100	2,2
Freight car 4-axle 10 ton	10	3,6	1	80	90	100	100	100	100	100	100	2,2
Freight car 4-axle 15 ton	15	3,6	1	80	90	100	100	100	100	100	100	2,2
Freight car 4-axle 20 ton	20	3,6	1	80	90	100	100	100	100	100	100	2,2
Freight car 4-axle 22,5 ton	22,5	3,6	1	80	90	100	100	100	100	100	100	2,2
Freight car 4-axle, 25 ton	25	3,6	1	80	90	100	100	100	100	100	100	2,2

Figure 4.7: Vehicle look-up table for all vehicles that is possible to find on segment 524.

Current traffic mix, segment nr 524

Vehicle type	Annual MGT
X2-locomotive	
X2 coach	
RC passenger locomotive	
Passenger coach std	2,1
X10A	
X10B	
RC freight locomotive	
Freight car 2-axle 5 ton	
Freight car 2-axle 10 ton	
Freight car 2-axle 15 ton	
Freight car 2-axle 20 ton	
Freight car 2-axle 22,5 ton	
Freight car 2-axle 25 ton	
Freight car 4-axle 5 ton	
Freight car 4-axle 10 ton	
Freight car 4-axle 15 ton	
Freight car 4-axle 20 ton	
Freight car 4-axle 22,5 ton	9,1
Freight car 4-axle, 25 ton	
Total	11,2

Future traffic mix, segment nr 524

Vehicle type	Annual MGT
X2-locomotive	
X2 coach	
RC passenger locomotive	
Passenger coach std	2,1
X10A	
X10B	
RC freight locomotive	
Freight car 2-axle 5 ton	
Freight car 2-axle 10 ton	
Freight car 2-axle 15 ton	
Freight car 2-axle 20 ton	
Freight car 2-axle 22,5 ton	
Freight car 2-axle 25 ton	
Freight car 4-axle 5 ton	
Freight car 4-axle 10 ton	
Freight car 4-axle 15 ton	
Freight car 4-axle 20 ton	
Freight car 4-axle 22,5 ton	
Freight car 4-axle, 25 ton	9,1
Total	11,2

Figure 4.8: A specification of the annual tonnage that each set of vehicles will add on to the track. The difference between current and future scenario is that all freights are moved from 22,5 to 25 ton axle load cars. Passenger traffic remains unchanged.

Field observations, segment nr 524

Break point, wear/fatigue

Curve radius where wear becomes dominant [m]	525

Estimated Track life

Track life [MGT]	400
At curve radius [m]	1000

Figure 4.9: From field observations, the user has to tell in what curve radius wear becomes dominant. Also the estimated track life (with current traffic mix) has to be defined.

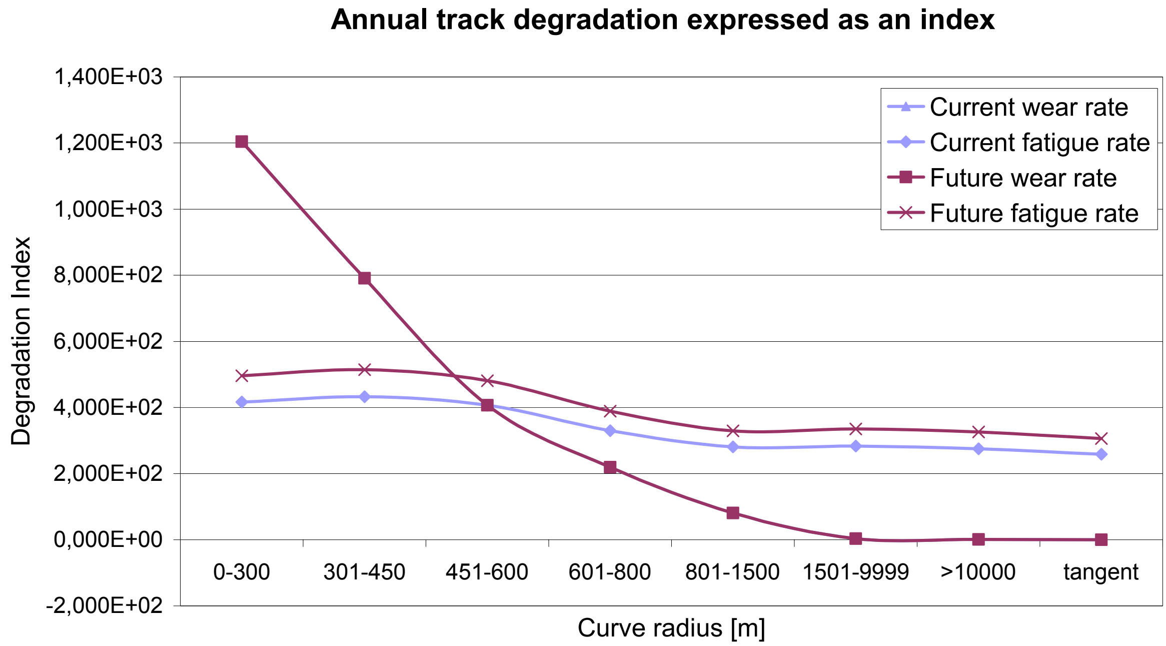

Figure 4.10: From the current and future traffic situations, plots can be made of rail wear and rail fatigue. Below a curve radius of 525m wear becomes dominant. Current and future wear plots are coincident.

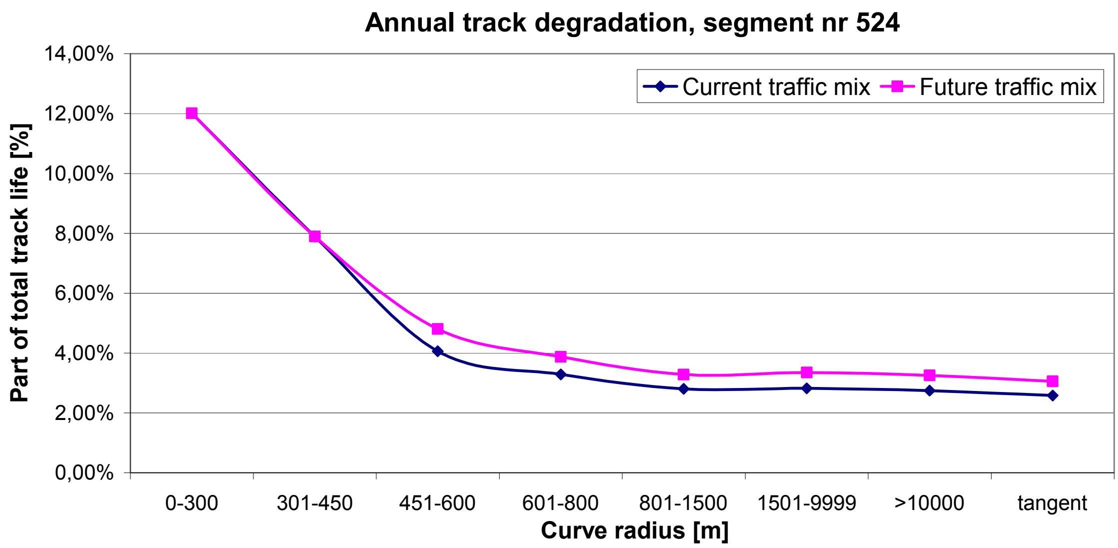

Figure 4.11: Taking worst case in Figure 4.10 will make this plot. This corresponds mainly to rail consumption but the other track components are expected to deteriorate in the same manner.

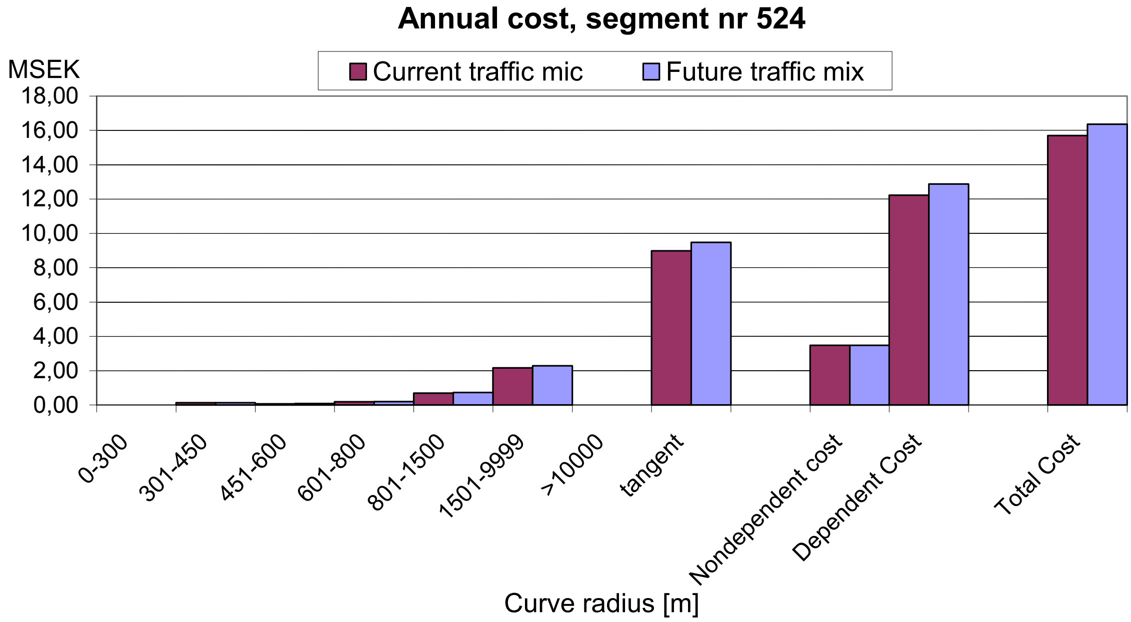

Figure 4.12: Based on the degradation rates presented in Figure 4.11, the traffic dependent costs given in Figure 4.6 are distributed along the segment. The length of each curve radius acts as a weight in the calculation. An increase of +4,2% in total cost is expected when increasing the axle load from 22,5 tons to 25 tons.

5 COMPARING DECOTRACK WITH OTHER RELEVANT MODELS

To confirm that DeCoTrack gives a realistic output, a comparative study has been performed during first half of 2002. It included a literature survey where a total of 900 abstracts have been scanned and where 40 articles have been read more thoroughly. Only articles from 1990-2002 were searched for and most of them are written after 1998 showing that degradation and maintenance cost simulation was a hot topic. Among the 40 articles read, 21 of them turned out to be relevant. They are overviewed in appendix B and can be found as references [15]-[34]. The studied articles show different approaches to simulation of maintenance needs and track degradation. Mainly they can be divided into two different approaches, as suggested by [15]:

- Cost based models
- Mechanical based models.

As expected the origin of each approach depends on the analyst. Economists prefer cost models while engineers prefer mechanical models. Cost based models have been developed especially in U.S. where a large number of railroads have been investigated and compared with parallel information of economics and traffic intensity, for example [16]. The conclusion thereof is that strictly economic studies tend to be difficult to analyse. The maintenance costs vary a lot over time during long time studies due to deregulations, business activity and changes in the maintenance strategy. On the other hand, strictly mechanical based models suffer from difficulties to convert from mechanical properties to economic properties. Our point of view is that the latter method is preferable: Mechanical properties tend to be objective and easily trended. Conversion to economic terms is done by using estimates of mean costs for each defect or maintenance activity pinpointed in the mechanical model.

The question of maintenance prediction and track degradation in economic terms seems to be of larger concern on heavy freight lines compared to lines with mainly passenger traffic. This might seem obvious due to a strong increase in maintenance cost with increasing axle load and tonnage. When reducing the question to track settlement and roughness, articles with studies for high-speed lines occur, one such report is [17]. Then it is not only the maintenance costs that are requested but also a tool to predict comfort and safety issues.

As far as this literature study can overview, two models seem to be close to or partly pass the complexity of DeCoTrack. They are the TRACS model [18], [19], developed by AAR and MIT in U.S. and the ITDM/TMPM model [20] - [22] developed at Queensland University in Australia. In the early 90´s Cole, Sherman & Associates in Canada presented a track maintenance system named TM$ presented in [23], [24]. It was based on statistical models based on field data. The system was implemented on several of Burlington Northern lines. In the same period CN, Canada, presented something similar called TMS [25]. The models in that system were based on experiences and research results from AAR and from the Canadian Institute of Guided Ground Transport.

A recent approach to modelling is presented by A. Zarembski in 2000 [26]. He uses an exponential degradation analysis on the superstructure, including ballast and turnouts, which produces economic terms as output. That model is very similar to DeCoTrack but it is in lack of vehicle classifying parameters other than axle load.

An overview of found articles and their content is presented in appendix B. Among them there are some with content relevant to DeCoTrack. Most articles refer direct or indirect to measurements done at the AAR/TTC test facility in Colorado, U.S. The research at TTC is strongly involved with the effects of increased axle load and ways to reduce or estimate the resulting maintenance costs. Problems related to passenger traffic such as the effect of speed on vertical track alignment and settlement has been addressed in other places. Research knowledge is then found in both Europe and Asia. When comparing DeCoTrack, the two most interesting models turned out to be ITDM/TMPM in Australia and TRACKS in U.S. They are presented in detail below:

5.1 ITDM - An Integrated Track Degradation Model

ITDM as presented in reference [20] and [21] is a track degradation model developed at Queensland University, Australia. The model simulates track degradation under varying traffic including the interaction between different track components. It is based on mechanistic relationships including train speed and axle load. Different sub-modules take care of rail, sleepers, ballast and subgrade issues. These modules are connected to a common frame in which the simulation is made in incremental steps of time and tonnage, see Figure 5.1. Although not actually written, such an arrangement should make it possible to introduce interrelationships between different degradation mechanisms and also to add effects of discrete maintenance activities such as grinding or rail replacement.

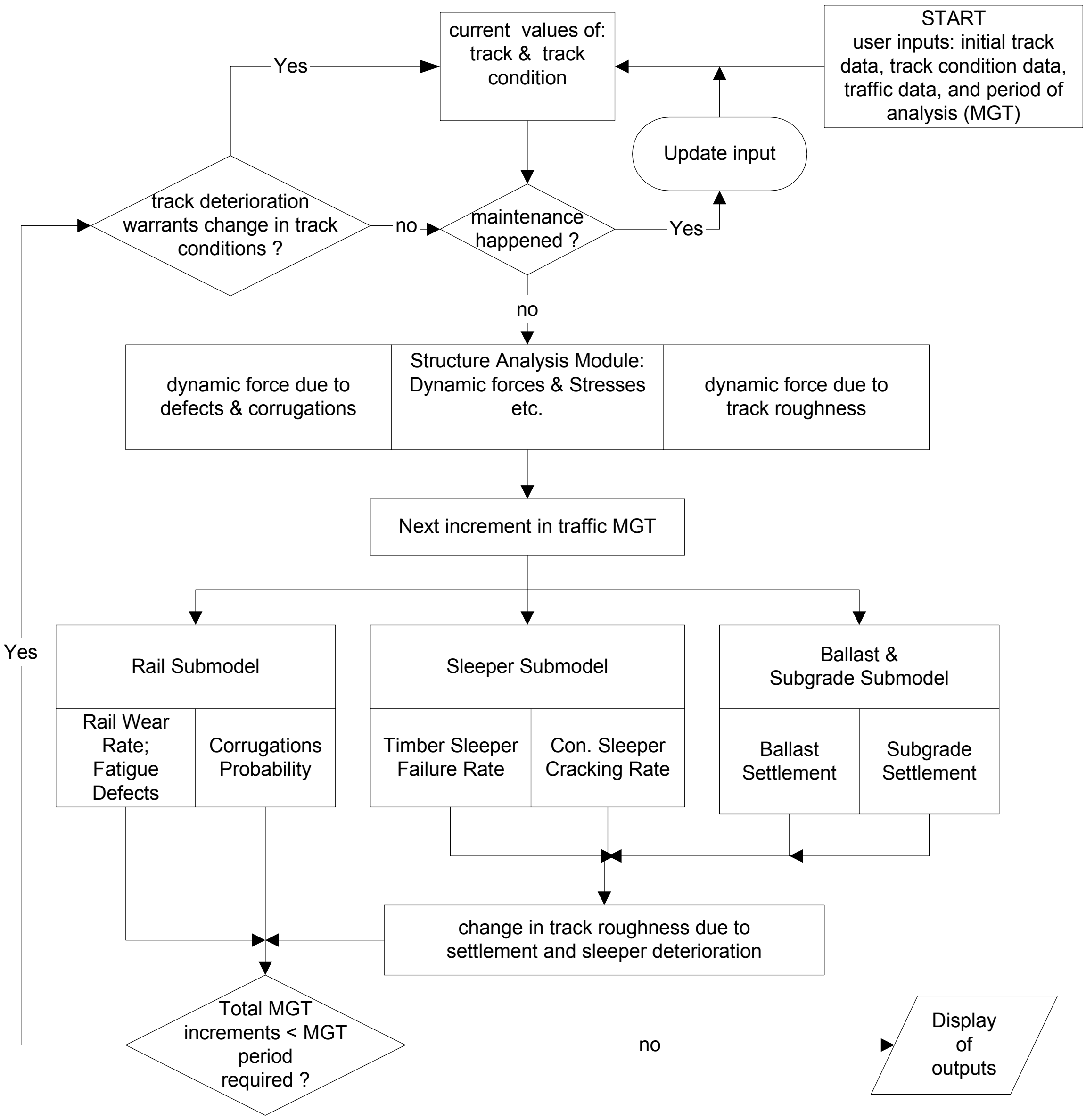

Figure 5.1: The ITDM model

5.1.1 ITDM Rail Model

The rail model in ITDM is restricted to wear only. In the article [20], the authors state that the interactive relationship between grinding and fatigue have to be established before implementation into ITDM. When it comes to wear, the authors have used a methodology where wear is proportional to the vertical axle load and to the angle of attack of wheel set to track. The equation used is:

(12) $$w_i = C_{i,1} k_k k_{1,i} C_{i,2} W_i \sin\psi$$

where

w_i= Wear rate on high or low rail top or high rail gauge wear
$C_{i..1}$= $7,61*10^{-6}$ for high rail top
$9,5*10^{-6}$ for low rail top
$12,1*10^{-6}$ for high rail gauge
$C_{i..2}$= 1 for gauge wear in curves with radius<500 m
1,7-0,0014*curve radius for curve radius 500-1199 m
0 for curve radius => 1200m
k_H= $51,05*e^{-0,0152H}$, where H=rail hardness,
(*authors comment: unit unknown, probably Brinell*)
$k_{l.i}$= Lubrication factor related to the coefficient of friction, μ. With μ=0,15-0,35 the factor varies between 1-1,6 in relative order. Different lubrication factors have been developed for the different wear cases.
W_i= Vertical wheel load when calculating top wear [kN]. Lateral load multiplied with a constant related to wheel profile and flange angle [3,5-4,4] when calculating gauge wear
ψ= Angle of attack [rad], typically 0,0058 at a curve radius of 500m

The model for wear is based on work done by P. Clayton and R.K. Steele at AAR during the 80'ies. The influence of lubrication seems to be based on empirical results from Australia.

5.1.2 ITDM Sleeper Model

The sleeper sub-model draws from S.T. Lamson and B. Dowdall at the University of Kingston. It describes the degradation of timber sleepers due to traffic, sleeper age and biological factors leading to decay. The dependence of traffic is assumed to be governed in a way that each standardized wheel loading cycle causes an equal amount of sleeper damage. Wheel loads are classified into categories, in which, each generates separate stresses (σi) into the sleeper. A standard loading cycle is that when the wheel pass generates a stress of magnitude σ_{std} into the sleeper. If the stress becomes lower than the actual number of wheel passages N_i is reduced to an equivalent N_{ieqv} as follows:

(13) $$N_{ieqv} = N_i\left(\frac{\sigma_i}{\sigma_{std}}\right)^{k_t}$$

With k_t calculated as:

(14) $$k_t = k_{Ag}k_{Drn}k_{Di}$$

where:

kt= Damage intensity factor
k_{Ag}= Sleeper age factor, typically 1-1,75
k_{Drn}= Drainage factor, 1-1,3
k_{DI}= Decay intensity factor, governed by climate and biological factors. Typical values are 1-1,3. A decay index map for Australia has been developed

The model seems to handle timber sleepers only.

5.1.3 ITDM Ballast and Subgrade Models

As described in article [21] the ITDM approach to ballast degradation and vertical track alignment is based on work performed by S.M. Chrismer at University of Massachusetts and by Z. Cai Et Al at Transportation Research Board in Washington. The vertical track alignment is described by:

(15) $$\sigma_{vo} = \sigma_{vo\min} + 0.15 * S_L$$

where:

σ_{vo}= Standard deviation of the vertical track alignment [mm]
σ_{vomin}= Standard deviation of track top line just after resurfacing [mm]
S_L= Average track settlement resulting from sum of settlement of all sub-layers [mm]

The track settlements are calculated from plastic strains of all sub-layers. The general equation for track settlement is given by:

(16) $$S_L = \varepsilon_b * h_b + \varepsilon_{sb} * h_{sb} + \delta_{sg}$$

where:

S_L= Average track settlement resulting from sum of settlement of all sub-layers [mm]
ε_b= Plastic strain of the ballast layer
h_b= Thickness of the ballast layer [mm]
ε_{sb}= Plastic strain of the sub-ballast layer
h_{sb}= Thickness of the sub-ballast layer [mm]
δ_{sg}= Sub-grade settlement [mm]

The plastic strain of each layer is a function of the number of load cycles, wheel loads, ballast quality and track modulus. This is better presented in article [27] by same authors. Their approach is to calculate a relative number of axle passages related to axle load, type of traffic and the vertical track alignment. That number of passages is given by:

(17) $$N_i = \left[350 + (360 - 350) x \frac{\sigma_{vo} - \sigma_{vomin}}{\sigma_{vomax} - \sigma_{vomin}}\right] x \frac{T_a}{40}$$

where:

Ni= Equivalent number of wheel passes in the ith wheel load category
σ_{vo}= Vertical track alignment [inch]
σ_{vomin}= Vertical track alignment just after maintenance [inch]
σ_{vomax}= Vertical track alignment at which maintenance is decided [inch]
T_a= Annual tonnage [tonne]

Something seems to be missed in the formula because it does not mention axle load but reference [27] gives some more information. A table based on formula (17) shows calculated values for different wheel loads, Figure 5.2. It is not explicitly mentioned but wheel load should by definition be half the axle load. The table is told to correspond to Australian railroads with typically σ_{vomin}= 3 mm and σ_{vomax}= 13 mm.

W_i	N_i x 10^3		
kN	Mixed Freight	Unit Trains	Freight & Passenger
0-50	$(347+\sigma_{vo})T_o/45$	$(406.3-1.1\sigma_{vo})T_o/45$	$(194.400.2\sigma_{vo})T_o/45$
51-100	$(357+\sigma_{vo})T_o/45$	$(70.2+1.6\sigma_{vo})T_o/45$	$(384.9-1.3\sigma_{vo})T_o/45$
101-150	$(269.5-1.5\sigma_{vo})T_o/45$	$(56.4+6.2\sigma_{vo})T_o/45$	$(276.3-2.1\sigma_{vo})To/45$
151-200	$(169.5-1.5\sigma_{vo})T_o/45$	$(403.3-10.3\sigma_{vo})T_o/45$	$(146.9-1.3\sigma_{vo})T_o/45$
201-250	$(5.5+1.5\sigma_{vo})T_o/45$	$(32.4+3.2\sigma_{vo})T_o/45$	$(15.3+1.9\sigma_{vo})T_o/45$
251-300	NA	$(0.15+0.65\sigma_{vo})T_o/45$	$(4.5+0.5\sigma_{vo})T_o/45$
301-350	NA	NA	$(2.1+0.1\sigma_{vo})T_o/45$
351-400	NA	NA	$(1.37+0.01\sigma_{vo})T_o/45$

Based on Chrismer, 1994, adapted for Australian conditions

Figure 5.2: A table showing weighted axle passages NI related to wheel load W_I and traffic type. SI-units

5.1.4 ITDM – Demonstration of Output

Several plots are presented from the model in reference [20]. Figure 5.3-Figure 5.6 are some of the interesting findings. One observation is the clear statement that both axle load and train speed are major parameters affecting rail wear.

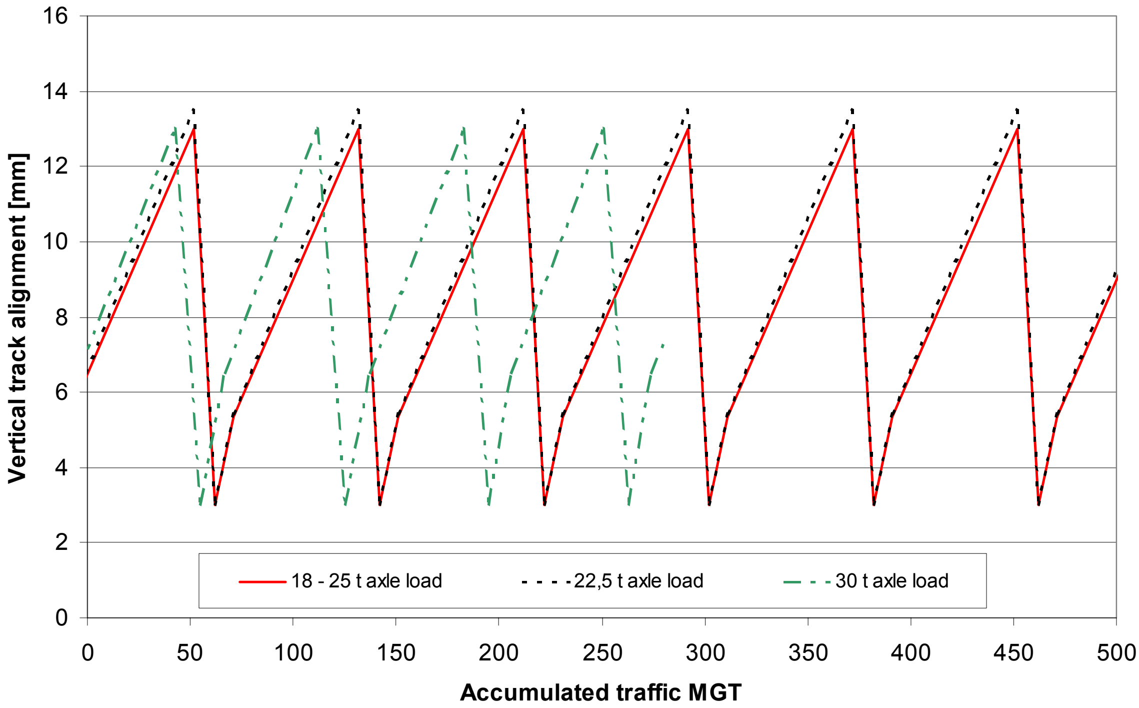

Figure 5.3: Effect of axle load on tamping demand.

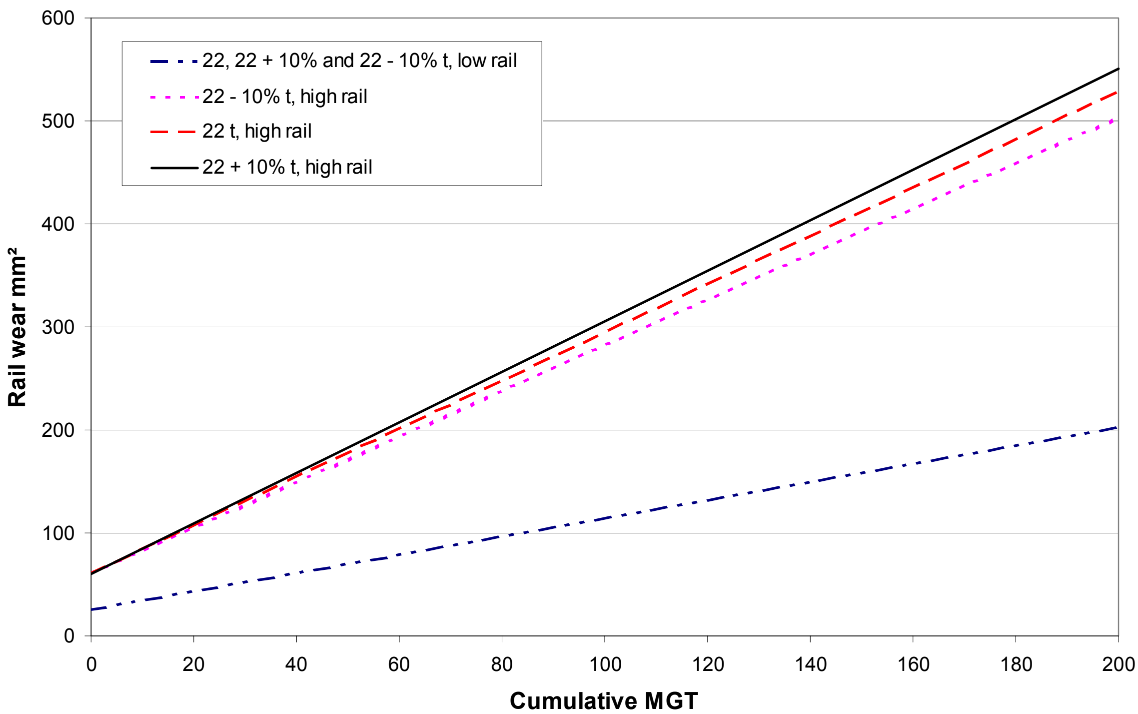

Figure 5.4: Sensitivity of rail wear to axle load. The effect of change in number of axles is included when plotting against tonnage.

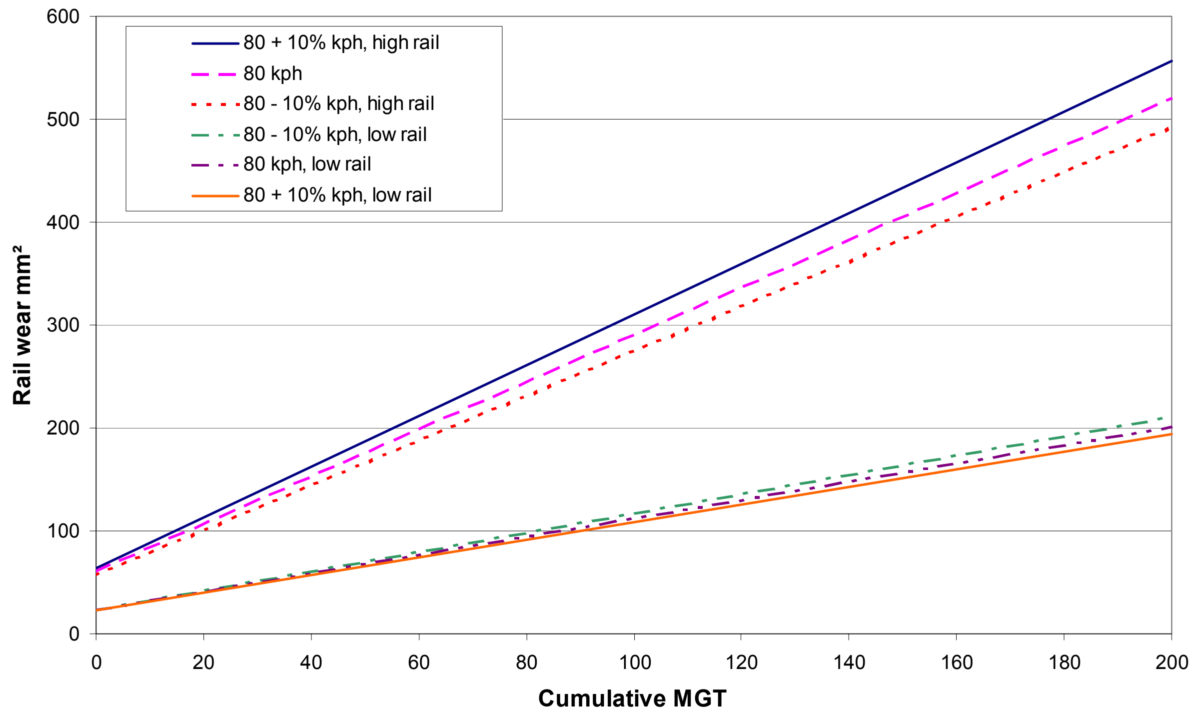

Figure 5.5: Sensitivity of rail wear to train speed in curves.

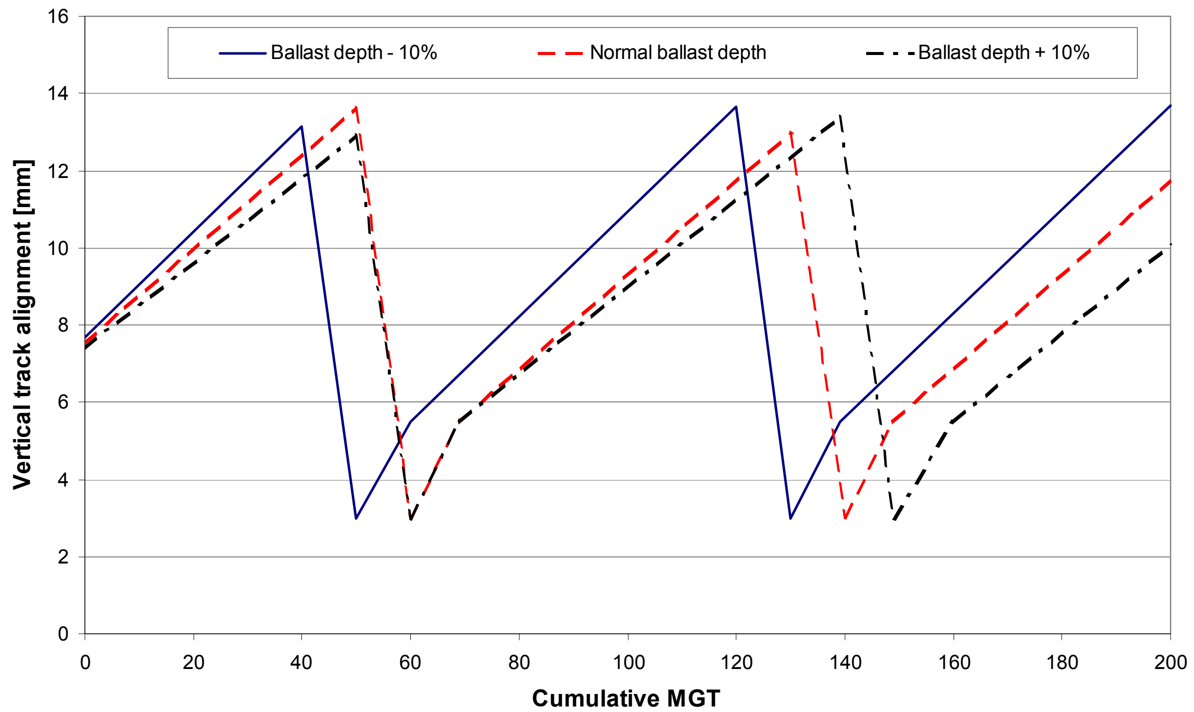

Figure 5.6: Sensitivity of vertical track alignment to ballast depth

5.2 TMPM – Track Maintenance Planning Model

Based on the track degradation model ITDM described in section 3.1, Simson et al [22] have developed a Track Maintenance Planning Model (TMPM). It is aimed to deal with track maintenance planning in the medium to long term. According to the authors, TMPM outputs the net present value of the financial benefits of undertaking a given maintenance strategy compared with a base-case maintenance scenario. A schematic model presentation is given as in Figure 5.7

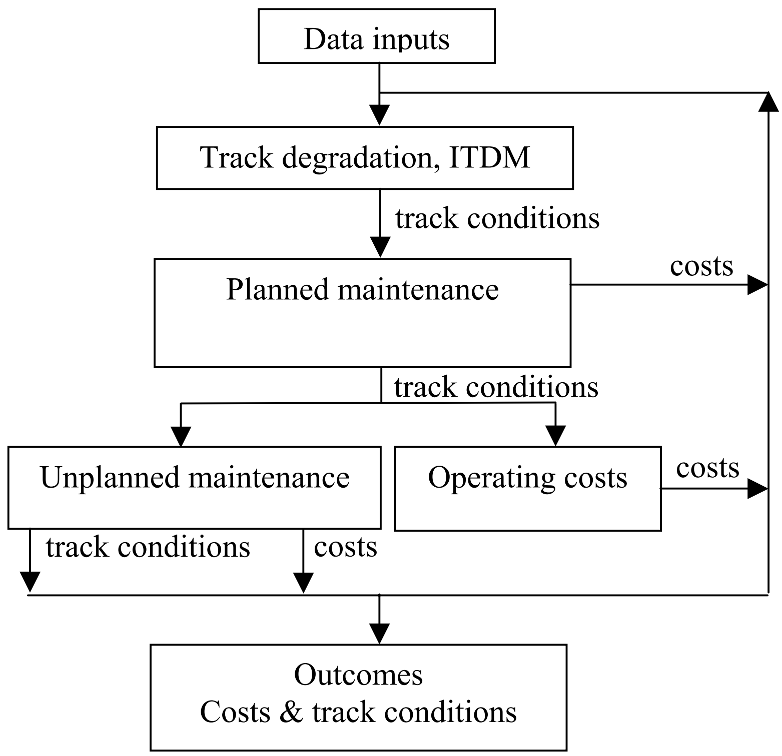

Figure 5.7: The TMPM model

Output from ITDM is mainly calculations on vertical track alignment, rail wear (including grinding) and sleeper degradation. The planned and unplanned maintenance models of TMPM determine the timing of maintenance interventions. They replace the default assumptions used in ITDM. In TMPM the train operating costs are calculated related to delay caused by varying speed restrictions on each segment along the line. The model also capable of handling costs of unplanned maintenance due to defective sleepers and planned maintenance such as tamping, resleepering and rerailing. According to the article, the model can provide the user with an insight into various possible scenarios. In particular the track engineer can assess the potential benefits of reduced operating costs from upgrading track infrastructure or the impact of changed traffic. This feature is told to be an advantage over the present world-leading track maintenance planning models.

5.3 TRACS – Total Right-Of-Way Analysis and Costing System

TRACS is a short of Total Right of Way Analysis and Costing System described in references [18] and [19]. It is a system (software) developed by AAR and Massachusetts Institute of Technology, MIT, in U.S. The model consists of several modules with a basic structure illustrated in Figure 5.8. It is a computer-based tool developed to assist rail management in addressing change in the area of infrastructure. By combining engineering–based deterioration models with life-cycle costing techniques the model estimates track maintenance and renewal costs as a function of route geometry, track components, track condition as well as traffic mix and volume. TRACS has been used by North American railroads for technology assessment, costing in support of pricing, budgeting, line consolidation and other studies. The deterioration models for track components within TRACS are based on both the specific investigations of components under controlled condition at the Transportation Test Center TTC in Colorado, and the labs at AAR Chicago Technical Center, as well as the service experiences of many of the AAR's member roads.

5.3.1 TRACS Model Description

As shown in Figure 5.8, TRACS has four components:

- Knowledge base: A definition of track components, information concerning component deterioration and policy parameters.
- Input files: Files, which contain traffic, route/track, and costs. These files are the key elements that define the scenario being modelled.
- Deterioration modules: Engineering-based deterioration models for rail, ties, ballast, turnouts and routine maintenance.
- Report module: Numerous reports show the required maintenance activities, component lives and renewal cycles and the economic/financial implications.

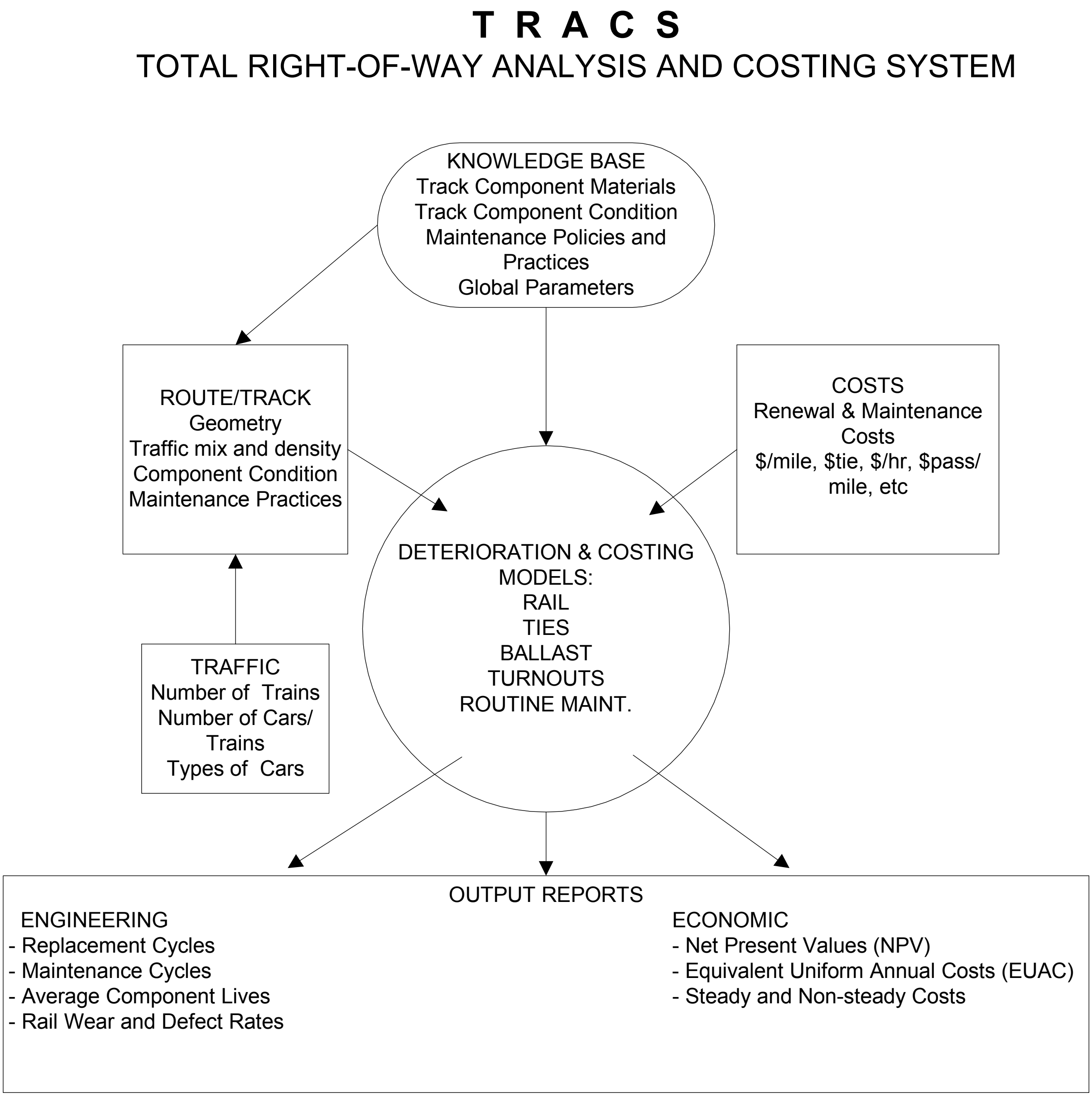

Figure 5.8: An overview of TRACS

TRACS is developed to combine engineering models with life-cycle costing techniques to provide a tool for people at various levels of the hierarchy and to address a wide range of problems relating to infrastructure management. For a typical run, the user defines the route and the traffic, while the knowledge base supplies defaults for the physical, financial and policy parameters.

The software includes an analysis function which handles models of track degradation regarding rail wear and rail fatigue and also ties. This is performed on a component level where each component is given attributes such as initial condition, material properties and component life. If a component reaches its life limit or reach a point where maintenance is a must, then that cost is automatically added in the simulation. It is also possible to define annual maintenance activities and costs that are added to the analysis. The analysis seems to be performed in an iterative way, e.g. day-to-day stepping. Maintenance activities and their corresponding costs are then accumulated by this formula:

(18) $M_{it}=\Sigma(M_{its}*L_s)$

where

M= Amount of maintenance
i= Index related to the type of maintenance
t= Index of year
s= Index of segment
L= Length of the segment

The model is used for several purposes such as:

- Technical assessment, e.g. what would be the effect of heavy axle loads on track costs?
- Situation specific costing, e.g. evaluation of the effects when changing number of trains on a route.
- Budgeting, e.g. how many meters of rail will have to be replaces over the next 10 years
- Rationalization analysis, e.g. an analysis of changes in costs when traffic is rerouted.

5.3.2 TRACS - Demonstration of Output

In reference [19] there are several examples of output from the model. Most diagrams show something called the Equivalent Uniform Annual Cost, EUAC, per mile over the route. Figure 5.9 - Figure 5.11 are diagrams from [19] rescaled to SI-units. Amongst, noticeable are Figure 5.9 that shows how sensitive rail costs are to curvature and Figure 5.10 that shows the dependence of lubrication and steel quality on rail costs. According to the later diagram, the costs increase about +50% when lubrication goes from good to poor. This is much less than the earlier AAR results have shown concerning wear rates. In reference [14] the reduction in rail wear can be more than 14 times when lubrication goes from μ=0,4 (bad) to 0,15(good). A possible explanation, although not given in the article text, might be inclusion of rail costs due to fatigue and grinding in the diagram. Lowering the wear rate with efficient lubrication leads at some stage to fatigue becoming the cost-consuming problem. Benefits from lubrication can then not be fully disseminated. The third diagram, Figure 5.11, shows that axle load make a relatively higher impact on maintenance costs on tangent track than in curves.

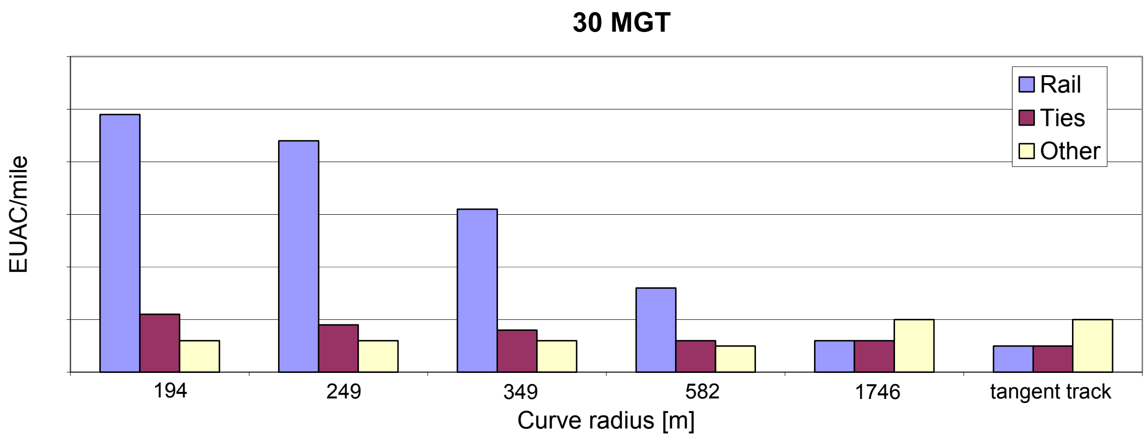

Figure 5.9: Costs of rail, ties and other components related to curvature

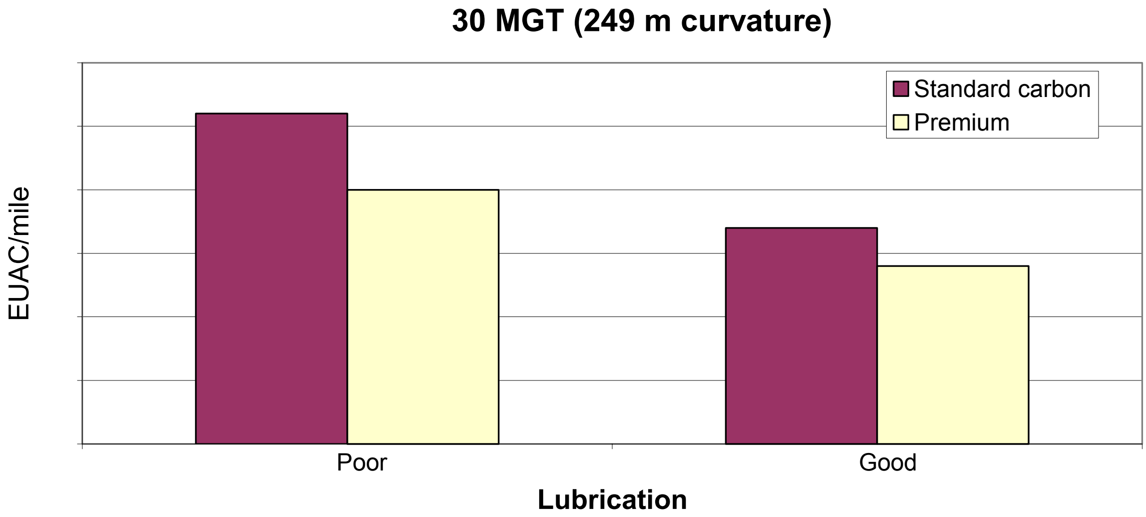

Figure 5.10: Effects on cost of rail due to lubrication and rail metallurgy in a 250 m radius curve.

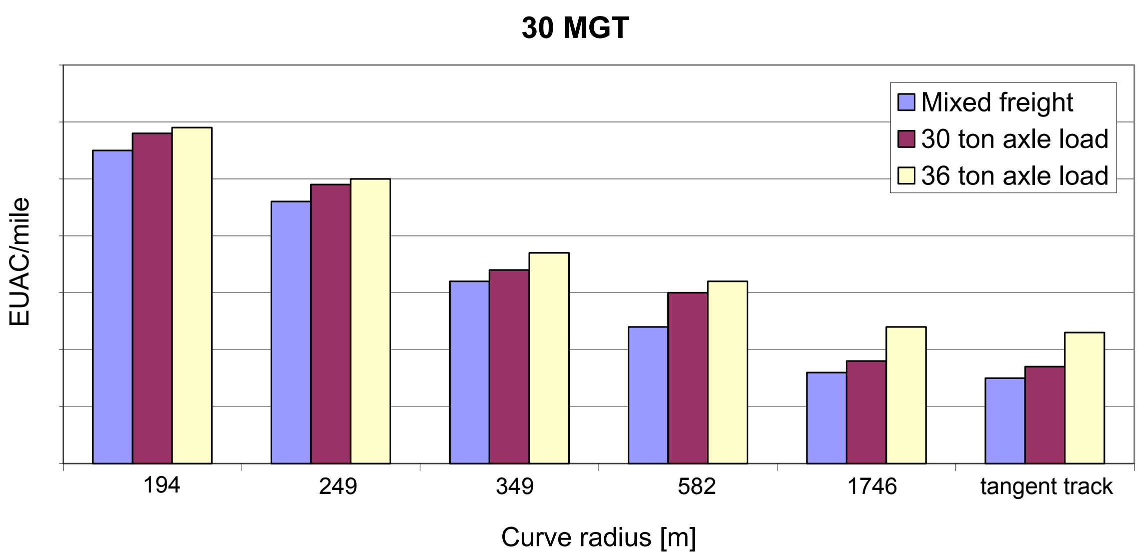

Figure 5.11: Total track maintenance costs for different traffic mixes

5.4 Damage Exponent Heavy Axle Load Analysis

In reference [26], A.M. Zarembski uses a method called The Damage Exponent Heavy Axle Load Analysis to investigate track maintenance costs on short lines when axle load is changed. The method is based on the following equation:

(19) Damage factor (per component)= $[P/P_0]^n$

where

P=	New axle load [ton]	
P_0=	Old axle load [ton]	
n=	Damage exponent with typical values:	
	Rail wear	1
	Rail fatigue (internal)	3
	Rail fatigue (surface)	1.8
	Rail joints	3.33
	Ties, timber	1.5
	Ballast, high quality	1
	Ballast, low quality	5.6
	Turnouts	3

Each component has it own exponent representing the ”damage per axle effect”. The exponent also includes costs due to necessary upgrades in any component to make it capable of handling increased axle loads.

The model is used for calculations in [26]. The results states that the total maintenance costs will increase by 17-23% on studied lines when all traffic is increased from 30 to 33 ton axle load. It is also found that 40% of the maintenance cost on rail is associated with rail joints.

The model does not include any costs that are independent of traffic, such as track inspection costs, weed spray, snow removal, signal maintenance, etc.

5.5 DeCoTrack Compared to the Other Models

Although several models claim to predict the degradation of different track, it is rather difficult to make comparative calculations. This is mainly due to the fact that formulas and assumptions are not fully presented in the articles. As a work-around, the content in presented diagrams and tables have been used to give values that can be compared with corresponding output from DeCoTrack.

5.5.1 DeCoTrack versus ITDM and TMPM

From the information given in articles [20]-[21] it is possible to compare model outputs regarding rail wear. The DeCoTrack model assumes rail wear to be proportional to the friction energy losses between wheel and rail and so seems ITDM. Thereby, wear is proportional to axle load and dependent on vehicle performance. ITDM expresses this relationship in terms of angle of attack of wheels to rail while DeCoTrack uses a vehicle wear constant. The diagram in Figure 5.5 shows rail wear rates as a function of train speed and by running the DeCoTrack with same train speeds a diagram, Figure 5.12, can be drawn. Both models show close to the same strong influence from speed on wear.

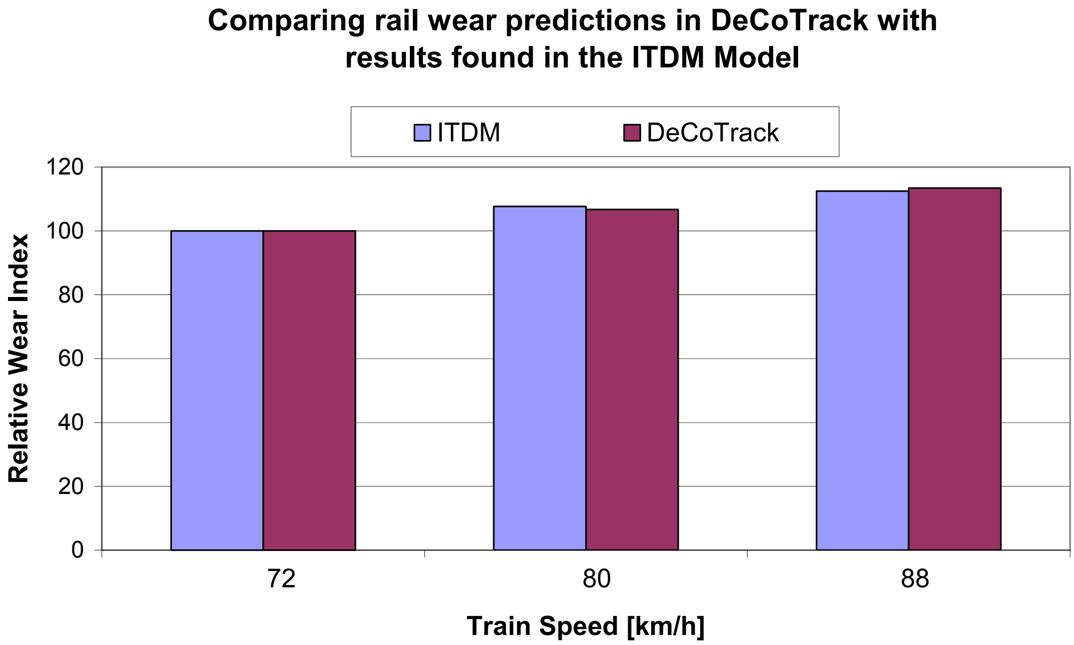

Figure 5.12: Rail wear as a function of speed. DeCoTrack compared to ITDM

Prediction of rail fatigue is only handled by DeCoTrack while ITDM on the other hand has a more detailed modelling of sleepers, ballast and track settlement prediction. Even the decay of timbers sleepers is included in the ITDM model. Unfortunately, the studied articles do not present enough information to make any benchmark on the ballast and track settlement predictions from each model.

Summarizing the comparisons of the models, they seem to be very close in output and both models exclude influence of grinding. As differences, ITDM does not handle rail fatigue problems at all but it uses angle-of-attack data as a smart way to classify vehicles and it seems to have a sophisticated sleeper and track settlement model

Predictions of costs are more difficult to compare. The TMPM model involves costs of train delay due to speed reduction and maintenance activities in field, which DeCo-Track does not. In the article [22] not output is presented that can be compared to that of DeCoTrack.

5.5.2 DeCoTrack versus TRACS

Among the models found in the literature survey, TRACS, is the most extensive one. With TRACS it is possible to simulate costs for track components such as rail, ties, ballast, turnouts. The simulation seems to be performed with incremental steps making it possible to auto schedule different maintenance activities including preventive maintenance. The cost of maintenance can be described as detailed as labour gang sizes, hourly wage rates, working hours a day and productivity of each gang. Neither costs for turnouts nor effects from preventive maintenance such as grinding are included in DeCoTrack but on the other hand the non-complexity for the user is in favour. Trying to compare the software outputs, a DeCoTrack test simulation was made on the same data used for the TRACS diagram presented in Figure 5.11. With an axle load of 30 tons, ordinary 4-wheel bogie cars, medium vertical track alignment and lubrication (μ=0,3) the result is given in Figure 5.13. The figure also shows a comparative plot from TRACS, which is an immediate copy of the 30-ton axle load plot in Figure 5.11. There is a good correlation between the models even if TRACS shows somewhat lower costs in curves. This is probably due to better lubrication in their simulation or due to positive net effects of grinding.

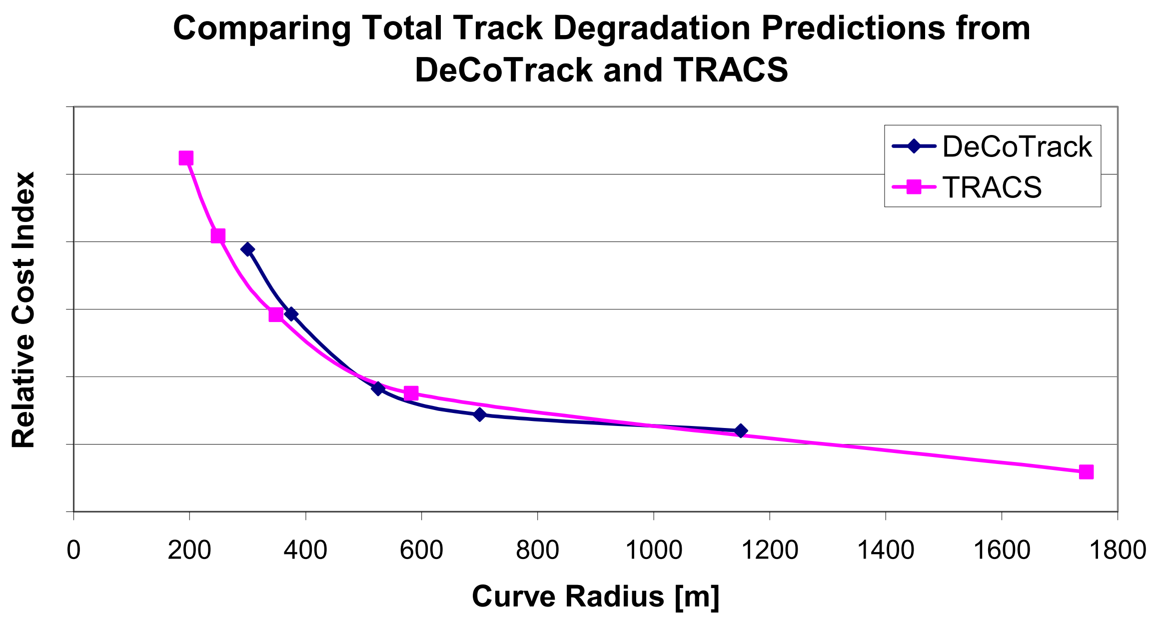

Figure 5.13: Total track degradation costs from DeCoTrack and TRACS as a function of curvature.

5.5.3 DeCoTrack versus Damage Exponent Heavy Axle Load Analysis

The very similar approach between DeCoTrack and the Damage Exponent Heavy Axle Load Analysis makes them easy to compare. Describing the DeCoTrack model in terms of the power law, formula (19), a comparative table can be presented, Figure 5.14.

Degradation parameter	Damage exponent n	
	By A.M. Zarembski	DeCoTrack
Rail wear	1	1
Rail fatigue (internal)	3	3
Rail fatigue (surface)	1.8	3 (no grinding!)
Rail joints	3.33	Missing
Ties, timber	1.5	1 (concrete!)
Ballast, high quality	1	1
Ballast, low quality	5.6	Missing
Turnouts	3	Missing

Figure 5.14: Damage exponents used by A.M. Zarembski and by DeCoTrack

As the presented formula represent a ”damage per axle effect” it will mean that an exponent=1 makes degradation proportional to gross tonnage. Assuming no change in annual gross tonnage, the reduced number of wheels will compensate the effects of increased axle load. Taking tare into account will probably make some benefits to the higher axle load, as the tare/cargo weight ratio will in most cases be reduced.

When it comes to differences between the models, the predicted rail surface fatigue is not of the same order. DeCoTrack with an exponent of 3 expects much more surface fatigue than the Zarembski model with an exponent of 1.8. Such a difference can be motivated because the current DeCoTrack model does not handle positive effects of preventive grinding while Zarembski’s model most probably does. An increased axle load by 20% will in the Zarembski case lead to +39% increase in surface fatigue while DeCoTrack estimates 73%. It is commonly known that an effective preventive grinding program might extend the rail life with 100% thereby making sense of both the above statements.

Another difference is the estimation of tie degradation. The Zarembski model suggests an exponent of 1.5 for timber ties while DeCoTrack has an exponent=1, having its focus on concrete.

On some points the Zarembski model is more extensive. It has exponents for rail joints, low quality ballast and turnouts. DeCoTrack does not handle any of these components.

On other points DeCoTrack is more ambitious. The effects of track geometry, lubrication, vehicle type and vehicle speed are all terms in DeCoTrack but not included in the model presented by Zarembski.

Summing up the comparative performance, DeCoTrack and the Damage Exponent Heavy Axle Load Analysis act very similar in the simulation of effects that both models predict. When discussing jointed rail, timber ties and turnouts the Damage Exponent Heavy Axle Load Analysis is more extensive and could therefore be helpful to study in future development of DeCoTrack.

5.6 Conclusions from the Comparisons Made

Based on the studied articles the DeCoTrack model is found to produce results close to the results found in other models although the approach differs. The detail level is not as thorough as, for example, in the models ITDM (origin Australia) and TRACS (origin U.S.). DeCoTrack does not use incremental time stepping as the other two models do but it is on the contrary easier to implement. Noticeable is that none of the articles studied gives a full description of how the presented models work and that makes it quite difficult to fully compare them with DeCoTrack.

As far as the found articles describe, none of the other models seems to include other vehicle parameters than the axle load. On that point, DeCoTrack is more comprehensive and it is very likely that wheel and boogie design and also the maintenance conditions of the vehicles plays a crucial role in the degradation of the track.

Searching for more external research knowledge on freight traffic leads undoubtedly to U.S. and the AAR/TTC test centre in Colorado. All of the three models ITDM, TRACS and the Damage Exponent Heavy Axle Load Analysis refer in some way to data from that centre. Also Australian, Canadian and South African railroad research teams seem to have established a good knowledge on such matters. Talking about fast speed or high speed passenger traffic and related maintenance issues, the major sources of knowledge can be found in Germany. France and Japan.

6 DOMESTIC DATA FROM CHANGED TRAFFIC CONDITIONS

During one year, 1997, Banverket (the Swedish National Rail Administration) did perform extensive field test with increased axle load on the line Hofors-Hällefors. The line is 168 km long and the traffic mainly consists of unit trains from Ovako Steel. The line is divided into five segments nr 322-326 with 6-9 MGT traffic on four of them and only 1.5 MGT on the last segment 326 between Ställdalen-Hällefors. The track standard was mainly jointed 50 kg rails on wood sleepers with Hey-Back fastenings or concrete sleepers with Pandrol or Hambo fastenings. On the last, low traffic segment, the track standard was only 43 kg jointed rails on wood sleepers with spike fastenings.

Before the test period, an axle load of 22.5 tons and a distributed load of 6.4 tons/metre were permitted with a speed limit of 90 km/h. During the tests, these values was increased to 25 tons and 7.2 tons/metre but with a reduced speed limit to 70 km/h on the first four segments of the line (Hofors-Ställdalen) and even 40 km/h on the last segment 326 (Ställdalen-Hällefors). No upgradation was done to the track but the higher axle load was introduced on a new type of car with a bogie of type Y25 that have better steering performance compared to the old car.

6.1 Domestic Sources

Several data files and reports have been written on the measurements done. This study is based on the following files and contents:

BANABS.XLS – Presents absolute position of track for track segments nr 322-326, during the test period week 41, 1996 to week 49, 1999.

HASTRAPP.WPD - The report handles a series of measurements during weeks 24-25, 1997 on the track between Ställdalen and Hällefors where some tests were performed, the speed was increased from 40 km/h to 60 km/h and the axle load was 25 tonnes. There is nothing in the report that indicates that the status of the track has changed after or during the increase of speed. However, the short test period makes it hard to valuate the results.

OFP.XLS - Non-destructive crack detection on rail on the line Hofors - Ställdalen, segments 322, 323 and 325.
Number of errors: 1996:17, 1997:12, 1998:9.The errors have decreased since the tests started.

RAPPMALL.WPD - Handles a series of measurements during one year on track segments 322-326. Contract works have been performed during the period and slighter changes of the measurement data may derive to these works. Besides that, there are no signs of an increased deterioration of the track as a result of the increased axle load.

RÄLSSLIT.XLS - Wear of rail measurements for track segments 322-326, during the period 96/11/25-99/12/01.
There is a slight increase of the vertical wear and an even slighter increase of the lateral wear for the upper rail, however there are almost no changes at all for the rolling on the right-hand/left-hand side for lower rail or the total width after three years. Track 326 section 128+815 indicates a high vertical wear and a high lateral wear.

RÄLSVAND.XLS - Creep of the rails Ställdalen-Hällefors.
Some tracks have remarkable values when it comes to the creep of the rails but these values can be derived to other factors than the increased axle load. Normal values in general.

RÖK.XLS - Subsidence in the superstructure for track segments 324-326.

SAMMANSTÄLLNING –97.XLS, -98.XLS and –99.XLS. Summary of the 25-ton axle load traffic, number of wagons and distributed percentage of axle load. The highest percentage share of traffic each year is the 24,5-25 tonnes axle load traffic. 1997: 31% 1998: 45% 1999: 37%.

SKARV.XLS - Rail bond deformation Ställdalen – Hällefors

SLIPER.XLS - Sleeper deterioration for track segments 322, 323 and 326.

SPÅRLÄGE.WPD - Measurement area A114-134 [326,114+120]. Changes in skewing noted. Height, height of arch and track gauge unchanged. The existing skewing is natural and derives to the season.

SPÅRVID2.XLS - Track gauge measurements for Ställdalen - Hällefors. Track gauge at some sections has increased up to 7mm, which is max.

UTBÖJ.XLS - Curving of the rail. Vehicles with 25 tonnes axle load running at 40 km/h and 60 km/h renders similar curving of the rail as rail with 5, 21 or 22,5 tonnes axle load at 90 km/h.

JANUARI.WPD, FEBRUARI.WPD, MARS.WPD, APRIL.WPD, MAJ.WPD, AUG.WPD, SEPT.WPD, OKT.WPD, NOV.WPD, DEC.WPD, JAN98.WPD, JULI.98.WPD – Monthly reports. No tendencies of an increased wear are indicated by the performed measurements. Everything is stable. Performed measurements and analyses indicates that the increased axle load has not lead to an increased wear or any other negative effect on the track derived to the increased axle load. Track bed measurement, manual track gauge measurement, absolute position of track, subsidence of the track, rail wear measurement, creep of the rails, rail bond deformation, sleeper wear, non destructive testing, specific track inspection, specific bridge inspection, geological measurements – all these indicate normal values for deterioration etc. A few deviant values are noted but they cannot alone be connected to the increased axle load, but rather to other factors. The visual examinations did not indicate on an increased amount of remarks due to the increased axle load. If you study the measurements performed individually, you can't see any systematic changes. One example is track bed measurements with dynamometer car EM-80E, where the diagrams often indicate track bed errors at different places compared to the different measuring periods. In other words, there is no way of isolating each error to each test. The errors are derived to other reasons most of the times. If you look upon some of the other measurements performed, there is no systematic or constant change that can be derived to the 25-ton axle load traffic with certainty. What, more or less, has changed is the movement in the embankment at the testing location Skäret. Where you in the beginning of May could see a slight acceleration of horizontal movements and pore pressure, however this can probably be derived to thawing of the ground and rich precipitation.

ÅRSRAPPORT STAX25BRMHOFORSHÄLLEFORS.DOC – An annual summary for 1997 of all measurements done and conclusions made. The increased axle load has not affected the track gauge. Average axle load during the test period was 23.9 tonnes. Small deviations of the reference value for the absolute position of the track are indicated, similar results for subsidence of the track. Rail wear measurements are not alarming. The creep of the rails is not alarming either. The rail bond deformation is normal. Non-existent sleeper wear compared to reference.
The non-destructive testing indicates that errors rather have decreased than increased compared to reference. As for geological measurements, the increased axle load has not contributed to an incontrollable movement in the embankment and its surroundings.
Rail wear, creep of the rails, track gauge, sleeper wear and rail bond deformation indicates extremely small deviations which can be derived to the short period of time in which the measurements were performed.

6.2 Overview of the Extracted Data

With the reports as a starting point, a table was made with questions necessary to get a comprehensive picture of the track status and the effect of the increased axle load. The table is shown in Figure 6.1

	HAS THE DETERIORATION SPEED CHANGED?			
	Yes	?(*)	No	**Additional comments**
Track bed measurement			**X**	Normal values.
Manual gauge measurement			**X**	2-3 mm deviation from reference measurements.
Absolute position of the track			**X**	3-4 mm deviation from reference measurements.
Subsidence in the superstructure			**X**	4-5 mm deviation from reference measurements.
Rail wear measurements			**X**	0,5 mm side wear and 0,2 mm height wear in average compared to reference measurements.
Creep of the rails			**X**	6-8 mm creep of the rails at most measurement points.
Rail bond deformation			**X**	Max deviation is 0,6 mm.
Sleeper wear			**X**	Curves. Normal values.
Non-destructive testing			**X**	Errors actually have decreased
Specific track inspection			**X**	Normal.
Specific bridge inspection			**X**	Normal.
Geological measurements			**X**	No uncontrolled movement in embankment and its surroundings.
Speed dependence			**X**	The short period of time for the tests makes it impossible to trust the results
Axle load			**X**	All tests indicate that the increased axle load does not affect the track status negatively.
Effect at different curvatures		**X**		No existing data on effects of different curvatures.
Lubrication		**X**		No data on effects by lubrication.
Vehicle		**X**		No data on effects by different type of vehicles.

(1) Can't be further commented without additional examinations.

Figure 6.1: Table with results from the tests and measurements made on the line Hofors-Hällefors

From the table it is obvious that no significant increase in degradation rates has been found when the axle load was increased.

6.3 Conclusion of Measurements on the Line Hofors-Hällefors

There is no indication in the reports that shows an increased deterioration derived to the increased axle load. At some sections there are indications of changes of the track status above normal. These changes can however be derived to other factors than the increased axle load. The favourable climate during the test period, the reduced speed limit and the new car bogie might fully compensate the negative effects on track of an increased axle load. The very small changes found and the large amount of uncertainty made me realise that this example can not be used for a relevant test of DeCoTrack. As we don´t yet have any other lines in Sweden with maintenance data both before and after a change in axle load, we can not test the model on real domestic data.

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7 CONCLUSIONS

A research work with a formulated research question is expected to answer the question. Therefore these conclusions reflect the questions given in chapter 2.1 and the goals given in chapter 2.2.

QUESTION1: *Can existing research results and experiences worldwide be used to predict changes in track degradation costs due to changes in traffic?*
ANSWER1: Yes. By using a large mix of research results and combine it with empirical data and mechanical engineering model I have found it possible. The output from the model is tuned by using real data for parameter adjustment and scaling

QUESTION 2: *Are the international research results representative for and usable in Swedish conditions ?*
ANSWER 2: Mainly yes. We have in Sweden a tuff climate and a lot of mixed traffic (passenger and freight trains on the same line) but a lot of the base technology is quite identical and so many of the typical problems are similar to those found in other countries. All phenomena are of cause not described which is further developed in the text below.

QUESTION 3: *Are there any shortcomings in today's knowledge of predicting track maintenance?*
ANSWER 3: Based on the studied articles and the content of visited conferences, there seems to be some parameters still not investigated. The vehicle condition and steering performance has not yet been described in relation to the track degradation. In DeCo-Track there is a hypothesis of how it can be done but that part is still unverified due to lack of relevant data. Other relevant things are the parts explicitly excluded from this research. Especially the effect of changed maintenance tasks such as grinding is not yet put into any model where its relation to lubrication, rail wear and rail fatigue can be simulated.

The Swedish rail network and the Swedish traffic mix of both freight and passenger traffic on same routes contribute to questions not answered by the foreign articles studied herein. The deregulated traffic with different kind of vehicles and operators impose a need for effective ways to evaluate and classify vehicle performance and its effect on the track degradation. By having such tools it should be possible to differentiate the freight rates and to stimulate future development of the rolling stock as well as to uphold its condition while in service.

Based on the studied articles the DeCoTrack model is found to produce results close to them found in other models although the approach differs. The detail level is not as thorough as, for example, in the models ITDM (origin Australia) and TRACS (origin U.S.). DeCoTrack does not use incremental time stepping as the other two models do, but it is on the contrary easier to implement. DeCoTrack also has a unique strength in

its handling of vehicle parameters with two classifiers representing wear and fatigue impact on the rail. Noticeable is that none of the articles studied gives a full description of how the presented models work and that makes it quite difficult to fully compare them to DeCoTrack.
Regarding the goals in chapter 2.2, all of them have been fulfilled. A model has been developed and verified by comparing it to other related models. The model has also been implemented into a software where effects of changes in traffic is very easy to simulate

The search for more external research knowledge on freight traffic leads undoubtedly to U.S. and the AAR/TTC test centre in Colorado. All of the three models ITDM, TRACS and the Damage Exponent Heavy Axle Load Analysis refer in some way to data from that centre. Also Australian, Canadian and South African railroad research teams seem to have established a good knowledge on such matters. Talking about fast speed or high speed passenger traffic and related maintenance issues, the major sources of knowledge can be found in Germany. France and Japan.

Future research is suggested to concentrate on vehicle classification. The domestic situation in Sweden with deregulation in traffic and mixed traffic on same routes highly prioritise such a decision. From an international point of view that effort might bring a useful complement the other models, which seem to be focused on the calculations on uniform freight traffic.

8 AREAS FOR FUTURE RESEARCH

Both the ITDM and the TRACS model are based on an incremental approach where single events such as rail grinding, relining and track renewal can be included. Such a method therefore has advantages in its ability to enhance the detail level in the simulation but on the other hand it is much more complex to initiate and small errors in input can grow rapidly in the iterative sampling process.

In spite of the differences in approach there are several valuable thoughts in the other models that might be added into DeCoTrack. In the following sections such areas of possible DeCoTrack improvement are presented.

8.1 Effects of the Track Standard

From the performed literature survey it is obvious that the rail degradation model can be further refined based on other researches. With a more detailed description of the track and a more extensive degradation model it is possible to add parameters such as rail hardness and maybe also to include the track stiffness and its influence on the rail degradation and vertical track alignment. The ITDM model described in reference [20] and [21] might bring ideas on how it can be done.

8.2 Effects of Maintenance Activities

Preventive maintenance plays a crucial role in the long time costs of track management. Especially rail grinding is a factor that should be added to the DeCoTrack model. None of the studied models are explicitly described to handle the effects of rail grinding but at least the TRACS model can be supposed to do so. Most probably it is included in the routine maintenance activities. Another term of interest is the dependence of tamping and relining where the ITDM model [20] contributes with some knowledge.

8.3 Effects of Component Selections

Timber ties and concrete ties are expected to behave quite different on the long run both in technical and economic terms. There seems to be studies done on degradation of ties and some of that knowledge could be added to DeCoTrack as in the ITDM model. Other components to add are the rail joints and turnouts, which are included in The Damage Exponent Heavy Axle Load Analysis described by A.M. Zarembski [26].

Turnouts are expensive to maintain and should therefore with favour be added to DeCoTrack.

8.4 Vehicle Monitoring and Classification

The vehicle behaviour on track is normally measured when the vehicle is to be type approved. The major interest is then to keep the rolling stock within safety limits. If one takes one step further and evaluates the vehicle track behaviour from a maintenance point of view it adds new demands. More research is then needed. The main issue is to find a fast, simple and reliable method to quantify vehicle behaviour by using wayside mounted monitoring equipment. That information can be used as input to an extended degradation model also including axle load, train speed, bogie design, wheel profile and wheel+bogie condition.

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Appendix A - Important Milestones in English and American Railway Development

Source: An Internet web-page by Pacific Southwest Railway Museum, www.sdrm.org

1630: Beaumont designs and builds wagon roads for English coal mines using heavy planks on which horses pulled carts and wagons.
1753: First steam engine arrives in the colonies from England.
1755: First steam engine in America is installed to pump water from a mine.
1758: An Act of Parliament establishes the Middleton Railway in Leeds. Thus the Middleton claims to be the oldest Railway in the world.
1769: Frenchman Nicholas Cugnot builds a steam carriage.
1774: Scotsman James Watt builds first "modern" stationary steam engine.
1776: English tram road is laid down with cast iron angle bars on timber ties.
1784: Murdoch (Watt associate) steam engine model runs 6 to 8 mph.
1789: Englishman William Jessup designs first wagons with flanged wheels.
1800: Oliver Evans, an American, creates the earliest successful non-condensing high pressure stationary steam-engine.
1804: Oliver Evans builds his first steam-powered boat, weight: 4,000 lbs.
1804: Matthew Murray of Leeds, England invents a steam locomotive which runs on timber rails. This is probably the **FIRST RAILROAD ENGINE**. Seen by Richard Trevithick before he builds his loco.
1804: Richard Trevithick of Cornwall builds 40 psi steam locomotive for the Welsh Penydarran Railroad.
1807: The very first passenger train ran from Swansea to Mumbles on March 25th.
1808: Trevithick builds a circular railway in London's Torrington Square. Steam carriage *Catch Me Who Can* weighes 10 tons and makes 15 mph.
1812: The first commercially successful steam locomotives, using the Blenkinsop rack and pinion drive, commenced operation on the Middleton Railway. This was the world's first regular revenue-earning use of steam traction, as distinct from experimental operation.
1812: American Colonel John Stevens publishes a pamphlet containing: *"Documents tending to prove the superior advantages of Railways and Steam Carriages over Canal Navigation."* He also states, *"I can see nothing to hinder a steam carriage moving on its ways with a velocity of 100 miles an hour."*
1813: Englishman William Hedley builds and patents 50 psi railroad loco which could haul 10 coal wagons at 5 mph, equal to 10 horses.
1814: Englishman George Stephenson builds *Blucher*, his first railway engine. Pulls 30 tons at 4 mph, but is not efficient.
1815: Stephenson's second engine: 6 wheels and a multitubular boiler.
1821: Englishman Julius Griffiths patents a passenger road locomotive.
1824: Construction begins on the 1st locomotive workshop in New Castle, England.
1824: Englishman David Gordon patents a steam-driven machine with legs which

imitates the action of a horse's legs and feet. Not successful.

1825: Stephenson's 8-ton *LOCOMOTION No. 1* built for the Stockton & Darlington Railroad. Capable of pulling 90 tons of coal at 15 mph. Stephenson plans all details of the line, and even designs the bridges, machinery, engines, turntables, switches, and crossings, and is responsible for every part of the work of their construction. (The passenger coaches of this time were all drawn by horses.)

1825: Colonel John Stevens builds a *steam waggon* which he placed on a circular railway before his housenow Hudson Terraceat Hoboken, New Jersey.

1826: The first line of rails in the New England States is said to have been laid down at Quincy, Mass., 3 miles in length and pulled by horses.

1827: The **Baltimore and Ohio Railroad** is chartered to run from Baltimore to the Ohio River in Virginia. It was the first westward bound railroad in America. Wind power (sail on carriage) was tried, followed by horse power, with the horse walking on a treadmill which drove the carriage wheels!

1828: Delaware & Hudson Canal Co. builds a railroad from their mines to the termination of the canal at Honesdale. Also pulled by horses.

1829: The first steam locomotive used in America, the English-built *Stourbridge Lion*, is put to work on the Delaware & Hudson. It is too heavy for the track (twice as heavy as had been promised by the builders), and is laid up next to the tracks as a stationary boiler.

1829: Peter Cooper of New York in 6 weeks time builds the *Tom Thumb*, a vertical boiler 1.4 HP locomotive, for the Baltimore & Ohio Railroad. It hauled 36 passengers at 18 mph in August 1830. It had a revolving fan for draught, used gun barrels for boiler tubes, and weighed less than one ton.

1829: James Wright of Columbia, PA. invents the cone "tread" of the wheel, which prevents wear of flanges and reduces resistance.

1829: Stephenson's *Rocket* wins a competition for locomotive power at the Rainhill Trials on the Manchester & Liverpool Railway. Capable of 30 mph with 30 passengers.

1830: The *Best Friend* is built at the West Point Foundery at New York for the Charlston & Hamburg Railroad. It was the **first completely American-built steam engine to go into scheduled passenger service**. It did excellent work until 1831 when the boiler exploded due to a reckless fireman, unexpectedly ending its, and his career.

1831: The 3.5 ton *De Witt Clinton* hauls 5 stage coach bodies on railroad wheels at 25 mph on the Mohawk & Hudson Railroad between Albany and Schenectady. This engine was lightly built, and was retired less than two years after going into service.

1831: The *South Carolina* was the first eight-wheeled engine.

1831: Robert Stevens, son of Colonel John Stevens, went to England and shipped back (unassembled) the *John Bull* for the Camden & Amboy Railroad in New Jersey. It was erected by mechanic Isaac Dripps, who had never seen a steam locomotive. There was no assembly manual. He made this the **first locomotive fitted with a bell, headlight and cowcatcher**, and it remained in service until

1866. Dripps went on to become superintendent of motive power for the Pennsylvania Railroad at Altoona.

1832: The *Brother Jonathon* was the first locomotive in the world to have a four-wheel leading truck. Designed by John B. Jervis for the Mohawk & Hudson Railroad.

1832: The *American* No. 1 was the first 4-4-0, the first of its class. It was capable of regular speeds of 60 mph with its 9.5" by 16" cylinders. Designed by John B. Jervis, Chief Engineer for the Mohawk & Hudson.

1832: The *Atlantic* on the B&O hauls 50 tons from Baltimore over a distance of 40 miles at 12 to 15 mph. This engine weighed 6.5 tons, carried 50 pounds of steam and burned a ton of anthracite coal on the round trip. The round trip cost $16, doing the work of 42 horses, which had cost $33 per trip. The engine cost $4,500, and was designed by Phineas Davis, assisted by Ross Winans. English locomotives burned bituminous coal.

1833: George Stephenson applies a small steam brake cylinder to operate brake shoes on driving wheels of locomotives.

1855: The first land grant railroad in the U. S. is completed. The Illinois Central arrives in Dunleith, Illinois (now East Dubuque).

1856: The first railroad bridge across the Mississippi River is completed between Rock Island, Illinois and Davenport, Iowa.

1860: Nehemiah Hodge, a Connecticut railway mechanic, patents a locomotive vacuum brake. Pressure is limited to atmospheric (14.7 psi), but practical considerations limit pressure to 7 to 8 psi. Thus, available braking power is low, especially above 3,000 feet altitude.

1862: President Abraham Lincoln signs the Pacific Railway Act, which authorizes the construction of the first transcontinental railroad. Theodore Judah had the vision to build a railroad across the Sierra Nevada mountains in California, and then to continue the railroad across the United States. **The Central Pacific Railroad** was financed by The Big Four: Collis Huntington, Leland Stanford, Charles Crocker and Mark Hopkins.

1868: Major Eli Janney, a confederate veteran of the civil war, invents the knuckle coupler. This semi-automatic device locks upon the cars closing together without the rail worker getting between the cars. This replaces the "link and pin" coupler, which was a major cause of injuries to railroad workers. A "cut" lever at the corner of the car releases the coupler knuckle making uncoupling safer.

1869: George Westinghouse, an inventive Civil War veteran, develops the straight air brake. A Pennsy 4-4-0 and a couple of passenger cars are fitted with the system and successfully demonstrated on April 13th.

1869: The **Central Pacific** and Union Pacific meet at Promontory Summit, Utah for the driving of the golden spike on May 10th.

1872: George Westinghouse patents the first automatic air brake. This is basically the same system as is used by today's railroads.

1876: All **Southern Pacific** and **Central Pacific** passenger cars converted to air brakes.

1883: The **Northern Pacific** is completed at Gold Creek, Montana.

1883: The Southern Pacific is completed.

1885: The Santa Fe is completed.

1893: The **Great Northern** is completed in the Cascade Mountains of Washington.

1893: Federal Railway Safety Appliances Act instituted mandatory requirements for automatic air brake systems and automatic couplers, and required standardization of the location and specifications for appliances such as handholds and grab irons necessary for employees' use. This applied only to interstate rail traffic.

1893: On May 10th locomotive #999 of the New York Central & Hudson River RR hauled four heavy Wagner cars of the *Empire State Express* down a 0.28% grade at record-braking speed. Although unverified, the conductor timed the speed at **112.5** mph over 1 mile, and at 102.8 mph over 5 miles. This 4-4-0 had 86" drivers for this run, and was later fitted with more normal 78" wheels as it now has on museum display.

1893: The **first mainline electrification** was in Baltimore, MD. A rigid overhead conductor supplied 675 VDC via one-sided tilted pantograph to the 96 ton 4-axle, 4-motor locomotives. These were very successful, hauling 1,800 ton trains up the 0.8% grade in the 1.25 mile Howard Street tunnel, where steam was not allowed to operate.

1900: Casey Jones rode the "Cannonball" into history on April 30th.

1903: New York state enacts legislation prohibiting the operation of steam locomotives on Manhattan Island in New York City south of the Harlem River after June 30, 1908. This spurred the electrification of New York City's trackage.

1907: Ground is broken on Sept. 7th by San Diego mayor John F. Forward dedicating the start of **John D. Spreckels'** San Diego & Arizona Railway.

1913: The **first commercially successful** internal combustion engine locomotive in the U.S. was built by General Electric for the **Dan Patch Line** in Minnesota. Locomotive #100 had two Model GM16 gasoline-electric 8" x 10" V8's rated at 175 HP @ 550 rpm each. It weighed 57 tons and rode on two four-wheel trucks (B-B).

1915: The Santa Fe Depot is dedicated in San Diego on March 7th.

1917: The **first Diesel-electric** locomotive in the U.S. was a prototype built by G.E. Number 4 had one model GM50 air injection two-stroke V8 rated at 225 HP @ 550 rpm powering one of two trucks. The cylinders had the same 8" x 10" dimensions as the GM16. It was never sold, serving only as a laboratory model at the Erie Works.

1918: The **first Diesel-electric** locomotive to be built **and sold** commercially was Jay Street Connecting RR #4. G.E. slightly revised its standard steeple cab straight electric locomotive car body and installed a single GM50. This unit was **not** successful, and after 6 months was returned to G.E. where it was used as a laboratory unit in developing improved control and propulsion systems.

1919: The golden spike is driven in the Carrizo Gorge, marking the completion of the

San Diego & Arizona Railway.

1923: **The Electro-Motive Engineering Corporation**, headed by H.L. Hamilton begins building gas-electric railcars in Cleveland, Ohio.

1923: **Ingersoll Rand** and G.E. combine to build 60-ton boxcab #8835. It used a model PR 6-cylinder in-line 10" x 12" solid injection engine rated 300HP @ 550 rpm. The excitation control system designed by Dr. Hermann Lemp was used, and was demonstrated on 13 different railroads over a 13 month period. Its performance in terms of reliability and economy of operation did much to advance the acceptance of the Diesel locomotive as a **replacement for the steam locomotive**. It was never sold.

1925: The **American Locomotive Company** (ALCO), along with G.E. and IR, builds its first Diesel electric loco. It was delivered under its own power to the Central Railroad of New Jersey and assigned as CNJ #1000. It was basically the same as #8835, with the same wheel arrangement and engine, but with many improvements. It operated as a switcher in the Bronx until 1957, and is now in the B&O museum in Baltimore, Md.

1926: Hamilton of **EMC** hires Richard Dilworth as chief engineer. Dilworth was a self-taught mechanical and electrical engineer who had helped put together G.E.'s early rail cars back in 1910.

1928: The **first Diesel-electric passenger locomotive built in North America** was a two-unit 2-D-1-1-D-2. It represented a joint effort between **Westinghouse, Canadian Locomotive Co., Baldwin and Commonwealth Steel Co**. It was numbered **Canadian National #9000**, and each unit had a Scottish-built Beardmore V12 12" x 12" engine rated 1,330HP @ 800 rpm. Max. safe speed was 63 mph.

1930: General Motors acquires the Winton Company on June 20th, and Electro-Motive on December 31st.

1934: The Union Pacific **M-10000** is dedicated in February. This Pullman-built 3-car all-aluminum articulated train was the **first streamliner in the US**. It was powered by a Winton V12 600 HP distillate engine, and was capable of 110 mph. It made a 12,625 mile coast-to-coast exhibition trip, and was seen by almost 1.2 million people at various stops. Went into service as the ***City of Salina*** on Jan. 31, 1935. The power car was designed by Richard Dilworth.

1934: The Burlington *Zephyr* is dedicated on April 18th. On May 26 this Budd-built 3-car articulated train of stainless steel made a record breaking dawn to dusk run from Denver to Chicago, 1016 miles, at an average speed of 77.6 mph and a top speed of 112.5 mph. It was the **first Diesel-electric streamliner in the US**, employing a Winton inline 8-cyl. 600 HP 201A two-stroke engine. The power car was designed by Richard Dilworth.

1934: Construction of the **first streamlined electric locomotives** begins. These were the Pennsy **GG-1**'s, which pulled high-speed passenger trains between NYC and Washington, DC. They developed 8,500 HP and cost $250,000. Production continued until 1943 and they were used into the early 1980's by AMTRAK.

1935: **EMC** builds #511 and #512, the **first self-contained Diesel passenger loco-**

motives in the US. The boxcar-like bodies housed two Winton V12 900 HP 201A engines, and were designed by Dick Dilworth and two draftsmen. The first unit sold went to the **B & O** as #50 to pull the *Royal Blue*. Retired in 1956, then saved at the National Museum of Transportation in St. Louis.

1970: Congress passes the Rail Passenger Service Act creating Amtrak, which today serves more than 20 million customers annually on its national network of intercity trains and employs 23,000 people.

Appendix B – Table Showing Functionality of Found Models

Comments to table:

x= Model include such dependence which is described in detail.

(x)= Model deals with such dependence but it is <u>not</u> described in detail.

Article	Dynamic forces	Rail fatigue	Rail wear	Ballast	Ties	Track roughness	Total cost	Other factors
An Integrated Model for Track Degradation Prediction Y. J. Zhang, M. Murray, L. Ferreira 8th WCTR Proceedings Published 1999			x	(x)	(x)	(x)		(x)
Compability and Constraints Between High-Speed Passenger Trains and Traditional Freight Trains Andres Lopez-Pita & Francesc Robusté Transportation Research Record 1742 Published 2001	x							
Rail Track Maintenance Planning Scott A Simson, Luis Ferreira & Martin H Murray Transportation Research Record 1713 Published 2000						x		
TRACS: A Tool for Managing Change Carl D Martland, Michael B Hargrove & Alvaro R Auzmendi Railway Track & Structures Published 1994		x	x		x		x	
Measurement and Prediction of Vehicle/Track Interaction Performance R D Fröhling, W Ebersöhn & H Scheffel Heavy Vehicles Systems, Int. J. of Vehicle Design, Vol. 6 Published 1999	x					x		
Eurobalt Optimises ballasted track Geoff A Hunt Railway Gazette International Published 2000						x		
Effects of Substructure on Track Performance Yu-Jiang Zhang, Dr Martin Murray & Dr Luis Ferreira International Conference on Traffic and Transportation Studies Published 1998						(x)		

Table continues on next page…

Table continued …

Comments to table:

x= Model include such dependence which is described in detail.

(x)= Model deals with such dependence but it is <u>not</u> described in detail.

Article	Dynamic forces	Rail fatigue	Rail wear	Ballast	Ties	Track roughnes s	Total cost	Other factors
TRACS: Tool for track infrastructure management Carl D. Martland och Michael B Hargrove Proceedings of the Infrastructure Planning and Management Published 1993		(x)	(x)	(x)	(x)		(x)	
Track Maintence Costs And Economies Of Density: An Analysis Of The Speed Factored Gross Tonnage Model Randplph R.Resor, Michale E. Smith Journal Of the Transportation Research Forum Published 1993							x	
Estimating Maintence-of-Way Costs for U.S. Railroads After Deregulation C. Gregory Bereskin Transportation Research Record Published 2000							(x)	
Irregular settlements of tha ballast on high speed lines Kira Holtzendorff, Berlin Journal for Railway and Transports Published 1999						x		
Modelling rail track performance, an integrated approach Y. J. Zhang, M. Murray, L. Ferreira Proceeedings of the Institution of Civil Engineers, London Published 2000			x	(x)	x	(x)		(x)
Sensitivity of Long-Term Infrastructure Condition To Initial Quality Rabi G. Mishalani and Ralph A. Olayé Journal of Infrastructure Systems Published 1999							(x)	

Table continues on next page…

Table continued …

Comments to table:

x= Model include such dependence which is described in detail.

(x)= Model deals with such dependence but it is not described in detail.

Article	Dynamic forces	Rail fatigue	Rail wear	Ballast	Ties	Track roughnes s	Total cost	Other factors
The Implications Of Heavy Axle Load Operations For Track Maintenance On Short Lines Allan.M.Zarembski, Zeta Tech Associates, Inc. American Railway Engineering & Maintenance of Way Association: Proceedings of the annual conference Published 2000		x	x	x	x		x	
Track Settlement Prediction Using Computer Simulation Tools Simon Iwnicki, Stuart Grassi, Walter Kik Vehicle System Dynamics Supplement 33 Published 1999	x					x		
Effects of track maintenance on the realibility of single track railroad line as a function of axle load Carl D. Martland, William E. Robert Proceedings of the American railway engineering association Published 1997							(x)	
An interactive track-train dynamic model for calculation of track error growth Lutz Mauer International Journal of Vehicle Mechanics and Mobility Published 1995						x		

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